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australian earth sciences convention

Geological Society of Australia,
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Canberra, Australian Capital Territory

20th Australian Geological Convention

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www.aesc2010.gsa.org.au

Earth systems:
change
sustainability
vulnerability
4-8 July 2010
National Convention Centre Canberra

Contents

Welcome to AESC 2010 3
Convention Organising Committee 3
Sponsors and supporters 4
Speakers 5
Awards 7
General information 8
Social program 11
Workshops 12
Additional meetings 13
Post-convention fieldtrips 13
Telephone directory 14
Sponsors 15
Supporters 16
Exhibitors 17
Program 26
Posters 43
Plenary abstracts 50
Concurrent abstracts 53
Poster abstracts 296

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GEOSCIENCE AUSTRALIA at AESC 2010



visit us at booths 1 & 4

Geoscience Australia is the nation's largest employer of geoscientists and the national custodian of geoscience information and data.

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- North Queensland geodynamics
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- Evolution of the Gawler Craton
- Natural hazards research in Australia and Oceania
- Prospectivity of the Capel and Faust basins

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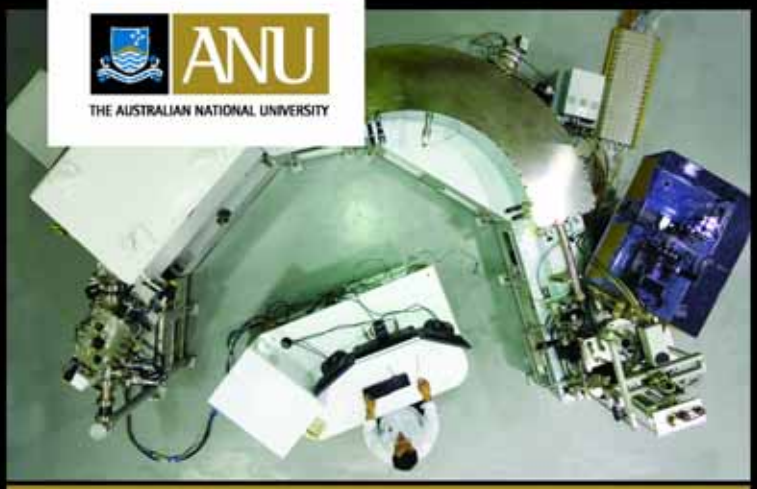
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- paleovalley groundwater systems
- Antarctic research
- Australian Stratigraphic Unit Index
- education and public awareness
- AUSTRALIA 2012 (34th IGC)

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http://rses.anu.edu.au/index.php

Welcome to AESC 2010

On behalf of the local organising committee and the Geological Society of Australia, I welcome you to AESC 2010 at the National Convention Centre in Canberra. I hope that you find the scientific and social programs enjoyable. I also encourage you to explore Canberra and the surrounding region during your stay.

Earth sciences have been almost constantly in the news this year, from the devastating Chile earthquake to the massive oil spill in the Gulf of Mexico, as well as climate change and the resources super profit tax. Next year, who knows? Nevertheless, I expect that the broad themes of hazards, resources and climate change will be topical for a long time yet. Indeed, our science is fundamental to human survival and is reflected in the Convention theme of *Earth Systems: Change, Sustainability, Vulnerability*. These are serious issues, but let's not lose sight of an important reason we go to conferences—to have fun!

So, have fun at AESC 2010.



Brad Pillans
Convenor, Convention Organising Committee

Convention Organising Committee

Brad Pillans (Convenor), The Australian National University
Allan Chivas, University of Wollongong
Frederick Cook, EARTHECONX
Michelle Cooper, Geoscience Australia
Sue Fletcher, Geological Society of Australia
Clinton Foster, Geoscience Australia
Brian Kennett, The Australian National University
John Mavrogenes, The Australian National University
Marc Norman, The Australian National University
Brad Opdyke, The Australian National University
Chris Pigram, Geoscience Australia
Monica Yeung, Gondwana Dreaming
Jane Carter, Conference Logistics
Renae Shepherd, Conference Logistics

Convention Secretariat
Conference Logistics

CONFERENCE LOGISTICS

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Speakers

Plenary speakers

Martin Brasier

Martin Brasier is Professor of Palaeobiology at the University of Oxford in the United Kingdom. He is also a Fellow of St Edmund Hall, Oxford. His other duties have included serving as Chairman of the Faculty of Earth Sciences; Chairman of the Subcommission on Cambrian Stratigraphy; membership of NSF panels; membership of NASA panels on life on Mars.

He also holds a Professorship at Memorial University, Newfoundland. His first popular science book “Darwin's Lost World” was published this year as a celebration of Darwin's 200th birthday.

His current areas of field activity include the Archaean of Australia and the Proterozoic and Cambrian of Australia, Asia and Oman as well as Britain. He often undertakes active comparisons between recent and ancient ecosystems, and he likes to pioneer innovative high resolution techniques, ranging from satellite imaging and field mapping to microscopic mapping using Confocal Microscopy, Laser Raman, NanoSims and other biogeochemical mapping techniques. All of these approaches are driven, however, by his search for innovative and provocative questions. Science is not a belief system - it is a unique system for the measurement of doubt.

Important resources available to his research group include: thousands of specimens relating to the origins of the major animal groups, accumulated during the last fifty years; thousands of polished thin sections relating to the earliest microscopic life; high quality Nikon Multiphot imaging facilities; an extensive library; and a field base for researchers and visitors on the coast of Pembrokeshire.

Patrick De Deckker

Patrick De Deckker is Associate Director, Earth Environment, Research School of Earth Sciences, Australian National University.

Patrick De Deckker completed a PhD in the Zoology Department at the University of Adelaide on salt lakes, their biota and Quaternary lacustrine deposits. He continued in this field during seven years of postdoctoral positions. He obtained a DSc from the same university, from the Department of Geology and Geophysics, for long-term accomplishment in the fields of limnology, palaeolimnology, palaeoceanography and micropalaeontology.

In 1988, Patrick joined the Australian National University and has held a full-time teaching position combined with research ever since. He led the informal Australian Marine Quaternary Program that brought together many people working on many aspects of marine science and deep-sea cores. During his entire career, Patrick’s work has always been multidisciplinary in nature with a common aim: to obtain information of relevance for the reconstruction of past marine and continental environments of importance for the understanding of global and regional climatic variability.

Rob Hough

Rob Hough is a research scientist with CSIRO Earth Science and Resource Engineering.

Using the largest research gold collection in Australia (valued at more than A$1 million), he is able to study properties of gold that have previously been overlooked, ignored or were not known to have existed. This research has allowed for a greater understanding towards the formation of gold deposits in the earth and challenges century old views of how gold nuggets are formed. This information will lead towards improved exploration methods that can be adopted by industry worldwide to help locate new deposits.

Robert has enjoyed a career in Earth and Planetary Sciences both locally and in the United Kingdom (UK). Starting out as a Postdoctoral Research Fellow in Planetary Sciences at The Open University in the UK, Dr Hough then came to Australia to work as a Royal Society research fellow for the Western Australian Museum. In 2004 he joined the CSIRO as a Postdoctoral Research Fellow, before becoming a Research Scientist in 2005.

Belinda Robinson

Belinda Robinson is CEO of the Australian Petroleum Production & Exploration Association Limited (APPEA).

She is a leading voice in public policy particularly around issues related to energy and resources. In addition to her position as Chief Executive of the Australian Petroleum Production & Exploration Association Limited, Belinda also sits on a number of advisory committees including the Government's Reference Group responsible for developing a national energy security policy and CSIRO's Energy Transformed Flagship Advisory Committees. She also chairs the Australian Industry Greenhouse Network and CSIRO's Wealth from Oceans Flagship Advisory Committee.

As Chief Executive of APPEA, Belinda is a determined and enthusiastic advocate of the role that Australia's vast reserves of natural gas, including in its export form as Liquefied Natural Gas, should be playing in stimulating Australia's economic growth by moving to a cleaner energy future.

Belinda came to APPEA from A3P, the Australian Plantation Products & Paper Industry Council, where she was the Chief Executive Officer for almost five years. She also spent nine years with the Federal Government including six in senior and executive positions within the Department of the Prime Minister and Cabinet where she was responsible for the oversight of a range of resource, primary industries and environment policy issues.

Belinda has also worked in a variety of resource planning roles in State and local governments.

She holds three degrees including a Master of Environmental Law from the Australian National University.

Keynote speakers

Martin Anderson, Water Research Laboratory, University of New South Wales

Graham Begg, GEMOC, Macquarie University

Roger Clark, Airborne Visible Infrared Spectrometer (AVIRIS) program, United States Geological Survey

Marco Fiorentini, Centre for Exploration Targeting, University of Western Australia

David Giles, Centre for Mineral Exploration Under Cover, University of Adelaide

Robert Green, HyspIRI Mission Co-Lead, Moon Mineralogy Mapper Instrument Scientist, AVIRIS Experiment Scientist, Jet Propulsion Laboratory, Pasadena, California, USA

Kliti Grice, Applied Chemistry Department, Curtin University

Phil Harris, GSI Consulting, Anglo American Corporation retired, Johannesburg, South Africa

Jennifer Heldmann, NASA Ames Research Centre, USA

Richard Henley, Research School of Earth Sciences, Australian National University

Andrew Kohlrusch, GHD Pty Ltd

Leah Moore, Faculty of Applied Science, University of Canberra

Wal Muir, MBA Petroleum Consultants

Colin Murray-Wallace, School of Earth & Environmental Sciences, University of Wollongong

Tim Naish, Director, Antarctic Research Centre, Victoria University of Wellington

Steve Ruff, Research Associate, Mars Space Flight Facility, School of Earth and Space Exploration, Arizona State University, USA

Mike Sandiford, School of Earth Sciences, University of Melbourne

John Schneider, Geoscience Australia

Tim Stern, Victoria University of Wellington, New Zealand

Mark van Zuilen, Centre for Geobiology, Bergen, Norway

Kevin Welsh, School of Earth Sciences, University of Queensland

Awards

Tuesday 6 July

Citation of the Mawson Medal

—by Dr Sue Meek, Chief Executive, Australian Academy of Science (Royal Theatre)

GSA Awards

—presented by Brad Pillans, GSA President (Royal Theatre)

S.W. Carey Medal
Awarded to a person distinguished in the field of tectonics (sensu lato). **The 2010 Medal is awarded to Bill Collins.**

Joe Harms Medal
Awarded to a person distinguished for excellence in mineral exploration and contribution to the discovery of ore deposits. **The 2010 Medal is awarded to Chris Bonwick.**

E.S. Hills Medal
A new medal of the Society awarded to a young (<40 years) Australian resident for outstanding contribution(s) to any branch of the geological sciences, anywhere. **The 2010 Medal is awarded to Nathan Daczko.**

W.R. Browne Medal
Awarded to a person distinguished for contributions to the geological sciences in Australia. **The 2010 Medal is awarded to Tony Cockbain.**

Thursday 8 July

AJES Awards

—presented by Anita Andrew, AJES Editor (Royal Theatre)

The F.L. Stillwell Award
The F.L. Stillwell Award is a medal awarded to the author or authors of the best paper of the year in the Australian Journal of Earth Science, judged by the Editorial Board. This award is supported by the Stillwell Bequest. Frank Leslie Stillwell, FAA, was a geologist in charge of the Mineragraphic Section of CSIR (later CSIRO) from 1929 to 1953.

2008 Winners: Andrew Heap and Peter Harris for their paper *Geomorphology of the Australian margin and adjacent seafloor* (AJES 55, 555–585).

2009 Winners: J. Braun, D. R. Burbidge, F. N. Gesto,M. Sandiford, A. J. W. Gleadow, B. P. Kohn and P. R. Cummins for their paper *Constraints on the current rate of deformation and surface uplift of the Australian continent from a new seismic database and low-T thermochronological data* (AJES 56, 99–110).

The David I. Groves Award
The David I. Groves Award is a medal award for the best paper published in the Australian Journal of Earth Sciences by a young author, who must be the senior author: the eligibility criterion is that the senior author, at the time of submission, must have had a first degree in any relevant science for less than six years.

2008 Winner: Justin Payne, the senior author of the paper *Temporal constraints on the timing of high-grade metamorphism in the northern Gawler Craton: implications for assembly of the Australian Proterozoic* (AJES 55, 623–640), written jointly with Martin Hand, Karen Barovich and Ben Wade.

2009 Winner: Jonathan Giddings, the senior author of the paper 'Interglacial carbonates of the Cryogenian Umberatana Group, northern Flinders Ranges, South Australia' (AJES 56, 907–925), written jointly with Malcolm Wallace and Estee Woon.

General information

Registration desk

The registration desk is located in the Main Foyer of the National Convention Centre. Staff at the registration desk will be able to assist you with any queries you may have relating to your registration, accommodation and social function bookings. The registration desk will be open during the following times:

Sunday 4 July	1500–1900
Monday 5 July	0730–1830
Tuesday 6 July	0800–1830
Wednesday 7 July	0800–1830
Thursday 8 July	0800–1700

The registration desk can be contacted during these hours on 0448 576 105.

Accommodation

For those delegates who booked accommodation through the Convention Secretariat, please ensure that accounts are settled in full prior to your departure and that the appropriate deposit has been deducted from your account.

Catering

Lunch, morning coffee and afternoon tea are included in your registration fee and will be served in the exhibition hall during the programmed breaks. Dietary requirements noted on your registration form have been passed on to the catering staff. Vegetarian options will be available during lunch but if you have advised other more specific dietary requirements (e.g. vegan, gluten intolerance) please ask one of the venue staff and they will provide you with your meal.

At the dinner, vegetarian meals will only be available for those who have previously advised.

Evaluation

Delegates are encouraged to complete the Convention evaluation form, as it assists the GSA to plan future Conventions. A link to the online evaluation form will be emailed to delegates at the conclusion of the Convention.

Exhibition hours

The exhibition will be open during the following times:

Sunday 4 July	1730–1900
Monday 5 July	1000–1830
Tuesday 6 July	1000–1830
Wednesday 7 July	1000–1830
Thursday 8 July	1000–1400

Helpers

There will be ‘helpers’ throughout the Convention venue to assist you. Helpers will be wearing blue AESC 2010 T-shirts.

Internet access

There will be an Internet Cafe with five terminals available. Please limit your time to ten minutes so that the facilities can be shared by as many delegates as possible. Internet cards can be purchased from the National Convention Centre Reception Desk.

Lost or found property

Please report any lost or found property to the Convention registration desk.

Luggage storage

During the Convention, luggage can be stored at the National Convention Centre Reception Desk.

Medical emergency

In case of an emergency, please contact any staff member of the National Convention Centre or the registration desk staff.

Mobile phones

As a courtesy to speakers and other delegates, please ensure your mobile phone is turned off or in silent mode during all sessions and social functions

Name badges

Your name badge is your entry to all sessions, exhibition, social functions (you will also require your ticket for the Convention Dinner and GeoTrivia), lunches and morning and afternoon teas. Please wear it at all times. If you misplace your name badge or tickets please see the staff at the registration desk for a replacement.

Notice board

A notice board will be maintained adjacent to the registration desk showing program changes, messages and other information. Please check the board regularly for updates.

Parking

Car parking is available at the National Convention Centre for a flat rate of $10.00 per day. The car park can be entered from Constitution Avenue. There is internal lift access from the car park entry level to both levels of the Convention Centre. Additional paid parking is available opposite the National Convention Centre for $7.50 per day.

Participant list

The participant list has been included in the convention satchel. Those delegates who have indicated on their registration form that they do not wish to have their details appear on the participant list have not been included.

Posters

Posters will be located in the exhibition hall and will be on display for the duration of the Convention. Poster board numbers will be displayed on all poster boards. Please look for your poster board number when setting up your poster. It is the presenter's responsibility to place and remove their poster and the Convention organisers will not be responsible for posters left behind at the end of the Convention.

Program changes

The Convention organisers cannot be held responsible for any program changes due to external or unforeseen circumstances. Please check the notice board located near the registration desk for any changes to sessions.

Secretarial services

The National Convention Centre can provide printing, photocopying and facsimile services for a small fee. Please visit the reception desk.

Smoking

Please note that the National Convention Centre is a non-smoking venue.

Speakers' preparation room

A speakers' preparation room is located in the Executive Room on the first floor of the National Convention Centre and will be open at similar times to the registration desk. All speakers must take their presentation to the speakers' preparation room a minimum of four hours prior to their presentation, or the day before if presenting at a morning session.

Speakers are also requested to assemble in their session room twenty minutes before the commencement of the session, to meet with their session chair and to familiarise themselves with the room and the audiovisual equipment.

Students

Registered students are required to present proof of student status when registering at the Convention registration desk.

Transport

AirLiner

The AirLiner bus service operates between Canberra City and Canberra Airport, Monday to Friday, every 30 minutes and on Saturday and Sunday approximately every hour. A one way ticket is $9.00, and $15.00 return. You can board the AirLiner bus from the central terminal right outside the main doors. For more timetable and pricing information visit www.airliner.com.au or contact Deanes Buslines on 02 6299 3722, or email travellerinfo@deanesbuslines.com.au.

Airlines

Qantas	13 13 13
Virgin	13 67 89
REX	13 17 13
Tiger	03 9335 3033

Buses around Canberra

ACTION is the major bus service provider in the ACT, with routes servicing all regions of Canberra. Please visit the ACTION website for more information: www.action.act.gov.au.

Rental cars

If you're a visitor to Canberra the best transport option is to rent a car, even if it is for a day trip. Rental car desks are located inside the central terminal area. While it is best to book ahead, rental cars are available on the day.

Avis	02 6249 1601	www.avis.com.au
Budget	02 6257 1305	www.budget.com.au
Europcar	13 10 45	www.europcar.com.au
Hertz	02 6249 6211	www.hertz.com.au
Thrifty	02 6248 9081	www.thrifty.com.au

Taxis

Taxis are available at all times of the day from the front of the Terminal. An average fare to the city is $24.00. The Convention venue is approximately 20 minutes by taxi from Canberra Airport.

Taxis Combined Services	13 22 27
Canberra Xpress	02 6260 6011

Viewing abstracts

Abstracts can be viewed online from the Convention website www.aesc2010.gsa.org.au. The above mentioned Internet Cafe is provided to view these abstracts.

Social program

Ice Breaker/Welcome Reception

Time: 1730–1900
Date: Sunday 4 July 2010
Venue: National Convention Centre Canberra, Exhibition Hall
Dress: Convention attire/neat casual
Cost: Included in full Convention registrations. If you are a day registrant or accompanying person and would like to attend, please see the staff at the registration desk. Additional tickets are $60 per person.

Education and Careers Evening

Time: 1600–1800
Date: Monday 5 July 2010
Venue: Geoscience Australia, Corner Jerrabomberra Avenue and Hindmarsh Drive, Symonston
Cost: Free of charge

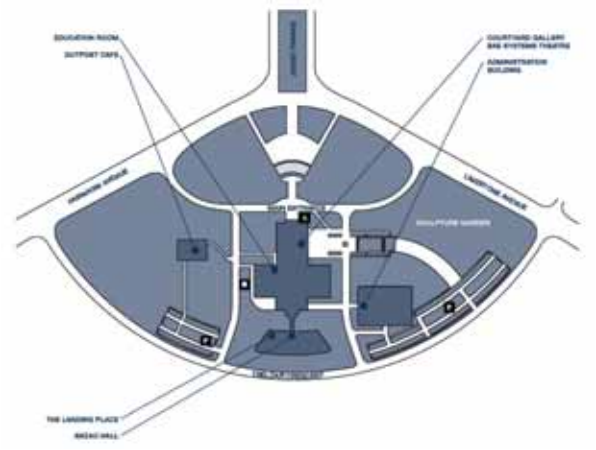
To celebrate the diverse nature and job prospects of this dynamic field of study, a free student and careers night is being held during the Convention at Geoscience Australia. Students, teachers, parents and interested members of the public will be able to engage with professionals from all around Australia and discover what careers exist in these fields and what study pathway to take.

GeoTrivia

Time: 1830
Date: Tuesday 6 July 2010
Venue: National Convention Centre Canberra
Dress: Smart casual
Cost: GeoTrivia is not included in the registration fee. The cost to attend is $35 per person. If you would like to attend, please check if there are still tickets available with the staff at the registration desk.

Convention dinner

Time: 1900 for 1930
Date: Wednesday 7 July 2010
Venue: ANZAC Hall, Australian War Memorial
Dress: Smart casual
Cost: The Convention dinner is not included in the registration fee. The cost to attend is $120 per person. If you would like to attend, please check if there are still tickets available with the staff at the registration desk.



Please refer to the Australian War Memorial map for the location of ANZAC Hall. The entrance to ANZAC Hall is located as shown by the line and circle.

Transport to and from the dinner

1830 Coach to collect delegates from Rydges Lakeside (at side of hotel—Edinburgh Street)
1845 Coach to collect delegates from Crowne Plaza (front) and Novotel Canberra (rear of hotel—Bay 7)
1850 Coach to collect Medina James Court (rear of hotel in Mort Street) and Mantra on Northbourne (rear of hotel in Mort Street)

2200 Coach transfer to hotels
2230 Coach transfer to hotels
2300 Coach transfer to hotels
2330 Coach transfer to hotels
2345 Coach transfer to hotels

Workshops

Geoheritage, geotourism and the geoscience professions workshop

Time: 1340–1710

Date: Tuesday 6 July

Venue: Murray Room, National Convention Centre

Please refer to the full Convention program (page 32–33) for more information

3D mineral spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium

Jon Huntington, CSIRO and AuScope

Date: Thursday 8 July and Friday 9 July

Venue: Murray Room, National Convention Centre

Please refer to the full Convention program (page 38–42) for more information

Sampling rocks and preparing minerals for high-quality isotopic geochronology

Time: 0800–1600

Date: Friday 9 July

Venue: Mini-bus pickup in central Canberra. More information to be provided at the Convention.

Fee: $20 and free for students.

Quality assurance in analytical geochemistry

Time: 1000–1600

Date: Friday 9 July

Venue: Geoscience Australia
Cnr Jerrabomberra Ave and Hindmarsh Drive
Symonston ACT 2609
www.ga.gov.au

Getting there: The No. 80 bus departs the Civic Bus Interchange at 0859 and arrives at Geoscience Australia at 0952. A return bus leaves Geoscience Australia at 1608.

The No. 4 bus departs the Civic Bus Interchange at 0907 and arrives at Geoscience Australia at 0952.

Fee: $65 for IAG and GSA members, $100 for non-members. Fee includes morning and afternoon tea and lunch.

The workshop is sponsored by the International Association of Geoanalysts and will discuss the latest practices for the production of 'reliable' geochemical data that are associated with measurement uncertainties fit-for-the-purpose. It will discuss the role of measurement uncertainty and how it is affected by such issues as sample preparation, sample heterogeneity and data acquisition. Participants will be given an overview of current understanding of metrological traceability and the proper use of reference materials.

Additional meetings

Date	Meeting name	Room	Time
Sunday 4 July	GSA Council Meeting	Swan Room	1000–1500
Monday 5 July	Australian Stratigraphic Commission	Torrens Room	1230–1400
	SGSEG Meeting	Murray Room	1730–
	Specialist Group in Sedimentology	Gallery Foyer	1800–1930
	GSA Annual General Meeting	Swan Room	1830–2030
Tuesday 6 July	AJES Editorial Meeting	Swan Room	1220–1340
	National Geochemical Survey of Australia	Derwent Room	1220–1320
Wednesday 7 July	Australia Geoscience Council Annual General Meeting	Derwent Room	1230–1330
	SGGMP Committee Meeting	Swan Room	1220–1340
	Geological Heritage Standing Committee	Derwent Room	1550–1830
	AuScope Informal Information Session (more information below)	Fitzroy Room	1710–
	AuScope's symposium on Wednesday will conclude at 5.10pm followed immediately by an informal information session focused on future research infrastructure requirements for the Australian continent. Developing consensus and clarity on this is an exciting challenge for the science community and as part of AuScope's activities between now and mid 2011, we will engage in a process of consultation to determine future infrastructure requirements for Australian earth and geospatial science. We invite all to join us for refreshments and to participate in this information session that will introduce the process and encourage participation in shaping the future infrastructure to underpin your future research efforts.		
Thursday 8 July	Earth Science History Group	Torrens Room	1630–1730

Post-convention fieldtrips

Lake George geology and geomorphology

Leader: Professor Patrick De Deckker
Date: Friday 9 July 2010
Duration: 2/3 day
Cost: $85
Departs: from the National Convention Centre at 0830, Friday 9 July.

Lake George, its fault scarp and its geological history make for an interesting trip. Even without the mysterious stories told in local folklore, the lake has a fascinating geological past! A great deal of work has been done to work out its geological history. In addition, its shores are home to some of the Canberra region's best wines! A day of geology, wine tasting and winery lunch.

Wee Jasper palaeontology

Leader: Dr Gavin Young
Date: Saturday 10 July 2010
Duration: 1 day
Cost: $190
Departs: from the National Convention Centre at 0815, Saturday 10 July
Travel by: 4x4 vehicles

The Wee Jasper valley is a must see destination for anyone with an interest in palaeontology. Inspect a 4-5 km section of stratigraphy (Kirawin/Sugarloaf to Hatchery Creek via limestones) from the oldest terrestrial arthropods from Gondwana, the world's oldest sharks, through the rise and demise of a coral reef housing the world's first tropical reef fish assemblage, then (subject to the weather and road conditions) visit some sites in the Hatchery Creek Formation known for containing the oldest roots and the oldest leaves. Includes lunch, morning and afternoon tea and local wine.

Telephone directory

Registration desk	0448 576 105
National Convention Centre	02 6276 5200

Accommodation

Rydges Lakeside Canberra	02 6247 6244
Medina Executive James Court	02 6240 1234
Breakfree Capital Tower	02 6276 3444
Mantra on Northbourne	02 6243 2500
The Brassey of Canberra	02 6273 3766
Crowne Plaza Canberra	02 6247 8999
Novotel Canberra	02 6245 5000
The Marque	02 6249 1411

Taxis

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Geoscience Australia assists the Australian Government and the community to make informed decisions about the discovery and development of mineral and energy resources, management of the environment, community safety and protection of critical infrastructure. Geoscience Australia, the national geoscience agency, is part of the Australian Government Department of Resources, Energy and Tourism.

For more information:

sales@ga.gov.au
T: 02 6249 9111

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The Research School of Earth Sciences consistently ranks as the top university program in Australia and among the top ten university-based geoscience programs in the world. We aim to tackle fundamental questions about the formation, evolution and present nature of the Earth and its place in the Solar System, with equal focus on the solid Earth and the oceans and environment. Our research is underpinned by world-class facilities in geochemistry, geochronology, paleoceanography, experimental petrology, rock deformation, geophysics, fluid dynamics and high performance computing (for details see http://rses.anu.edu.au/facilities/index.php). Our wide range of skills and effective collaborations between scientists with different expertise, coupled with our laboratory facilities, enables us to creatively apply observational, experimental, numerical modelling and theoretical approaches to a broad spectrum of questions in earth science. We have also pioneered development of unique instrumentation to address major problems in earth science through our outstanding mechanical and electronic workshop facilities. The challenge of understanding the Earth offers excellent research opportunities. We welcome postgraduate students, research collaborations and partnerships to address key questions in earth science.

For more information:

Prof Andrew Roberts
Director
Research School of Earth Sciences
ANU College of Physical and Mathematical Sciences
Building 61, Mills Road
The Australian National University
Acton ACT 0200

Director.RSES@anu.edu.au
T: 02 6125 2487
F: 02 6125 0756

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The role of the exploration group is to add value to Rio Tinto by discovering or acquiring resources that can increase future cash flows. It is organised into regional multi-commodity teams, with head offices in the UK, the US and Australia, supported by commodity and commercial specialists. Programs are prioritised on a global basis, with investment decisions driven not by location or choice of commodity but rather by the quality of each opportunity. We are currently actively exploring in 17 countries.

Contact details

Sue Thornton
Exploration Australasia
Rio Tinto
410 Ann Street
Brisbane 4000

Sue.Thornton@riotinto.com
T: 07 3029 1812
F: 07 3029 1105

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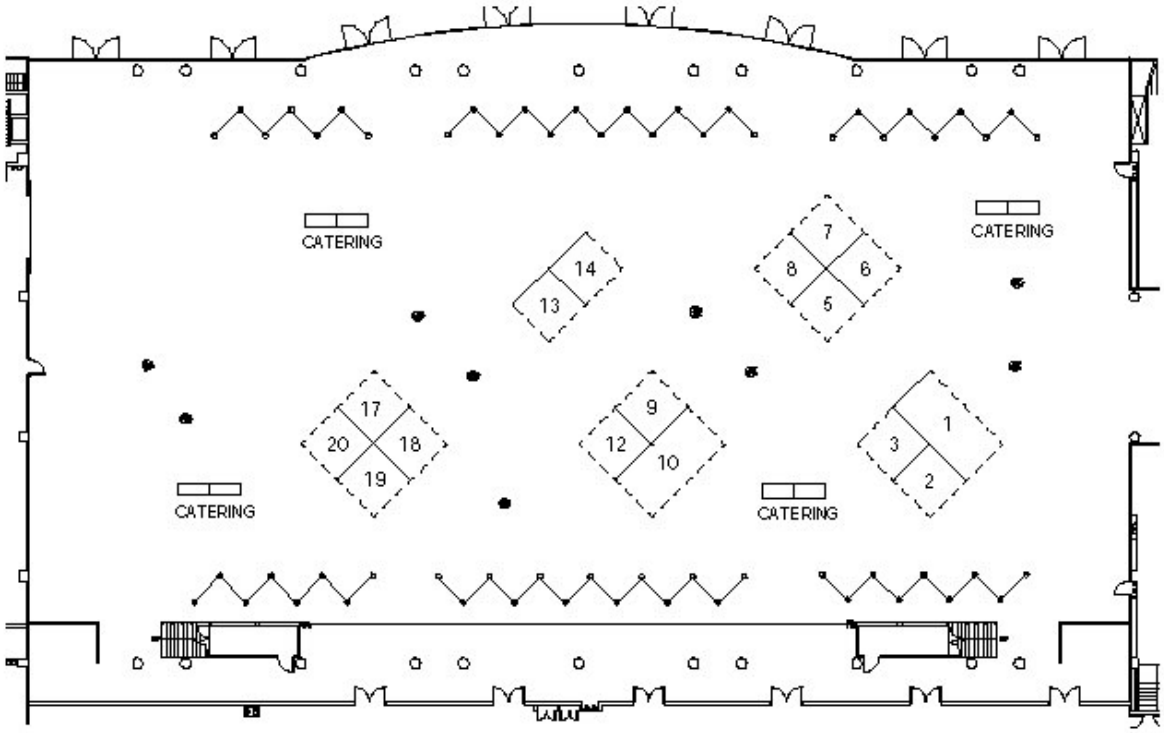
Exhibitors

Exhibition hours

The exhibition will be open during the following times:

Sunday 4 July	1730–1900
Monday 5 July	1000–1830
Tuesday 6 July	1000–1830
Wednesday 7 July	1000–1830
Thursday 8 July	1000–1400

Exhibition floor plan



Booth no.	Organisation	Booth no.	Organisation
1	Geoscience Australia	10	Geological Society of Australia
2	Queensland Government	12	Prospectors Earth Sciences
3	Geological Survey of New South Wales	13	Integrated Ocean Drilling Program (IODP)
5	GNS Science/Rafter Radiocarbon	14	Specim Hyperspectral from Adept
6	Australian National University	17	AuScope
7	Australian Scientific Instruments	18	GeoScience Victoria
8	Actlabs Pacific	19	Internet Cafe sponsored by Industry & Investment NSW
9	Archimedes Financial Planning	20	Taylor & Francis

Booth 1

Geoscience Australia

Geoscience Australia assists the Australian Government and the community to make informed decisions about the discovery and development of mineral and energy resources, management of the environment, community safety and protection of critical infrastructure. Geoscience Australia, the national geoscience agency, is part of the Australian Government Department of Resources, Energy and Tourism.

Our display features the latest

- continent-scale maps and datasets (surface geology, gravity, magnetics, radiometrics and soil chemistry)
- regional-scale geophysical datasets
- energy and mineral systems studies (3D modelling and prospectivity assessments)
- offshore petroleum exploration opportunities
- frontier sedimentary basin studies
- high-quality marine geophysical datasets
- seafloor mapping for marine management
- tsunami hazard modelling in Australia and Oceania
- Australian Geomagnetic Reference Field
- national information to support disaster management decisions
- groundwater systems modelling
- geoscience education materials
- preparations for the AUSTRALIA 2012 (IGC) in Brisbane.

Contact details

T: 02 6249 9111
sales@ga.gov.au

www.ga.gov.au

Applying geoscience to Australia's most important challenges

Booth 2

Queensland Government

The Geological Survey of Queensland (GSQ), as part of the Department of Employment, Economic Development and Innovation, provides geoscience and resource information to improve the understanding of the geology and minerals and energy resource potential of Queensland. GSQ provides comprehensive information through publications and maps, digital data sets and compilations, and access to core and rock collections. GSQ projects include a revision of the geology of the Mount Isa region, geophysical data acquisition and collaborative drilling funded under the Smart Exploration and Smart Mining—Future Prosperity programs. Projects to investigate the potential for carbon capture and storage and geothermal energy are also under way.

Contact details

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Booth 3

Geological Survey of New South Wales

The Geological Survey of New South Wales develops the necessary geoscientific information framework to encourage mineral exploration and support land use assessment and natural resource management. A focus through the New Frontiers initiative, includes the release of new geological mapping and geophysical data, geochemistry, isotope data, 3D modelling together with new interpretations of the tectonic evolution of New South Wales. New products released at the Convention include:

- explanatory notes for the Koonenberry Belt geological maps
- Koonenberry Belt geological maps at 1:25 000 scale over Mt Arrowsmith, Warratta, Tibooburra and Mount Poole / Mount Browne
- Thomson Orogen DVD (Version 2)—update of work-in-progress that includes revised interpretation, improved depth-to-bedrock model, new age dating and updated imagery
- statewide geophysical data (Version 2) available as a 4xDVD set

Contact details

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Booth 5

GNS Science/Rafter Radiocarbon

GNS Science is an earth science research institute focusing on geological resources, environmental science, and natural hazards. Our Rafter Radiocarbon and GNS Stable Isotope Lab provide radiocarbon dating and isotope analysis on a commercial basis for clients worldwide. We also do some cosmogenic analysis and prepare thin sections.

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www.gns.cri.nz/nic/rafterradiocarbon
www.rafterradiocarbon.co.nz

Booth 6

The Australian National University

THE AUSTRALIAN NATIONAL UNIVERSITY

The Research School of Earth Sciences consistently ranks as the top university program in Australia and among the top ten university-based geoscience programs in the world. We aim to tackle fundamental questions about the formation, evolution and present nature of the Earth and its place in the Solar System, with equal focus on the solid Earth and the oceans and environment. Our research is underpinned by world-class facilities in geochemistry, geochronology, paleoceanography, experimental petrology, rock deformation, geophysics, fluid dynamics and high performance computing (for details see http://rses.anu.edu.au/facilities/index.php). Our wide range of skills and effective collaborations between scientists with different expertise, coupled with our laboratory facilities, enables us to creatively apply observational, experimental, numerical modelling and theoretical approaches to a broad spectrum of questions in earth science. We have also pioneered development of unique instrumentation to address major problems in earth science through our outstanding mechanical and electronic workshop facilities. The challenge of understanding the Earth offers excellent research opportunities. We welcome postgraduate students, research collaborations and partnerships to address key questions in earth science.

Contact details

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Booth 7

Australian Scientific Instruments

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Australian Scientific Instruments (ASI) is a subsidiary of ANU Enterprises (ANUE), the commercial arm of the Australian National University (ANU). ASI manufactures the world-renown SHRIMP IIe sensitive high resolution ion microprobe, the Alphachron helium thermochronology instrument and the unique Paterson high temperature, high pressure rock deformation apparatus.

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- The Institution of Engineers Australia, Engineering Excellence Award

ASI's close relationship with university scientists also confers an advantage over many of its competitors because new concepts can be evaluated in a research environment recognised in academic circles as world class, and the results are communicated widely by scientists to their scientific counterparts via journal articles and conferences, reinforcing the equipment's scientific credibility.

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Booth 8

Actlabs Pacific

Actlabs Pacific has a purpose built laboratory near the Perth Airport domestic terminal. This laboratory was established in 1998 after Activation Laboratories purchased the WMC Exploration Division laboratories in Kalgoorlie. Our new sample preparation facility in Bayswater significantly increases our capacity in Perth and allows us to offer faster turnaround. We have expanded our facilities in Perth to offer Flame AA, ICP/AES and ICP/MS analysis on a range of digestion products and fusion products. This allows us to provide a full range of analyses from trace level analysis to high grade assays. We also offer several other forms of analysis, including C and S elemental analysis and traditional assays such as titrimetry. Our association with Activation Laboratories in Canada also allows us to offer a wider range of analyses including XRD, XRF, HR-ICP/MS and nuclear techniques such as instrumental neutron activation analysis and delayed neutron counting. Over half our staff have been with the company for over 10 years and we have been able to maintain a base of experienced and qualified personnel. Many of our laboratory technicians are currently enrolled or have completed a Certificate II, III or IV training in Laboratory Techniques.

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Sample Prep: Actlabs Pacific Pty Ltd.
18 John Street
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Booth 9

Archimedes Financial Planning

Archimedes Financial Planning undertakes extremely thorough and personalised analyses of people's financial status, needs and objectives. Specialising in resource industry Australian citizens or residents who live throughout Australia and internationally, we provide highly advanced risk management techniques such as Efficient Frontier investment portfolios.

Specialist expertise areas include:

- wealth creation planning
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- mortgage broking and finance (through Australian Loan Company)

The advisers of Archimedes Financial Planning Pty Ltd provide financial services as authorised representatives of Professional Investment Services Pty Ltd, ABN 11 074 608 558, AFSL Holder No. 234951.

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Booth 10

Geological Society of Australia

The Geological Society of Australia was established as a non-profit organisation in 1952 to promote, advance and support earth sciences in Australia.

Key strategies are to:

- cater for a wide diversity of members
- influence the decision-making processes of government, particularly to support geoscience research and teaching
- encourage and promote wider community awareness and application of earth sciences
- provide media and forums for communication in the earth sciences.

Members represent all earth science professions, including geologists, geophysicists, geochemists, palaeontologists, geotechnical and engineering geologists, environmental geologists, and associated professions. Members come from the minerals and petroleum industries, government departments, research and education institutions and consultancy groups.

The Society has a division in each state and territory, and regular meetings are held Australia-wide, at which members may keep in touch with scientific developments, present the results of their work and contribute to discussions on vocational and scientific topics. Specialist groups cater to different sectors of the earth sciences.

The GSA publishes journals for earth scientists and the community. *The Australian Journal of Earth Sciences*, is the official journal of the Society, *The Australian Geologist*, is GSA's quarterly member magazine.

Contact details

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Sydney NSW 2000

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www.gsa.org.au/index.html

Booth 12

Prospectors Earth Sciences

The supplier of choice for many geologists, earth scientists and outdoor professionals, across Australia and around the world; Prospectors imports and distributes some of the world's leading professional brands, including Suunto Precision Instruments, Breithaupt, Brunton, Rite in the Rain, Saunders-USA, Freiberg, Yamayo, and Pesola.

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Prospectors Earth Sciences Pty Ltd
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www.prospectors.com.au

Booth 13

Integrated Ocean Drilling Program (IODP)

The Integrated Ocean Drilling Program (IODP) aims to solve global scientific problems by taking continuous core samples of rocks and sediments at a great variety of sites in the world's oceans. IODP carries out deep scientific coring in all the world's oceans using a variety of platforms, and provides 'ground truthing' of scientific theories that are based largely on remote sensing techniques. IODP's key research areas are described in IODP's 'Initial Science Plan' and are:

- deep biosphere and ocean floor
- environmental changes, processes and effects
- solid earth cycles and geodynamics.

Australia and New Zealand form the Australia-New Zealand IODP Consortium (ANZIC), and the two countries have access to all IODP activities including shipboard and post-cruise research, participation in planning committees and groups, and visits from outstanding scientific speakers.

Both countries provide members of the ANZIC Governing Council, and of the ANZIC Science Committee. The Australian involvement is funded by the Australian Research Council, 14 universities, and three government agencies, and the marine geoscience peak body MARGO (see link to ANZIC membership and funding).

Potential Australian IODP expedition applicants should check what expeditions are open on the International IODP web page, and can contact Neville.Exon@anu.edu.au for further information or visit www.iodp.org.au.

Contact details

The Australian IODP Office is based at the Research School of Earth Sciences at the Australian National University and is the international and ANZIC contact point.

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New Zealand's partnership is led by GNS Science in Wellington

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drill.gns.cri.nz

Booth 14

Specim Hyperspectral from ADEPT

Specim is a world leader in the manufacture and supply of hyperspectral systems and components. Specim's products are applicable to airborne and ground-based systems that include field and laboratory-based hyperspectral scanners. Their products are used worldwide for wide ranging applications, including mineralogy and mining, agriculture, environment, food and water, life sciences, recycling, industrial and many others. SPECIM's hyperspectral imagers and systems cover wavelengths from near UV to long wave infrared. They supply fully integrated systems to end-users or hyperspectral spectrographs, imagers and optics to OEM's and systems integrators.

SPECIM is represented in Australia and New Zealand by Adept Electronic Solutions who are specialists in machine vision and imaging. Founded in 1988 Adept has established itself as the leading and largest specialist vision technology supplier in Australia. With offices in Sydney, Melbourne and Perth, Adept sells and supports its products throughout Australia and New Zealand. Employing a team of experienced technical specialists allows Adept to value add its product sales by providing expert technical support to its wide range of customers, including end-users, systems integrators and OEMs.

Contact details

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T: Melbourne 03 9555 5621
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www.specim.fi
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Booth 17

AuScope

AuScope is an organisation managing a national earth science infrastructure program. Through its six components—AuScope Grid and Interoperability, Simulation, Analysis and Modelling (SAM), Earth Imaging, Geospatial Framework, National Virtual Core Library and Earth Composition and Evolution—it aims to redefine knowledge transfer and access for Australian earth science researchers to contribute to an earth model for the Australian continent.

Visitors to the AuScope booth will experience the seamless access being developed to earth science research through the AuScope portal as well as the cutting edge work of the AuScope simulator—a toolkit of simulation, modelling, inversion and data mining tools.

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Booth 18

GeoScience Victoria

Victoria's Department of Primary Industries facilitates, promotes and regulates the state's mineral, oil, gas, geothermal energy and extractive exploration and mining.

GeoScience Victoria (GSV)—a branch of DPI—provides the exploration industry and government with expert regional-scale geoscientific data and knowledge. GSV works with academic and commercial collaborative partners to produce high-quality products such as geological maps, scientific reports, results of prospectivity studies, GIS data packages and 3D models.

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www.dpi.vic.gov.au/earth-resources

Booth 19

Internet Cafe sponsored by Industry & Investment NSW

The internet cafe will have five terminals available. The Convention abstracts will also be available on these computers. Please limit your time to ten minutes so that the facilities can be shared by as many delegates as possible.

Booth 20

Taylor & Francis

Building on two centuries of experience the Taylor & Francis Group, incorporating Routledge, has grown rapidly over the last two decades to become a leading international academic publisher. With offices in London, New York, Singapore and Melbourne, the Group publishes more than 1,500 journals and 1,800 books each year.

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KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

Program

MONDAY 5 JULY

	PLENARY 1					
0830–0910	Welcome to Country Conference Opening—The Hon Martin Ferguson AM MP, Minister for Resources and Energy and Minister for Tourism					Royal Theatre
0910–0950	**Belinda Robinson**	ENERGY FOR GENERATIONS: AUSTRALIAN OIL AND GAS				Royal Theatre
	01RA **RESOURCES** Chair: Hugh Davies (Bradman Theatrette)	**01EA** **ENVIRONMENT** Chair: Patrick De Decker (Nicholls Theatrette)	**01SA** **SOCIETAL** **Resource security** (Sutherland Theatrette)	**01DA** **DYNAMIC EARTH** **Geodynamic evolution of Australia** Chair: Russell Korsch (Royal Theatre)	**01LA** **LIFE AND SOLAR SYSTEM** **Archean and Proterozoic life** Chair: David Wacey (Menzies Theatrette)	**01TA** **TOPICAL** **Paleomagnetism—the McElhinny/McFadden Symposium** Chair: Andrew Roberts (Fitzroy Room)
0950–1010	Controls on mineralisation at the Porgera gold deposit, PNG **Angela Halfpenny**	Reconstructing past extreme events based on U-series dating of uplifted reef blocks and lagoon sediments **Jian-Xin Zhao**	Australia's Minerals Inventory: how it is compiled and how it ranks globally **Ian Lambert**	Initiation of subduction on the Gondwanan continental margin in north-west New South Wales **Robert Musgrave**	Early Earth **Therese Schneck**	New Zealand marine magnetic signature over the last 50 ky **Gary Wilson**
1010–1030	Fluid-driven growth of fracture networks: experimental approaches and implications for fluid pathways in hydrothermal ore systems **Stephen Cox**	Intensified massive coral mortality since 1860 AD in the southern South China Sea **Kefu Yu**	Peak resource production—does Australia have a problem? **David Denham**	South-directed oroclinal folding in the Lachlan Fold Belt: unravelling Mid-Late Silurian fold belt assembly to solve apparent Ordovician–Early Silurian complexity **Ross Cayley**	Sun → Earth → crust → biosphere → life: what do the elemental abundances tell us? **Aditya Chopra**	
1030–1100	Tea and posters					

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

MONDAY 5 JULY

	01RB RESOURCES Chair: Andrew Tomkins (Bradman Theatrette)	01EB ENVIRONMENT Chair: Patrick De Decker (Nicholls Theatrette)	01SB SOCIETAL **Geological hazards** Chair: Sara Pozgay (Sutherland Theatrette)	01DB DYNAMIC EARTH **Geodynamic evolution of Australia** Chair: Ross Cayley (Royal Theatre)	01LB LIFE AND SOLAR SYSTEM **Archean and Proterozoic life** Chair: David Wacey (Menzies Theatrette)	01TB TOPICAL **Paleomagnetism—the McElhinny/McFadden Symposium** Chair: Phil Schmidt (Fitzroy Room)
1100–1120	El Indio revisited—the secret life of enargite-gold deposits **Richard Henley**	A novel technique for coupled stable-isotope and trace-element determination in single ostracod shells applied to a late Quaternary record from the Gulf of Carpentaria, Australia **Laurent Devriendt**	Validation of the impacts of the 2004 Indian Ocean tsunami on Geraldton, Western Australia **Nick Horspool**	4D crustal-scale geological systems modelling in western Victoria and its implications for crustal accretion, strain partitioning and fluid flow **Tim Rawling**	Oxygenating the Earth: were Archean stromatolites constructed by cyanobacteria? **Malcolm Walter**	An improved radiocarbon chronology and calibration over the Laschamp event: ^{14}C – ^{10}Be cross synchronisation **Vladimir Levchenko**
1120–1140		Speleogenesis in Cainozoic limestones on a passive continental margin south-eastern Australia. **Susan White**	Overturned cliff-top mega-boulders at Little Beecroft Head, Jervis Bay, NSW, Australia: a mega-tsunami or aboveground bolide impact about 20 ka BP? **Anne Felton**	Earliest Permian non-collisional orogeny and basin formation in the southern New England Fold Belt sector of the Terra Australis Orogen **Peter Cawood**		Late Carboniferous-Early Permian paleomagnetic poles from regolith in cratonic Australia **Brad Pillans**
1140–1200	Ore formation as a primarily physical process—a new perspective on the mineral systems method **Jon Hronsky**	The Quaternary geological record of southern Australia—more than just dead rocks and old kangaroo bones **Colin Murray-Wallace**	Earthquake location using coda waves **David Robinson**	The Wongwibinda Complex: a HTLP metamorphic terrain **Stephen Craven**	Two possible sulphur metabolisms preserved in a 3.4 billion-year-old sandstone **David Wacey**	Carboniferous and Permian palaeomagnetism in New South Wales **Robert Musgrave**
1200–1220	Structural controls and timing of gold mineralisation and alteration in the Braidwood Granodiorite, NSW **Patrick Harvey**		Major earthquakes in Oceania: how well do we understand them? **Phil Cummins**	Crossing the Tasman: tracking Torlesse Terrane rocks from New Zealand into the New England Orogen **Christopher Adams**	Identification of carotenoid breakdown products in the 1.64 Ga Barney Creek Formation, McArthur Basin, northern Australia **Carina Lee**	Paleomagnetic investigation of the Late Devonian reef complexes of the Canning Basin, Western Australia **Eric Tohver**
1220–1340	Lunch and posters					

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

MONDAY 5 JULY

	01RC RESOURCES Chair: Angela Halfpenny (Bradman Theatrette)	01EC ENVIRONMENT Chair: Bradley Opdyke (Nicholls Theatrette)	01SC SOCIETAL **Geological hazards** Chair: Nick Horspool (Sutherland Theatrette)	01DC DYNAMIC EARTH **Intraplate and passive margin processes** Chair: Peter Cawood (Royal Theatre)	01LC LIFE AND SOLAR SYSTEM **Archean and Proterozoic life** Chair: Malcolm Walter (Menzies Theatrette)	01TC TOPICAL **Paleomagnetism —the McElhinny/McFadden Symposium** Chair: Bob Musgrave (Fitzroy Room)
1340–1400	The Spinifex Ridge 3.3 Ga porphyry-style Mo-Cu deposit, East Pilbara, Western Australia, the world's oldest **Mark Barley**	δ^{18}O-derived temperature records from the Australian flat oyster, *Ostrea angasi* **Sarah Tynan**	Natural hazards risk research in a changing world **John Schneider**	Geochronology and geochemistry of post-collisional Cenozoic alkali-rich porphyries in Eastern Tibetan Plateau, Yunnan, China **Yong-Jun Lu**	Opening the phosphate window onto early life—the 1900 Ma Gunflint Chert **Martin Brasier**	How does Chinese loess become magnetised? **Andrew Roberts**
1400–1420	Doriri Creek Pd-Pt-Ni prospect, an unusual low temperature hydrothermal platinum group element occurrence, south-eastern Papua **David Lindley**	Morphological variation, composition and age of submerged reefs on the Great Barrier Reef **Elizabeth Abbey**		Experimental phase and melting relations of metapelite in the upper mantle—implications for the petrogenesis of intraplate magmas **Carl Spandler**	The origin of biomarkers (molecular fossils) of eukaryotes and oxygenic cyanobacteria in Archean and Proterozoic rocks **Jochen Brocks**	
1420–1440	The pre-1.8 Ga tectono-magmatic evolution of the Kalkadoon-Leichhardt Belt—implications for the crustal architecture and metallogeny of the Mt Isa Inlier, north-west Queensland, Australia **Frank Bierlein**	Sea level and ice volume during the last interglacial **Andrea Dutton**	Interferometric synthetic aperture radar for natural hazard monitoring: case studies in Western Australia and Papua New Guinea **John Dawson**	Post rift thermal evolution of Tasmania and the South Tasman Rise: insights from low-temperature thermochronology **Ling Chung**	Organic geochemical evidence of a diverse microbial ecology in the 2.7 Ga Tumbiana Formation from stromatolitic outcrop samples, Fortescue Basin, Western Australia **Jessica Coffey**	A heretic view of the Alice Springs Orogeny: Australia-Asia collision and tectonic extrusion **Chris Klootwijk**
1440–1500	Hyperspectral remote mapping of Archaean lithologies and hydrothermal alteration mineralogy in the Eastern Goldfields Superterrane, Australia **Carsten Laukamp**	Lead isotopic evidence for an Australian source of aeolian dust to Antarctica at times over the last 170,000 years **Patrick De Deckker**	Risk monitoring and maintenance programs at Falls Creek Alpine Resort—linking hydrogeological understanding to risk management **Grant Jones**	Geomorphic tracers of mantle flow beneath the Australian continent **Mike Sandiford**	The evolution of sterol biomarkers in the Proterozoic **Amber Jarrett**	Magnetic overprinting of the Brachina Formation/Ulupa Siltstone, Southern Adelaide Foldbelt, prior to Delamerian deformation **Phillip Schmidt**
1500–1520	Assessment of mineral prospectivity of the northern Flinders Ranges, South Australia, using GIS analysis **Wayne Cowley**	Southern high latitude record of the first glacial events of the Cainozoic **Stephen Gallagher**	Precusory signals of the Sumatra-Andaman earthquake: what could we have known? **Paul Tregoning**		Assessing microbial diversity during the deposition of a Neoproterozoic (c.800 Ma) saline giant: evaporites as an archive for Precambrian halophiles **Richard Schinteie**	Magnetic characteristics of the Hiltaba Suite granitoids and volcanics: Late Devonian overprinting and thermal history of the Gawler Craton **Phillip Schmidt**
1520–1550	Tea and posters					

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

MONDAY 5 JULY

	01RD RESOURCES Chair: Mike Leggo (Bradman Theatrette)	01ED ENVIRONMENT Chair: Bradley Opdyke (Nicholls Theatrette)	01SD SOCIETAL **Geological hazards** Chair: Bridgette Lewis (Sutherland Theatrette)	01DD DYNAMIC EARTH **Intraplate and passive margin processes** Chair: Tim Rawling (Royal Theatre)	01LD LIFE AND SOLAR SYSTEM **Archean and Proterozoic life** Chair: David Wacey (Menzies Theatrette)	01TD TOPICAL **Paleomagnetism—the McElhinny/McFadden Symposium** Chair: Chris Klootwijk (Fitzroy Room)
1550–1610	Alunite: internal textures, compositions, and their implications for exploration and alteration **Zhaoshan Chang**	Coral and speleothem reconstructions of ocean-atmosphere dynamics in southern Indonesia during the 8.2 ka event **Julie Mazerat**	Quantifying the risks of geological storage of CO2 **Charles Jenkins**	What is driving intraplate deformation in the Mount Lofty and Flinders Ranges, South Australia? **Solomon Buckman**	Applications of Raman spectroscopy for early life studies **Mark van Zuilen**	New paleomagnetic study of the 1450 Ma Lakhna Dyke Swarm in the Bastar Craton, India: implications for the Mesoproterozoic supercontinent **Sergei Pisarevsky**
1610–1630	Pyrite-based LA-ICPMS trace element and sulphur isotope delineation of a sidewall convection system **Garry Davidson**	Tropical western Pacific surface ocean circulation variability (1920–1984) as inferred from a high-resolution radiocarbon record of a Marshall Islands' coral **Rebecca Norman**	Constraining dryland salinty hazard in the Lithgow Valley, NSW **Marion Winkler**	Thermal weakening localises intraplate deformation along the southern Australian continental margin **Simon Holford**		Palaeomagnetic evidence for cross-continental megashearing in Australia during Late Neoproterozoic: no need for pre-750 Ma Rodinia breakup **Zheng-Xiang Li**
1630–1650	Reduction of oxidised arc basalts **Andrew Tomkins**	Did Port Phillip Bay nearly dry up between 2700 yr BP and 1000 yr BP—seabed channelling evidence, seismic and core dating **Guy Holdgate**	Using the 'Coupled Human-Environment Systems Framework' for exploring issues of hazard and risk: if it is worth doing—do it properly **Dale Dominey-Howes**	Basalt assault: dissecting long-term intraplate volcanism along Australia's Indo-Pacific mantle interface **Frederick Sutherland**	Investigating modern and ancient biosignals using NanoSIMS **Matt Kilburn**	Design of a database of remanent magnetisation dominated magnetic field anomalies **Clive Foss**
1650–1710	The behaviour of chalcophile elements in evolving back-arc basins **John Mavrogenes**	A 1,000 year rainfall record for SE Australia using speleothem hydrological proxies **Janece McDonald**		Rapid emplacement of one of the world's greatest continental magmatic provinces—precise age constraints on the Bushveld Complex **Richard Armstrong**	Are Archean microfossils really biomorphs? **Andrew Christy**	Pre-Adelaidean palaeomagnetism for the Gawler Craton, South Australia: the Pandurra Formation and Blue Range Beds **George Williams**
1710–1830	Posters					
1730	SGSEG Meeting					Murray Room
1800–1930	Specialist Group in Sedimentology meeting					Gallery Foyer
1830–2030	Geological Society of Australia AGM					Swan Room

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

TUESDAY 6 JULY

	PLENARY 2					
0830–0910	Citation of the Mawson Medal by Dr Sue Meek, Chief Executive, Australian Academy of Science GSA Awards—presented by Brad Pillans, GSA President – SW Carey Medal – Joe Harms Medal – ES Hills Medal – WR Browne Medal					Royal Theatre
0910–0950	**Patrick De Deckker** (Mawson lecture)	LATE QUATERNARY PALAEOCEANOGRAPHIC INVESTIGATIONS IN THE AUSTRALIAN REGION: RELEVANCE TO CLIMATE MODELS				Royal Theatre
	02RA **RESOURCES** Chair: Kevin Wills (Bradman Theatrette)	**02EA** **ENVIRONMENT** Chair: Stephen Gallagher (Nicholls Theatrette)	**02SA** **SOCIETAL** **IGC Symposium** (Sutherland Theatrette)	**02DA** **DYNAMIC EARTH** **Geodynamic evolution of Australia** Chair: Daniela Rubatto (Royal Theatre)	**02LA** **LIFE AND SOLAR SYSTEM** (Menzies Theatrette)	**02TA** **TOPICAL** **Brian Logan Symposium** Chair: Bradley Opdyke (Fitzroy Room)
0950–1010	The effect of dissolved sulphide in silicate melts on the solubility and crystal/melt partitioning of Ni and other potentially chalcophile elements **Hugh O'Neill**	Timescale of soil formation for weathering profiles developed over andesitic volcanics **Puthiyaveetil Othayoth Suresh**	Promoting the geosciences of our region: the 34th IGC **Ian Lambert**	Testing the behaviour of Hf isotopes in rutile in a high-temperature metamorphic environment **Tanya Ewing**		Syn-tectonic platform evolution of Late Devonian reef complexes, northern Canning Basin, Australia: implications for platform architecture, paleogeography and mass extinction **Annette George**
1010–1030	Origin of nickel-rich sulphide assemblages in the Betheno deposit, Yakabindie, WA: evidence from synchrotron X-ray fluorescence mapping **Stephen Barnes**	Soil residence time in weathering profiles measured using uranium-series isotope disequilibria **Suresh Puthiyaveetil Othayoth**	Shaping a continent—building a nation: a geology of Australia **Richard Blewett**	Dislocation recovery and damping in deformed synthetic and natural upper mantle materials **Robert Farla**		Depositional and post-depositional controls on reservoir quality, Latest Devonian–Early Carboniferous Fairfield Group, Lennard Shelf, Northern Canning Basin, Australia **Zahra Seyedmehdi**
1030–1100	Tea and posters					

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

TUESDAY 6 JULY

	02RB RESOURCES Chair: John Mavrogenes (Bradman Theatrette)	02EB ENVIRONMENT Chair: Stephen Gallagher (Nicholls Theatrette)	02SB SOCIETAL IGC Symposium Chair: David Denham (Sutherland Theatrette)	02DB DYNAMIC EARTH Geodynamic evolution of Australia Chair: Graham Baines (Royal Theatre)	02LB LIFE AND SOLAR SYSTEM Chair: Mark van Zuilen (Menzies Theatrette)	02TB TOPICAL Brian Logan Symposium Chair: Bradley Opdyke (Fitzroy Room)
1100–1120	Geochemistry of the late Archean Windimurra layered mafic intrusion: insights into voluminous mantle melt evolution and the role of fO_2 **Oliver Nebel**	Stable isotopes of seawater from the Australian North West Shelf **Laura Richardson**	Living Australia **John Laurie**	Long-lived, autochthonous development of the Murchison Domain, Yilgarn Craton **Tim Ivanic**	International timescale calibration of the Late Permian – Early Triassic of Australia **Ian Metcalfe**	Carbonate platform signature of greenhouse worlds **James Frederick Read**
1120–1140	Evidence for plagioclase re-equilibration under magmatic conditions **Dominique Tanner**	The impact of decadal climate variability on estuarine sedimentation: a case study on the Hopkins and Glenelg estuaries, south-east Australia **Mark Warne**	Out of Gondwana **Marita Bradshaw**	New constraints on Palaeoproterozoic tectonism in the Harts Range, Arunta Region, Central Australia **Lachlan Hallett**	The mountains that triggered the Late Neoproterozoic increase in oxygen and the radiation of animals **Ian Campbell**	
1140–1200	Platinum-group element geochemistry of mineralised and non-mineralised komatiites and basalts **Marco Fiorentini**	Rhodoliths: a new biogenic archive of environmental change? **Nicholas Darrenougue**	Old, flat and red: the origins of the Australian landscape **Lisa Worrall**	An Australian tectonic reconstruction at ~1650 Ma: a Baltica link **Alexis Lambeck**	Modern humans extant at least 195 ka ago **Ian McDougall**	Stromatolite morphogenesis: the legacy of Brian Logan's work on stromatolite classification **Robert Burne**
1200–1220		Holocene climate reconstructions and modelling from Australian speleothems **Matt Fischer**	Living on the edge—waterfront views **Brendan Brooke**	North Queensland geodynamics—a new subsurface perspective **Paul Henson**		
1220–1340	Lunch and posters					
1220–1320	National Geochemical Survey of Australia meeting					Derwent Room

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

TUESDAY 6 JULY

	02RC RESOURCES Chair: Brent McInnes (Bradman Theatrette)	02EC ENVIRONMENT (Exhibition Hall)	02SC SOCIETAL **IGC Symposium** (Sutherland Theatrette)	02DC DYNAMIC EARTH **Geodynamic evolution of Australia** Chair: Narelle Neumann (Royal Theatre)	02LC LIFE AND SOLAR SYSTEM Chair: Jochen Brocks (Menzies Theatrette)	02TC TOPICAL **Ernie Nickel Symposium** Chair: Andrew Christy (Fitzroy Room)	02WC **Geoheritage, geotourism and the geoscience professions workshop** (Murray Room)
1340–1400	Improvements to the Australian crustal temperature image **Ed Gerner**	**POSTERS**	Innovative use of geoscience systems approaches to characterise and manage Australia's water resources **Ken Lawrie**	How continents grow, really! Some lessons from the Australian plate **David Giles**	Terrestrialization of the biota and atmospheric fluctuations during the Middle Palaeozoic **Gavin Young**	A renaissance in Australian mineralogy **Peter Williams**	Opening remarks **Angus Robinson** and **Susan White** Geoheritage overview paper—current status **Jane Ambrose** Definitions of geoheritage/ geoconservation/ geodiversity/geotourism discussion **Susan White** Mining heritage issues—AusIMM
1400–1420	The National Geochemical Survey of Australia: why, how and when? **Patrice de Caritat**		Foundations of wealth—Australia's major metallic mineral provinces **David Huston**		Atmosphere-ocean states and the mass extinction of species **Andrew Glikson**		
1420–1440	Australia's new marine research vessel: geoscience implications **Andrew Heap**		The bulk commodities underpinning economic growth in Australia and the region **Paul Kay**	Felsic magmatism and the Mesoproterozoic evolution of the west Musgrave Province, central Australia **Hugh Smithies**	Mass extinctions or mass hysteria: symbioses as the soothsayers of doom **Martin Brasier**	New minerals from the phosphate deposits north-east of Adelaide, South Australia **Bill Birch**	
1440–1500	Australian energy resource assessment 2009 **Lynton Jaques**		Deep heat: meeting future energy needs **David Champion**	Geophysical constraints on the tectonic evolution and 3D crustal architecture of the Southern Nawa Domain, Gawler Craton **Graham Baines**	Biomarker distributions and isotopic signals associated with the Permian/Triassic and Triassic/Jurassic mass extinction events: a global perspective **Kliti Grice**	Hydroxylian pseudorutile—a new mineral from the Murray Basin? **Ian Grey**	
1500–1520	Exploration targeting criteria for hydrothermal Ni systems **Ignacio González-Álvarez**			Cooling and exhumation history of the north-eastern Gawler Craton, South Australia **Caroline Forbes**		'Silver chloro-antimoniate': over 80 years of characterisation **Ian Graham**	
1520–1550	Tea and posters						

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

TUESDAY 6 JULY

	02RD RESOURCES Chair: Oliver Nebel (Bradman Theatrette)	02ED ENVIRONMENT Chair: Andrea Dutton (Nicholls Theatrette)	02SD SOCIETAL **Salinity** Chair: Marion Winkler (Sutherland Theatrette)	02DD DYNAMIC EARTH **Geodynamic evolution of Australia** Chair: Caroline Forbes (Royal Theatre)	02LD LIFE AND SOLAR SYSTEM (Exhibition Hall)	02TD TOPICAL **Ernie Nickel Symposium** Chair: Bill Birch (Fitzroy Room)	02WB **Geoheritage, geotourism and the geoscience professions workshop** (Murray Room)
1550–1610	U-Th-Pb-He double dating of zircon from the diamondiferous Ellendale E9 lamproite pipe **Brent McInnes**	Sr/Ca in planktonic foraminifera G. ruber: a proxy for surface ocean carbonate saturation state? **Ryan Owens**	Manifestations of dryland salinity in the Windellama area, NSW **Brian Jenkins**	New geochronology from the Mount Painter Province, South Australia—linking the Gawler Craton and Curnamona Province **Narelle Neumann**	POSTERS	What really controls coordination number in mineral crystal structures? **Andrew Christy**	Nominations under the Australian Government Heritage System **Jane Ambrose** Enhancing promotion of existing geoheritage sites National Landscapes Program Concluding remarks and discussion Angus Robinson
1610–1630	Maturation statistics of nitrogen aggregation in alluvial diamond: New South Wales and Kalimantan **Larry Barron**	Utilising tandem paleotemperature tracers to open new dimensions in paleoclimate study **Brad Opdyke**	Localised saline fluxes in the Upper Murray Catchment landscape, NSW **Rob Muller**	The Svecofennian of Fennoscandia and Eastern Europe—a Lachlan Fold Belt analogue **Ian Williams**		New minerals and type localities in Tasmania **Ralph Bottrill**	
1630–1650	Hyperspectral insights in the 3D mineralogy of a channel iron ore deposit: implications to exploration, mining and ore genesis **Maarten Haest**	The boron geochemistry of siliceous sponges **Andrea de Leon**	Using geomorphology and stratigraphy to clarify a dryland salinity, soil sodicity and vegetation distribution puzzle at Capertee Valley, Western Blue Mountains, NSW **Leah Moore**	Inheritance and polymetamorphism in monazite: examples from Central Australia and the alps **Daniela Rubatto**		Mafic-hosted secondary mineralisation from the Shangri La Pb-Ag-Au-Cu mine, Kimberley, Western Australia **Peter J Downes**	
1650–1710	Alteration mapping for IOCG exploration in the Gawler Craton using geologically constrained potential field inversions **Richard Chopping**	Clumped-isotope thermometry **Allan Chivas**	Enhancing strategic management of erosion and salinity hazard in the Goulburn Area, NSW, through characterisation of regolith materials, hydrogeology, vegetation distribution and land use **Sarah Wilson**	The biogeochemical status of the Palaeo-Pacific Ocean: clues from the early Cambrian of South Australia **David McKirdy**		Closing remarks **Bill Birch**	
1710–1830	Posters						

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

WEDNESDAY 7 JULY

	PLENARY 3					
0830–0910	Launch of the Australian Geological Heritage Garden—Gary Rake, CEO, National Capital Authority					
0910–0950	**Robert Hough**	COLLOIDAL GOLD IN SUPERGENE AND HYPOGENE SYSTEMS				
	03RA **RESOURCES** **AIG Symposium** Chair: Michael Edwards (Bradman Theatrette)	**03EA** **ENVIRONMENT** **IODP Symposium** Chair: Phil O'Brien (Nicholls Theatrette)	**03SA** **SOCIETAL** **Education** Chair: Alan Goode (Sutherland Theatrette)	**03DA** **DYNAMIC EARTH** **Restless earth** Chair: Anya Reading (Royal Theatre)	**03LA** **LIFE AND SOLAR SYSTEM** **Planets wet and dry** Chair: Marc Norman (Menzies Theatrette)	**03TA** **TOPICAL** **AuScope Symposium** Chair: Bob Haydon (Fitzroy Room)
0950–1010	Why geological mapping is important **Graham Teale**	IODP 318 Cenozoic East Antarctic ice sheet evolution from Wilkes Land Margin sediments: preliminary results **Kevin Welsh**	Rethinking curriculum design using core representations **Jim Woolnough**	Is the Earth's inner core a conglomerate of anisotropic domains? **Hrvoje Tkalcic**	Isotope tracing of water in the solar system **Trevor Ireland**	AuScope+: opportunities, challenges and responsibilities **Mike Sandiford**
1010–1030	Application of IP geophysics to practical geology for mineral exploration **Stephen Collins**		Sustaining a new high school EES course in Western Australia **Leah Moore**	4.5 billion years of crust-mantle evolution from a modern isotopic perspective **Vickie Bennett**	Pressure-temperature phase diagrams of the Earth and Mars **Eriita Jones**	AuScope Geospatial: measuring the contemporary deformation of the Australian crust **Gary Johnston**
1030–1100	Tea and posters					

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

WEDNESDAY 7 JULY

	03RB RESOURCES **AIG Symposium** Chair: Mike Smith (Bradman Theatrette)	03EB ENVIRONMENT Chair: Phil O'Brien (Nicholls Theatrette)	03SB SOCIETAL **Education** (Sutherland Theatrette)	03DB DYNAMIC EARTH **Restless earth** Chair: Myra Keep (Royal Theatre)	03LB LIFE AND SOLAR SYSTEM **Planets wet and dry** Chair: Marc Norman (Menzies Theatrette)	03TB TOPICAL **AuScope Symposium** Chair: Bob Haydon (Fitzroy Room)
1100–1120	Architectural controls on Paleozoic porphyry gold–copper mineralisation in the Cadia Valley, NSW **Dave Cooke**	Australia's involvement in IODP: what it means for our scientists **Neville Exon**	Valuing EES education in Australia: where to from here? **Leah Moore**	A subduction model for the formation of the New England oroclines **Gideon Rosenbaum**	Origin and interpretation of valley networks in Sinus Sabaeus, Mars **Bo Yi Wang**	Simulation, analysis and modelling in AuScope **Louis Moresi**
1120–1140	The importance of good geological control in resource estimation with several examples **Peter Stoker**	Preliminary results from IODP Expedition 317 (Canterbury Basin, New Zealand) **Bob Carter**		Subduction dynamics, lateral slab edges, intraplate volcanism and mantle plumes **Wouter Schellart**	New surface clutter simulations of Mars Express MARSIS data support extensional tectonic history of Pickering Crater (Mars) **Graziella Caprarelli**	AuScope earth imaging—progress with geotransects **Brian Kennett**
1140–1200	Geological mapping in civil engineering **Alan Moon**	Biogeochemical and geomicrobiological evidence for an ultra-deep anaerobic methane oxidation zone in the Nankai Trough sub-seafloor **John Moreau**	Correlation between school certificate performance and HSC performance at Knox Grammar School **Steven McClean**	Mantle instability, surface uplift and volcanism behind active plate margins of the Pacific **Tim Stern**	Mid- and low-latitude layered deposits on Mars: geological significance **Katie Perrin**	The AuScope National Virtual Core Library—establishment and achievements **Jon Huntington**
1200–1220	Geohazards—their identification and management **Greg Kotze**	IODP Expedition 323 in the Bering Sea: environmental change over 5 million years recorded in deep-sea sediment **Kelsie Dadd**	Engaging digital natives in earth science **Katrina-Lee Jones**		Slope morphology of Twin Peaks, Mars Pathfinder landing site **Steven Hobbs**	Mineralogical validation of the AuScope NVCL **David Green**
1220–1340	Lunch and posters					
1220–1340	SGGMP Committee meeting					Swan Room
1230–1330	Australian Geoscience Council AGM					Derwent Room

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

WEDNESDAY 7 JULY

	03RC RESOURCES **AIG Symposium** Chair: Greg Kotze (Bradman Theatrette)	03EC ENVIRONMENT Chair: Neville Exon (Nicholls Theatrette)	03SC SOCIETAL **Education** Chair: Steve McClean (Sutherland Theatrette)	03DC DYNAMIC EARTH **Restless earth and earth structure** Chair: Kate Selway (Royal Theatre)	03LC LIFE AND SOLAR SYSTEM **Planets wet and dry** Chair: Gabriella Caprarelli (Menzies Theatrette)	03TC TOPICAL **AuScope Symposium** Chair: Andy Barnicoat (Fitzroy Room)
1340–1400	Forensic petrology **B Jane Barron**	Magnetostratigraphic records from Eocene-Miocene sediments cored in the Equatorial Pacific: initial results from the Pacific Equatorial Age Transect (PEAT) IODP Exp 320/321 **Christian Ohneiser**	Data Metallogenica—the next generation **Alan Goode**	Reconstructing the early Jurassic to present Pacific and proto-Pacific basins: implications for circum-Pacific plate margins **Maria Seton**	NASA's Lunar Crater Observation and Sensing Satellite: mission overview and first science results **Jennifer Heldmann**	Minerals Down Under National Research Flagship: linking AuScope to the broader minerals industry value chain **Jonathan Law**
1400–1420	Groundwater dependent ecosystems **Jonathan Fawcett**	Sr, Nd and Pb isotope data from the Shirshov Massif of the Shatsky Rise, north-west Pacific **David Murphy**	The educational benefits of an international seismic monitoring network in schools—the 'SISMOS à l'École' project at Telopea Park School, Canberra **Matthew Knafl**	Timor collision: deformation and tectonic implications **Myra Keep**		Implementing spatial information services at GeoScience Victoria **Paul McDonald**
1420–1440	Professionalism in the geosciences through the Australian Institute of Geoscientists **Mike Smith**	Antarctic ice shelf and ice stream processes based on geomorphic features imaged by sidescan sonar, Prydz Bay, Antarctica **Philip O'Brien**	Education and public awareness today for the geoscientists and geoscience challenges of tomorrow **Kate List**	The role of lower crustal flow in the formation of subaqueous Archaean continental flood basalts **Nicolas Flament**	The bulk composition and thermal structure of the CoRoT-7b Exoplanet **Frank Wagner**	Developments in the analyses of geodetic GPS data **Chris Watson**
1440–1500	Geoscientists—our relevance in the age of technology **Andrew Kohlrusch**	Applying geoscience to map benthic habitats through space and time: George V Shelf, East Antarctica **Alix Post**	The benefits to student learning of participation in marine research cruises **Kelsie Dadd**	Melting of carbonated eclogite at 9-20 Gpa—implications for carbonate mantle metasomatism **Ekaterina Kiseeva**	Bulk chemistry and habitability of the rocky planets that are probably in orbit around Alpha Centauri A and B **Jose Robles**	Virtual Rock Laboratory: enabling computational minerals science research **Dion Weatherley**
1500–1520		Reconstruction of the southern Indian Ocean environment over the last 40ka using radiolarian (protista) proxies **John Rogers**		Experimental evidence of high pressure stability of Na-rich amphibole in subduction zone environments **Cassian Pirard**	Water vapour abundance in the lower Venusian atmosphere **Sarah Chamberlain**	Scientific results from the AuScope Geospatial infrastructure **Paul Tregoning**
1520–1550	Tea and posters					
1550–1830	Geological Heritage Standing Committee meeting					Derwent Room

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

WEDNESDAY 7 JULY

	03RD RESOURCES **AIG Symposium** Chair: Greg Corbett (Bradman Theatrette)	03ED ENVIRONMENT Chair: Neville Exon (Nicholls Theatrette)	03SD SOCIETAL (Exhibition Hall)	03DD DYNAMIC EARTH **Restless earth and earth structure** Chair: Tim Stern (Royal Theatre)	03LD LIFE AND SOLAR SYSTEM **Planets wet and dry** Chair: Vickie Bennett (Menzies Theatrette)	03TD TOPICAL **AuScope Symposium** Chair: Mike Sandiford (Fitzroy Room)
1550–1610	The Australian geothermal industry—an overview **Catherine Stafford**	Antarctic and Southern Ocean influences in global Late Pliocene cooling **Tim Naish**	POSTERS	Through a glass darkly: imaging the Earth's interior from the surface **Malcolm Sambridge**	Early mantle depletion on a small igneous asteroid: new evidence from Nd isotopic compositions of basaltic eucrites **Marc Norman**	Modelling across the scales: the data and resolution challenge **Lutz Gross**
1610–1630	Industrial minerals: big but not sexy!! **Ted Ambler**			Architecture of the Prydz Bay region, Antarctica, from magnetotellurics **Kate Selway**	Lu-Hf system in the bulk silicate earth: the effects of non-chondritic composition and 176Lu accelerated decay **Yuri Amelin**	Advances in geochemistry, past, present and future **Simon Turner**
1630–1650	Iluka Resources heavy mineral exploration in the Eastern Eucla Basin, South Australia **Ian Warland**	Structure and evolution of the Hunter Ridge, North Fiji Basin, SW Pacific: results from three voyages of R/V 'Southern Surveyor' **Leonid Danyushevsky**		Magnetotelluric surveys across major Archean tectonic boundaries in southern Western Australia **Mike Dentith**	The tectonics of tiny worlds: Enceladus and the spectrum of planetary dynamics **Craig O'Neill**	The future of geodetic science: implications for Australia's infrastructure and investment **Chris Rizos**
1650–1710	The joys of having rocks in your head **Greg Mortimer**	Volcaniclastic sediments formed by submarine hydrothermal eruptions in the Manus Basin, Papua New Guinea **Raymond Binns**		The Capricorn orogen: crustal structure and evolution from a passive seismic transect **Anya Reading**	Meteoritic signatures in ≥3.7 Ga rocks from the Isukasia terrane (Greenland): present knowledge and future directions **Allen Nutman**	Imaging beneath the Australian continent: infrastructure needs to meet the challenges of the 21st century **Nick Rawlinson**
1710–1830	Posters					AuScope: informal information session

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

THURSDAY 8 JULY

	PLENARY 4						
0830–0910	AJES awards—presented by Anita Andrew, AJES Editor – Stillwell 2008 – Stillwell 2009 – David I Groves 2008 – David I Groves 2009						Royal Theatre
0910–0950	**Martin Brasier** WHAT ARE WE TO MAKE OF THE EDIACARA BIOTA?						Royal Theatre
	04RA **RESOURCES** Chair: Solomon Buckman (Bradman Theatrette)	**04EA** **ENVIRONMENT** Chair: Ralf Haese (Nicholls Theatrette)	**04SA** **SOCIETAL** **Heritage** (Sutherland Theatrette)	**04DA** **DYNAMIC EARTH** **Geodynamics and minerals** Chair: Russell Korsch (Royal Theatre)	**04LA** **DYNAMIC EARTH** **Earth structure** Chair: Simon Richards (Menzies Theatrette)	**04TA** **TOPICAL** **Earth science history** (Fitzroy Room)	**04WA** **3D mineral spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium** (Murray Room)
0950–1010	The Paterson AEM Survey, Western Australia: enhancing prospectivity using regional AEM data to image Paleozoic-Mesozoic paleotopography **Ian Roach**	Keep-up, catch-up or give-up: implications of shallow transect coring, Heron Reef, Great Barrier Reef, Australia **Luke Northdurft**	Monitoring of the Burrup Peninsula Aboriginal petroglyphs **Erick Ramanaidou**	Minerals and energy resources: outcomes of lithosphere–mantle geodynamic coupling **Graham Begg**	Carbonate melts released from subducted sediments at sub-arc depth **Jörg Hermann**	The past is the key to the present: Australian geological mapping, 1830s to WW2 **David Branagan**	Making the NVCL greater than the sum of its parts. Symposium goals **Jon Huntington**
1010–1030	Exploring and developing placer and uranium mineral potential of the Eucla Basin and peripheral palaeovalleys **Baohong Hou**	Marine-terrestrial transitions associated with the world's oldest coral reef fish assemblage (Early Devonian, Wee Jasper, New South Wales) **Gavin Young**	Weathering history of rock surfaces associated with Aboriginal rock art, Burrup Peninsula, Western Australia **Brad Pillans**		Geochemistry and geochronology of sinter deposits as an exploration tool for geothermal systems **Tonguç Uysal**	The science and mapping of the Victorian exploring expedition of Burke and Wills, and of the related relief expeditions of 1860–1862 **DA McCann**	Imaging spectroscopy of the Earth from AVIRIS **Robert Green**
1030–1100	Tea and posters						

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

THURSDAY 8 JULY

	04RB RESOURCES **Uranium** Chair: Roger Skirrow (Bradman Theatrette)	04EB ENVIRONMENT Chair: Ralf Haese (Nicholls Theatrette)	04SB SOCIETAL **Salinity** (Sutherland Theatrette)	04DB DYNAMIC EARTH **Geodymanics and minerals** Chair: Geoff Fraser (Royal Theatre)	04LB DYNAMIC EARTH **Earth structure** Chair: Richard Arculus (Menzies Theatrette)	04TB TOPICAL **Earth science history** (Fitzroy Room)	04WB **3D mineral spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium** (Murray Room)
1100–1120	U-series isotope characterisation of an arid region sedimentary-hosted uranium mineralised system **Melissa Murphy**	Organic geochemistry and chronology of the Macquarie Marshes, NSW **Lili Yu**	Geomorphological Influences on regolith distribution and salt store in the Moruya area, south-east NSW **Jenna Bishop**	Understanding the processes of mineral systems with synchrotron x-ray fluorescence mapping **James Cleverley**	Australian basins in 3D **Simon van der Wielen**	Imaging the Australian continental crust and its margins—a chronicle of deep seismic profiling, 1946–2006 **Douglas Finlayson**	Reading geochemical processes from HyLogged/NVCL mineralogy **John Walshe**
1120–1140	Uranium-copper systems in Westmoreland region, Northern Australia: fluid inclusion studies and geochemical modelling of basinal fluids **Terrence Mernagh**	Using Mg/Ca as a tracer for 'ocean acidification' in recent marine sediments from the Great Barrier Reef **Merinda Nash**	Using the hydrogeological landscapes approach to identify and profile salt manifestation in the Boro Road area, near Braidwood NSW **Kathleen Harvey**	Shallow-dipping subduction beneath New Guinea and the geologic setting of the Grasberg, Ok Tedi, Frieda River and Porgera mineral deposits **Hugh Davies**	The age of deposition and metamorphism of the Jack Hills metasedimentary belt from in situ U-Th–Pb geochronology of monazite and xenotime **Janet Muhling**	The evolution of naming and defining rock units in Australia: a story of cooperation for good communication **Catherine Brown**	A 3D model of a supergene gold deposit determined from spectrally-derived mineralogy **Scott Halley**
1140–1200	Geochemical alteration and associated REE mobility at the Ranger 1 No 3 Mine, Northern Territory, Australia **Louise Fisher**	Coral calcification in the central Great Barrier Reef: assessing the combined impacts of terrestrial runoff, global warming and ocean acidification **Juan-Pablo D'Olivo**	Impact of ephemeral streams on salinisation of soils and groundwater in western Victoria **John Webb**	Cobar Superbasin architecture—control on the mineralisation **Vladimir David**	Late Jurassic-Early Cretaceous volcanism on the North West Shelf: onset of flood basalt volcanism? Evidence from high resolution seismic reflection data and outcrop analogues **Max Rohrman**	A national scientific and economic masterstroke: the quarter-million geological mapping of Australia **Larry Harrington**	Application of SWIR spectra within the Hellyer – Mt Charter alteration zone, western Tasmania **Kim Denwer**
1200–1220	Are there any sandstone-hosted uranium systems in the Eromanga Basin? **Simon van der Wielen**	Predicting the impact of ocean acidification on carbonate mineral stability in eastern Joseph Bonaparte Gulf **Ralf Haese**	The ongoing controversies concerning dryland salinity in Australia: causes, assumptions, management and suspect science **Glen Bann**	Manganese deposition associated with oblique extension during Mesoproterozoic basin development, Woodie Woodie Mine, East Pilbara **Sarah Jones**	$^{40}Ar/^{39}Ar$ Geochronology of the West Kimberley Province lamproites: constraints on Australian plate geodynamics **David Phillips**	1:250,000 geological mapping in Queensland—from black and white aerial photographs and Landrovers to integrated digital datasets **Ian Withnall**	Quantification of HyLogging data for the development of a 3D physicochemical model of channel iron ore **Martin Haest et al**
1220–1340	Lunch and posters						

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

THURSDAY 8 JULY

	04RC RESOURCES Chair: Terrence Mernagh (Bradman Theatrette)	04EC ENVIRONMENT Chair: Bradley Opdyke (Nicholls Theatrette)	04SC SOCIETAL **Groundwater** (Sutherland Theatrette)	04DC DYNAMIC EARTH (Exhibition Hall)	04LC DYNAMIC EARTH **Restless earth** Chair: Nick Rawlinson (Menzies Theatrette)	04TC TOPICAL **Earth science history** (Fitzroy Room)	04WC **3D mineral spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium** (Murray Room)
1340–1400	Coal seam gas in Australia **Wal Muir**	Aminostratigraphy of Late Quaternary Gulf St Vincent, South Australia: amino acid racemisation dating of single foraminifera, *Elphidium* **W Anthony Nicholas**	Regional mapping of palaeovalley groundwater resources in arid Australia **Steven Lewis**	**POSTERS**	Oxygen and Hf isotopic constraints on 150 My of subduction-generated magmatism in the South Patagonian Batholith, South America: implications for tracking plate configurations and movements **Mark Fanning**	Northern Territory—1st edition 1:250,000 mapping **Peter Dunn**	Seeing the wood for the trees: what spectral wavebands are best suited for your geological setting **Sasha Pontual**
1400–1420		Re-evaluation of microbial deposits from Shark Bay and their geologic significance **Ricardo Jahnert**	Groundwater interactions in the Lower Murrumbidgee catchment, New South Wales **Bear McPhail**		Varying lithospheric rigidity during Paleogene/Neogene evolution of the SW Pacific: evidence from New Caledonia Trough **Ron Hackney**	History of 1:250,000 geological mapping of Western Australia **Dennis Gee**	The iron chefs: modelling spectral mixtures of iron oxides and clays for applications in the iron ore industry **Erick Ramanaidou**
1420–1440	Development of an atlas of CO2 geosequestration potential for NSW **Alexandra Golab**	Preserved biomarkers in ephemeral saline lake sediments as constraints on inland regional evaporative regimes **Claudia Jones**	Pilbara Coast Groundwater Study **Gregory Street**		The seismic potential and 4D geodynamic evolution of the Vanuatu Arc **Simon Richards**	Regional geological mapping in South Australia **Robert Dalgarno**	Status of the CSIRO TIR spectral library of anhydrous silicates **Martin Schodlok**
1440–1500	Igneous intrusions in the sedimentary basins of eastern Australia: implications for hydrocarbon generation and CO2 storage potential **Lila Gurba**	Radiocarbon dating of Archaeal lipids in microbial mats from an Australian salt lake **P Sargent Bray**	Northern Australia's water resources: the vitality of groundwater **Richard Cresswell**		The Australian-Antarctic depth anomaly: interacting tectonic and geodynamic processes **Joanne Whittaker**	History of 1:250,000 geological mapping of NSW and ACT **David Robson**	Joint mineralogical interpretation of SWIR and TIR HyLogging data **Andy Green and Martin Schodlok**
1500–1520	Indian Gondwana coal and greenhouse gas control technologies **Krishna Sappal**	Microbiological and geochemical characterisation of the saline playa Lake Gnarpurt, western Victoria **Chris Munday**	Upland swamps, siltstone aquitards and discrete interval borehole sampling in the Woronora Plateau of the Sydney Basin **Mark Peterson**		The petrogenesis of A-type granite : an end-member of granite formation mechanisms **John Foden**	History of the quarter-million-scale geological map program in Victoria **Alfons VandenBerg**	Planetary thermal infrared emission mineral spectroscopy **Steve Ruff**

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

THURSDAY 8 JULY

1520–1550	Tea and posters						
	04RD **RESOURCES** Chair: Ian Lambert (Bradman Theatrette)	**04ED** **ENVIRONMENT** (Nicholls Theatrette)	**04SD** **SOCIETAL** **Groundwater** (Sutherland Theatrette)	**04DD** **DYNAMIC EARTH** **Earth structure** Chair: Graham Begg (Royal Theatre)	**04LD** **DYNAMIC EARTH** **Restless earth** Chair: John Foden (Menzies Theatrette)	**04TD** **TOPICAL** **Earth science history** (Fitzroy Room)	**04WD** **3D mineral spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium** (Murray Room)
1550–1610	Western Amadeus Basin: revised Neoproterozoic correlations and prospectivity **Peter Haines**		Geochemical and water quality implications of changing dynamics in surface water–groundwater interactions **Martin Andersen**	He, Ne and Ar in peridotitic and eclogitic paragenesis diamonds from the Jwaneng Kimberlite, Botswana—constraints on diamond formation **Masahiko Honda**	Seamount and ocean island record preserved in accretionary complexes **David Buchs**	Production of the Australian 1:250,000 scale geological map series **Ian O'Donnell**	Insights from HyLogging Lindemans Bore, Murphy Inlier and Tennant Creek cores in the Northern Territory **Belinda Smith**
1610–1630	Rift evolution in the Capel and Faust basins, offshore eastern Australia, and implications for regional petroleum prospectivity **Takehiko Hashimoto**			Geological architecture and evolution of the southern Gawler Craton: improved constraints from recent geochronology and reflection seismic imaging **Geoff Fraser**	Recycling of oceanic crust into upper mantle magma sources—melting behaviour of up-welling, heterogeneous mantle **Greg Yaxley**	Overview and economic significance of first edition 1:250,000 geological mapping of Australia **Don Perkin**	Quantitative spectral mineralogy of bauxites **Graham Walker**
1630–1650	Surface and sub-surface geology of the Capel-Faust Basins, offshore eastern Australia: influence of basement structure **Nadege Rollet**		Management of groundwater lenses on small islands in the Pacific **Ian White**	Magnetotelluric survey along the east–west Southern Flinders Ranges seismic traverse, South Australia **Tania Dhu**	Experimental constraints on chlorine behaviour in subducted sediments **Huijuan Li**	Papua New Guinea and Indonesian Papua 1:250,000 scale geological mapping—tales from the past **Hugh Davies**	Calibration of HyLogging spectral data to derive quantitative mineral abundances **Kay Yang and Peter Mason**
1650–1710			Hydrochemical facies and hydrological processes within a subtropical coastal catchment, Fraser Coast, Queensland **Genevieve Larsen**	Remote sensing of mineral systems in the Gawler-Curnamona—a new HyMap-calibrated ASTER mosaic in South Australia **Matilda Thomas**	New backarc magma types, active boninite magmatism, fresh peridotites: reports of some recent Marine National Facility voyages to the south-west Pacific **Richard Arculus**		Algorithms for fast modelling and interpretation of mineral spectra **Mark Berman**
1630–1730	Earth Science History Group meeting						Torrens Room
1830–2030	NVCL Operations/Access Committee meeting						Murray Room

KEY	Plenary Speaker	Keynote Speaker	Invited Speaker	Poster Session

FRIDAY 9 JULY

	05WA 3D Mineral Spectroscopy of the Earth's skin—1st National Virtual Core Library Symposium — Murray Room
0900–0930	Invited keynote: Mineral spectroscopy: surprises and lessons learned from exploration of the Earth and planets—**Roger Clark (USGS)**
0930–0950	Comparisons between the Canadian Athabasca and South Australian Cariewerloo Basins: HyLogging insights into unconformity related uranium—**Alan Mauger et al**
0950–1010	Characterisation of Canning Basin petroleum core and Gascoyne Province molybdenum prospect cores: cases studies from GSWA's NVCL HyLogging—**Lena Hancock**
1010–1030	HyLogging applied to gold exploration: validation and potential for industry uptake—**Tony Roache**
1020–1040	Tea and posters
1040–1100	Linking drill core, field sample and airborne mineralogy: Lachlan Orogen and Broken Hill examples from the NSW NVCL node—**Bill Reid and Meagan Clissold**
1100–1120	Hidden mineral systems in our drill core archives: the NVCL opportunity—**Tim Baker**
1120–1140	NVCL future—panel discussion
1140–1200	NVCL future—panel discussion
1200–1220	NVCL future—panel discussion
1220–1320	Lunch and posters
1320–1340	C3DMM—Building a seamless 3D mineral map of the Australian continent—**Carsten Laucamp**
1340–1400	Validation of HyLogging data with geochemistry and geologic information at the GSQ NVCL node—**Joseph Tang and Suraj Gopalakrishnan**
1400–1420	Publishing the NVCL to the Web—**Ryan Fraser et al**
1420–1440	Victorian HyLogging case studies—**Emily House**
1440–1500	Earth science education opportunities of the AuScope NVCL—**Andrew McNeill and Jon Huntington**
1500–1530	Tea and posters
1530–1550	Tasmanian case studies and MRT NVCL operations—**David Green and Mike Vicary**
1550–1610	Status of the NVCL hardware—**Lew Whitbourn**
1610–1630	Hyperspectral core imaging—**Timo Hyvärinen and Rainer Baars**
1630–1700	Invited keynote: Applications of near infrared core imaging—**Phil Harris**
1700	Symposium close

Posters

(Exhibition Hall)

Ordered by theme and presenter surname

Number	Presenter	Poster title
Dynamic earth: from crust to core		
1	Jade Anderson	Geochronological, metamorphic and structural evolution of the Kanjamalai Hills, Tamil Nadu
2	James Austin	Lateral Fault Inversion and Polyharmonic Folding in the Budawang Synclinorium, Deua Valley, NSW, Australia
3	Graham Baines	The tectonic evolution of the Atlantis Bank oceanic core-complex, Southwest Indian Ridge
4	Cari Bertram	U-Pb Laser ICPMS Zircon Constraints on the Depositional age and Provenance of the Kurnool Group, Cuddapah Basin, Southern India
5	Katherine Boston	Textural relationships of monazite and allanite during prograde metamorphism
6	Lidena Carr	Architecture of the Arrowie Basin, South Australia, based on deep seismic reflection data
7	Andrew Christy	Pressure-dependent Zr-in-rutile thermometry of western Chinese eclogites from varied tectonic settings
8	Stephen Dick	Developing the Geology of New South Wales in a 3D Framework
9	Patricia Durance	Preservation of geochemical diversity of primitive magmas signals the occurrence of multiple melting regimes at the southern end of the North Fiji Basin
10	David Durney	The significance of early hybrid and superposed folds for tectonic transport directions in Ordovician greywacke and slate of the Bermagui area, NSW
11	Joel Fitzherbert	The Lockhart Igneous Complex: Plutonic links with volcanism during Silurian rifting, eastern Lachlan Orogen, southeastern Australia
12	John Foden	Changing conditions of mantle wedge melting across arc as illustrated by changing iron isotopes compositions
13	Chris Foudoulis	Reducing the Risk of Sample Contamination in Geochronology
14	Angela Halfpenny	Comparison Of Dynamically Recrystallised Quartz Rich Microstructures Utilising Electron Backscatter Diffraction
15	Simon Holford	Compressional deformation and uplift of Australia's 'passive' southern margin
16	Huiqing Huang	Petrogenesis of Jurassic Jiuyishan Fayalite-bearing Granites and Tectonic Implications
17	Gary J Huftile	Using soft-sediment deformation to date paleoseismic events in bore holes, IODP Leg 319, Kumano basin, Nankai Trough, Japan
18	Magdalena Huyskens	The Andros detachment, Cyclades, Greece: time of shear zone activity and the original nature of the fault zone
19	Tsuyoshi Iizuka	In situ U-Pb and Sm-Nd isotopic systematics of monazites from metasediments in Mt Narryer, Western Australia: Constraints on the tectonothermal history and provenance
20	Ian Jackson	New Forced-Oscillation Methods For Laboratory Study Of The Seismic Properties Of Cracked And Fluid-Saturated Crustal Rocks
21	Chulantha Jayawardena	Strike-slip characteristics of the Willunga Fault at Sellicks Beach, Fleurieu Peninsula, South Australia
22	Heejin Jeon	Implications of contrasting patterns of inherited zircon in the Late Palaeozoic granites of the Lachlan and New England fold belts

Number	Presenter	Poster title
23	Aurore Joly	A New 3D Model for Architectural Evolution of the Granite-Tanami Orogen
24	Mark Kendrick	Volatile Subduction in Alpine Serpentinites
25	Matt Kilburn	Earth Science Applications for Advanced Secondary Ion Mass Spectrometry (SIMS)
26	Barry Kohn	Improved constraints on the timing and tempo of continental extension using low temperature thermochronology
27	Russell Korsch	Geodynamic implications of a 2008 north-south deep seismic reflection profile across the Curnamona Province, South Australia
28	Natalie Kositcin	North Queensland Geodynamic and Mineral System Synthesis
29	Paul Lennox	Deformation Patterns of the Wyangala Granite, Wyangala Dam District, Eastern Lachlan Fold Belt
30	Pengfei Li	Structural evolution of the Texas orocline: field observations from the hinge zone (Mosquito Creek, southeast Queensland)
31	David Lindley	Plate tectonic models in Melanesia
32	Julie Mackintosh	Age and Basin Evolution of the Cuddapah Supergroup, India
33	Sarah Marshall	Metamorphism of Large Hot Orogens: revisiting the Eastern Ghats classic
34	Laure Martin	The CO2 paradox in subduction zones: insight from partial melting experiments on altered oceanic crust
35	Kara Matthews	A Geodynamic Modelling Approach to Constraining the Location of Cretaceous Subduction East of Australia
36	Sarlae McAlpine	Mantle peridotites from the active New Britain-West Bismarck Arc front
37	Mark McLean	Three-dimensional modelling in the Melbourne Zone, southeast Australia
38	Elizabeth Metz	Metamorphic and geochronological constraints within a proposed continental suture in Southern India
39	Gabriele Morra	Global Models of Coupled Plate Motions and Mantle Flow
40	Laura Morrissey	The metamorhic evolution of the Eastern Warumpi Province
41	Allen Nutman	New 1:20,000 Scale Geological Maps and Synthesis of the Isua Supracrustal Belt and Adjacent Orthogneisses, Southern West Greenland: A Window into the Eoarchaean
42	Tomas O'Kane	Trench Dynamics Of The Northern Melanesian Arc
43	Matthew Pankhurst	Towards Understanding Orogenic Collapse: Investigating The Role Of Sub-Continental Lithospheric Mantle Using Geochemical Approaches
44	Danielle Payne	New insights into the post-rift depositional history of the Mentelle Basin based on seismic facies mapping
45	David Phillips	Calibrating cosmogenic 21Ne Geochronology for application to quaternary volcanic chronology, landscape evolution and palaeo-climate change
46	Michael Pocock	The petrogenesis and evolution of the Western Ravenswood Batholith, northeast Australia
47	Sara Pozgay	High Resolution Imaging of the Core-Mantle Boundary with PcP-P Seismic Traveltime Data
48	Leonardo Quevedo	Plate-Mantle Interaction Modelling using Parallel Fast Multipole Boundary Element Method and Multigrid Finite Differences
49	Robert Rapp	Physical and Chemical Characteristics of Crustal Rocks in the Mantle Transition Zone: Experimental Constraints at 15-23 GPa
50	Nicholas Rawlinson	New imaging results from the WOMBAT seismic array project in southeast Australia
51	Billy Reid	Structure and tectonic evolution of the central Eastern Ghats Province, India: Araku-Anantagiri-Visakhapatnam

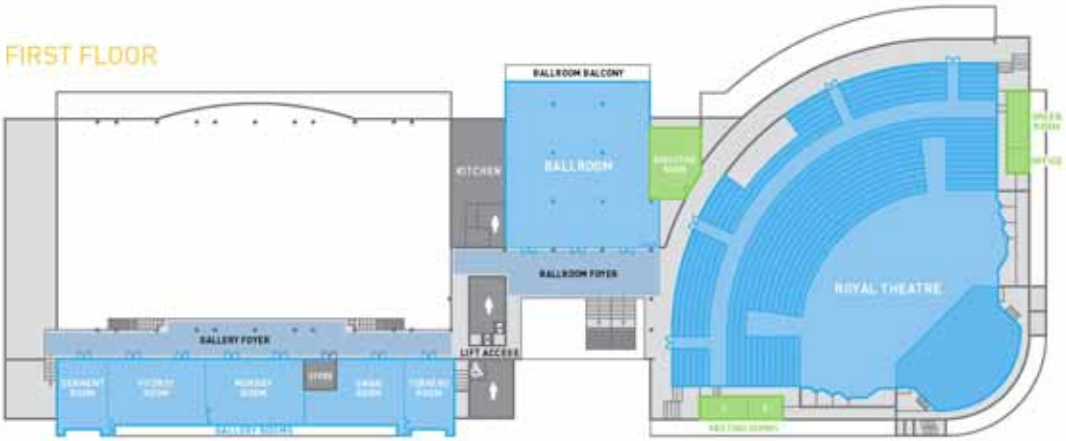
Number	Presenter	Poster title
52	Stephanie Rowe	Mechanism of formation and age of charnockite magmatism in the palghat-cauvery shear system, Southern India
53	Indrajit Roy	Curie depth map from airborne magnetic data – a tool to study tectonic settings of Gawler Craton, South Australia
54	Michelle Salmon	AusMoho: The Moho Map of the Australian Continent
55	Michelle Salmon	New Results from the South Australian Seismic Arrays
56	Malcolm Sambridge	iEarth: A new collaboration for inverse modelling in the Earth Sciences
57	Dulcie Saroa	Constraints on gold and base metal mineralisation within the Wau Structural Basin in Papua New Guinea
58	Erdinc Saygin	Rayleigh and Love Wave Ambient Noise Tomography of Australian Continent
59	Wouter P Schellart	Quantifying the Bending Radius and Bending Dissipation During Subduction with 3D Geodynamic Models
60	Stirling Shaw	A Reconnaissance study of 176Hf/177Hf ratios in zircons from the New England Batholith
61	Grace Shephard	Contribution of mantle convection to the Miocene reversal of the Amazon River
62	Phillip Skladzien	3D Victoria's basin and basement model building workflow – creating the next generation of exploration tools for Victoria
63	Hugh Smithies	The Alcurra Suite and implications for orthomagmatic Ni-Cu-PGE mineralization during the Giles Event, central Australia
64	Paolo Sossi	The Northern margin of the Ferrar Large Igneous Province: the petrogenesis and differentiation history of the Red Hill dolerite-granophyre, Tasmania, and the Wisanger Basalts, Kangaroo Island
65	Aleksandr Stepanov	Experimental Study Of Monazite/Melt Trace Element Partitioning
66	Reddy Talusani	Giant Plagioclase Basalts from Northeastern Part of Deccan Volcanic Province, India
67	Brianna Telenko	High pressure metamorphism during intracratonic orogenesis in the Amata region, Musgrave Province: physical conditions and rates
68	Ian Tyler	New Geochronology from the Biranup Zone of the Albany-Fraser Orogen: Paleoproterozoic Magmatism and Mesoproterozoic Reworking
69	Elizabeth Vanacore	Multiple Seismic Analyses of the SEAL3 Array Dataset to Determine Crust and Lithosphere Structure in Central New South Wales
70	Alec Walsh	Constraining the thermal evolution of a large intracontinental orogen
71	Lloyd White	Simulating Australia-Antarctica break-up and fault development along Australia's southern margin using Pplates deformable reconstruction software
72	Ben Williams	Incorporation of Strategic Fieldwork into 3D Modelling Workflows
73	Simon Williams	Understanding the geodynamics of ocean basins using satellite magnetic observations
74	Sabin Zahirovic	Can geodynamic modelling help resolve the India-Eurasia collision controversy?
Earth's environments: past, present and future		
75	Paolo Abballe	The Origin of Organic Matter in Surface Sediments of the Australian Continental Shelf from Compound-Specific d13C and D14C Analysis
76	Glen Bann	The use of electromagnetic induction (EM and AEM) surveys for dryland salinity management: the applicability for mapping and monitoring activities in upland landscapes
77	Glen Bann	The use of electromagnetic induction (EM) surveys for ecological research and sustainable holistic agronomy management activities in heterogeneous upland environments

Number	Presenter	Poster title
78	Thomas Bodin	Change Point Modelling for Detecting Regime Shifts in Paleoclimate Data
79	Maxwell Brown	Late Palaeoproterozoic palaeochannels of the Robinson River area, McArthur Basin, NT
80	Katherine Brownlie	Palaeofire records and sedimentation (pyrocolluviation) in the context of past and current climate change
81	Robert Burne	The Stromatolites of Hamelin Pool – Brian Logan's Contribution Re-assessed
82	Kelsie Dadd	Cenozoic volcanism in the Capel-Faust Basins, northern Lord Howe Rise
83	Neville Exon	Miocene Shelf-Edge Deltas and Influence on Slope Morphology, Australian Northwest Shelf
84	Adriana Garcia	A Palaeoenvironmental Study In Wetlands From Semi-Arid Australia: The Macquarie Marshes, NSW
85	Eric Heidecker	High Resolution Correlation of Hydroclimatic Change and an Aerosol Emission Event, Upper Devonian Burdekin Basin, Queensland
86	Kyle Horner	Development of a Geochemical Toolbox to Quantify Groundwater Dynamics in the Semi-Arid Lower Murrumbidgee Aquifer System, Australia
87	Jung Ok Kang	Calcification and pH changes in corals from the Southern Great Barrier Reef
88	Jin Li	Getting Seabed Sediments Right: Application of a Simulation Experiment to Predict Seabed Mud Content on Australian Margin
89	John McDonald	Strontium Isotope Composition Variations in the Lower Murrumbidgee Groundwater System, NSW, Australia
90	W Anthony Nicholas	Post-glacial development of the Black Sea: a problem of two radiocarbon-based chronologies
91	Mostafa Sabouhi	Facies Analysis and Depositional environment of the Oligocene-Miocene Qom Formation in the Central Iran (Semnan area)
92	Gretchen Sites	Hydrogeochemistry and groundwater-surface water connectivity of the Broken River, Victoria, Australia
93	Rogerio Uagoda	Geochronological study of a non-carbonate karstic system, middle Paraiba do Sul river valley, SE-Brazil
94	Gary Wilson	ANDRILL Targets Coulman High, Ross Sea, Antarctica to Recover History of the West Antarctic Ice Sheet
Geoscience in the service of society		
95	Douglas Finlayson	Canberra landscapes shaped by geology - the centenary of Pittman's 1910 geological map that helped shape the design for Australia's capital city
96	Russell Lord	Interpretation of Field Portable XRF Test Results
97	Sara Pozgay	A New Master of Natural Hazards Program at The Australian National University
98	Jesse Robertson	Cooling and solidification of channelized viscoplastic lava flows
99	Hrvoje Tkalcic	Towards Automated Seismic Moment Tensor Inversion in Australia Using 3D Structural Model
Life and the solar system		
100	Katherine Adena	The geochemistry of volcanic and impact glasses from the Taurus-Littrow Valley on the Moon
101	Graziella Caprarelli	A Search for Evidence of Volcano-Ice Interactions in Amenthes, Eastern Hemisphere, Mars
102	Aditya Chopra	Evolution of the stoichiometry of the essential elements of life
103	Barbara Frasl	Solar Wind Exposure Effects on Lunar Metal Grains
104	Simeon Hui	Provenance and Age Distribution of Lunar Impact Spherules from Apollo 16: Integration of Major and Trace Element Chemistry and 40Ar/39Ar Ages

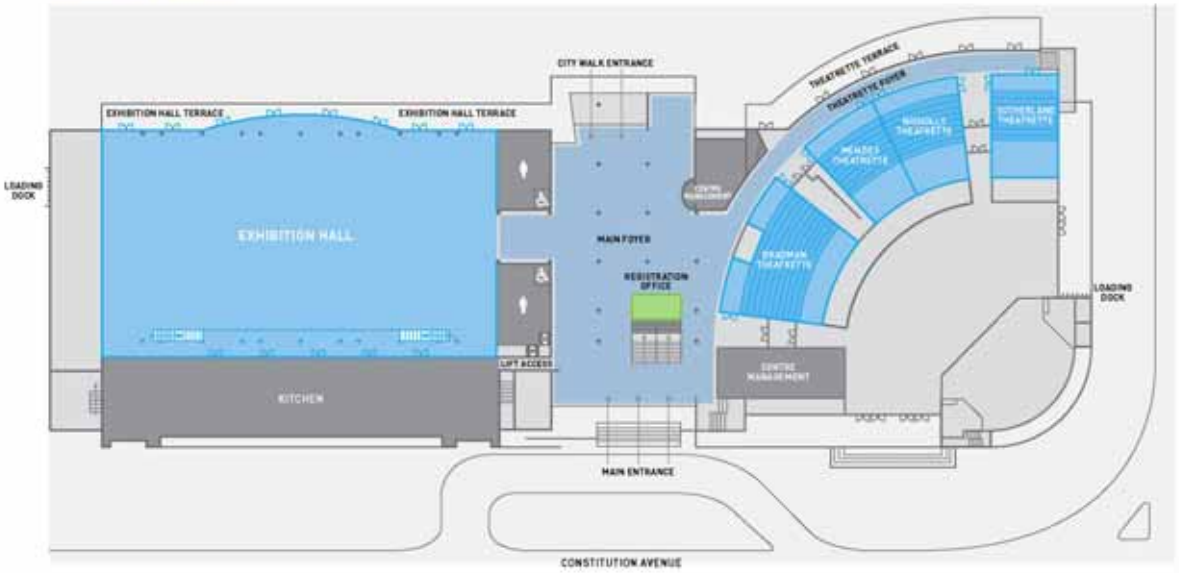
Number	Presenter	Poster title
105	Carina Lee	Identification of carotenoid breakdown products in the 1.64 Ga Barney Creek Formation, McArthur Basin, Northern Australia
106	Seann McKibbin	Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) mapping of olivine trace element distribution in the pallasite meteorite Brahin
107	David Wacey	Pyrite-munching Microbes in the Early Archean
108	David Wacey	SIMS and TEM: Complementary Techniques to Study Stromatolites and Early Life on Earth
Resource security: supporting the nation		
109	Michelle Cooper	Will My Hydrangeas Be Pink Or Blue? Field pH and Soil Colour Results from the National Geochemical Survey of Australia
110	Mike Craig	Data acquisition, processing, interpretation and data delivery from the Pine Creek airborne electromagnetic survey, Northern Territory
111	Andrew Cross	SHRIMP U-Pb detrital zircon provenance of Cretaceous and Cenozoic sediments in the Lake Frome region: Constraints on the architecture of sandstone-uranium systems
112	Garry Davidson	Pyrite variation and radiogenic isotope geochemistry of datable minerals at Coronation Hill Deposit, Northern Territory
113	Arianne Ford	Mineral potential mapping in a frontier region – A case study from Mongolia
114	Phil Gilmore	The COGENT II Project: Making precompetitive geoscience data accessible across New South Wales
115	Lila Gurba	Carbon Dioxide Geological Storage Opportunities of the Gunnedah, Bowen, and Surat Basin Areas in NSW – Regional Mapping
116	Diane Jorgensen	Data from the deep: new geological results from Geoscience Australia's marine survey of frontier basins, southwest Australian margin
117	Mark Kendrick	Noble gases and halogens in metamorphic ore-forming environments
118	Mazhar Khan	The use of water bore cuttings in phosphate exploration, Georgina, Wiso and Daly basins, Northern Territory, Australia
119	David Lindley	Platinum group element mineralization in the Papuan Ultramafic Belt, southeastern Papua
120	Songfa Liu	Uranium Mineral Systems In The Paterson Region, WA: Constraints From Regional AEM Survey Data
121	Brent McInnes	Time-temperature History of the Permian Tinowon Formation Coal Seam Gas Reservoir Revealed by Integrated U-Th-Pb-He and Fission Track Techniques
122	Robert Nicoll	Palaeozoic Palaeontology and Geochemistry of Windjana-1 Well, Southeastern Bonaparte Basin, Australia
123	Chris Osborne	Regional 3D modelling of the Latrobe Valley Coal Resource
124	Nerida Peljo	What do we know about that geological unit?
125	Ollie Raymond	Information Models for the Australian geoscience community: GeoSciML, EarthResourceML and GroundwaterML
126	Tony Roache	Mineralogical and Spatial Validation of Hyperspectral Indices: A Co-ordinated Approach Towards Exploration Uptake
127	Tony Roache	Short Wavelength InfraRed Reflectance Spectroscopy: A New Tool In Very Low-grade Petrology
128	Brian Rusk	It's Easy To Distinguish The Type Of Hydrothermal Ore Deposit Based Only On Trace Elements In Hydrothermal Vein Quartz
129	Brian Rusk	Texture, Paragenesis and Trace Element Concentration of Quartz in Gold mineralised veins from Warrior Mine, Charters Towers, Queensland

Number	Presenter	Poster title
130	Martin Schodlok	A new reference library of thermal infrared reflectance spectra of minerals and rocks derived from CSIRO'S TIR-HyLogger
131	Reddy Talusani	PGE, Au, Ni, Cr and Cu Variations in the Komatiites from the Mahakoshal Greenstone Belt, Central India
132	Ian Tyler	Encouraging exploration for the long-term sustainability of Western Australia's resources sector: the WA Government's Royalties for Regions Exploration Incentive Scheme
133	Lesley Wyborn	Thinking Out Cloud: the Need for Increasing Virtualisation of Australian Geoscience Data to Underpin Cost Effective Deep Exploration
Topical		
134	Phillip Blevin	Cassiterite – The Zircon Of Mineral Systems? A Scoping Study
135	John Cliff	Australia's IMS 1280 Large-Radius Ion Microprobe
136	Terrence Mernagh	Applications of mico-Raman Spectroscopy for the Identification of Minerals and their Polymorphs
137	Bill Reid	HyLogger alteration fingerprints of NSW type deposits and their regional application

FIRST FLOOR



GROUND FLOOR



Plenary abstracts

(in program order)

PLENARY 1
Energy for generations: Australian oil and gas

Belinda Robinson[1]
[1]Australian Petroleum Production and Exploration Association

It has been 40 years since world class oil discoveries were made in the Gippsland and Carnarvon basins. Despite these early successes, only around 12 out of 50 of Australia's known sedimentary basins have been explored. Why is this? Have we found everything of significance there is to be found or are the costs and risks simply too high to justify frontier exploration? In this environment of low exploration and unknown prospectivity and with an ever increasing demand for liquid hydrocarbons, should Australia be considering seriously overcoming the impediments to exploring our frontier areas or accept that the country's hydrocarbon future lies in gas rather than oil?

Australia's oil reserves have been in decline for nearly a decade. We currently import more than we export and we are confronted with an ever-increasing liquids trade deficit. Does it matter? Will our export of liquefied natural gas ameliorate any concern?

Australia has abundant reserves of natural gas—of around 164 tcf of conventional resources and over 153 tcf of unconventional resources such as CSG. Whether it is produced and used domestically or exported in the form of LNG, natural gas provides the key to Australia and the world moving to a cleaner energy future.

Optimising Australia's hydrocarbon future demands a multi-faceted strategic approach.

Incentives for exploration may assist in attracting investment but do not guarantee discovery. The industry is capable of undertaking remote and deep exploration, but the fiscal and economic settings need to reflect high costs and high risks. Flow through shares and corporate tax based initiatives are relevant as is the need to consider improving acreage management terms.

Natural gas requires a very different approach.

While gas investment announcements having been coming thick and fast, many of these are staging statements or declarations of intent and aspiration rather than firm project commitments. With talk of a global LNG glut and Australia's place as an expensive LNG investment destination, our strengths must not be allowed to translate into complacency. Qatar, Nigeria, Algeria, Trinidad and Tobago, Indonesia, and Malaysia are formidable competitors and, if Australia is to realise its full potential as an LNG super-supplier we must be ever mindful of building as competitive a position as possible. Relevant here are public policies that risk cost loading and taxation regimes that take account of the high capital costs, high risks and long lead-times associated with multi-billion dollar gas projects.

Within Australia, if natural gas is to compete effectively with coal as a source of electricity generation, a level playing field is required but this appears as far away as ever in the absence of a price on carbon and a tax rate that can be hundreds of times higher than for coal. With the right policy and fiscal settings, natural gas can be the destination fuel of the future, along with renewable energy, low-emissions coal and possibly even nuclear energy. Efficient, transparent markets that allow each energy source to compete equally and on its merits will always deliver better, cheaper outcomes than interventionist, distortionary policies that advantage one energy source over another.

With its vast resource and energy endowment and geographic location, Australia is ideally positioned to capture the benefits of a rapidly developing region and a world that is demanding large volumes of cleaner burning fuel. Realising and extracting the full potential of Australia's oil and gas sector can ensure energy security for tomorrow's generations and the relegation of economic stimulus packages, to history.

PLENARY 2
Late Quaternary palaeoceanographic investigations in the Australian region: relevance to climate models

Patrick De Deckker[1]
[1]Research School of Earth Sciences, The Australian National University

Australia is strategically located on the globe as it is surrounded by three oceans, the Indian, Southern and Pacific Oceans and these primarily control Australia's climate.

The presentation will provide, firstly, an overview of modern oceanic circulation in our region. Emphasis will be given to the Indo-Pacific Warm Pool [IPWP], the region north of Australia that today registers sea-surface temperatures >28°C. This large body of water, which sees the transiting of Pacific water into the Indian Ocean, is best described as the 'heat engine' of the globe, and is a significant source of low-salinity water that is linked with the monsoonal system. The importance of the IPWP in global oceanic circulation will also be discussed.

Three oceanic currents will be discussed; these are the Leeuwin, East Australian and Flinders Currents which play vital roles in the transport of waters of different temperatures and salinity and which also control plankton distribution and oceanic productivity.

The second part of the presentation will concentrate on the Quaternary history of the oceans in our region. Questions such as 'was the Leeuwin Current always as active as today?' and 'did the intensity of the East Australia Current that affects the dynamics and ecology of the Tasman Sea vary in the past, especially during sea level oscillations and glacial/interglacial cycles?'

Key deep-sea core records will inform us that the oceans have become progressively warmer over the last 450,000 years. This is an important signal for understanding the evolution of Australian continental climates and aridity.

Substantial changes in the oceans in our region are also recognised for the Holocene spanning the last 12,000 years of Earth history. These changes and their amplitudes, as well as cyclicities in some cases, require documentation as they clearly demonstrate broad shifts which climate modellers need to envisage in their attempt at predicting future climatic and oceanic changes. Of note is that the last 5 millennia differed from the earlier part of the Holocene. Of importance also is that oceanic conditions well documented for the last few decades, which show a rise in sea level and temperature, reverse the long-term trend that operated previously.

PLENARY 3
Colloidal gold in supergene and hypogene systems

Robert M Hough[1]
[1]CSIRO Earth Science and Resource Engineering

New studies of gold are revealing how metallography is a key component of our understanding of the deposition of precious alloys in primary ore systems. Alluvial gold nuggets once thought to be secondary in origin have now been shown to be the erosional residue of hypogene systems, i.e. primary. A new frontier in both hypogene and supergene systems is the nano domain. In hypogene settings gold at all scales can be metallic and particulate as has been directly observed in refractory ores, or the so called 'invisible gold' in pyrite and arsenopyrite. Such nanoparticulate and colloidal transport of gold is a viable mechanism of dispersing the gold during weathering of ore deposits. These gold nanoparticles, long known about in materials sciences and manufacturing have now been seen in these natural environments. Such colloids are also likely to play an important role in gold transport in hydrothermal deposits. The regularly heterogeneous distribution, trace concentration and nanoparticulate grain size of metallic gold in all ore systems has made it difficult for direct observation. Yet, it is critical to be able to establish a broad view of the microstructural/microchemical residence of the actual gold in a given sample. New generation element mapping tools (MAIA at the Australian Synchrotron) now allow us to 'see' this invisible gold component for the first time and to probe its chemistry and controls on deposition.

Deposition of supergene (secondary) gold in the regolith is a product of the dissolution of hypogene gold from the a primary deposit (hosted by sulphides or quartz), transportation in solution and then re-precipitation elsewhere in the weathering profile. Weathered fracture surfaces in quartz veins in saprolite have been observed to contain exceptionally rich populations of ultra-thin and nanoparticulate triangles and hexagons of supergene Au crystals. Similarly, gold nanoparticles as spheres have recently been observed in opalline silica accumulations. The single crystals and ultra thin Au nanoplates suggest rapid deposition of gold in this environment, completed on the order of days rather than over prolonged timescales, and driven by evaporation. This process has been emulated by laboratory experiments, in which similar gold nanoplates have been precipitated by evaporation of Au chloride solutions but also more widely through reactions to reduce Au ligands. The natural nanoparticulate fraction of Au probably occurred as a colloidal suspension before final deposition as metallic particles and raises the question of how common a process is this in all gold depositional settings? Such particles have been imaged in refractory ores hosted in sulphides, in geothermal systems and in volcanic fumaroles but have also been postulated to exist more broadly in epithermal systems and mesothermal quartz veins where amorphous and opalline silica veins occur. The silica and thus the accompanying gold in those veins are thought to have formed through colloidal processes. As a colloidal suspension, the gold content of transporting media could reach very high concentrations and may thus be a key process contributing to the formation of high grade gold. Colloids have been observed to be stable to 400°C but once the colloidal particles interact or lose charge they destabilise and deposit gold very rapidly, as such they could lead to local very high accumulations of gold. In supergene environments colloidal transport may lead to quite distal dispersion of the gold.

PLENARY 4
What are we to make of the Ediacara biota?

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Without key elements in the biosphere, Ediacaran organisms ecosystems may have worked in ways that seem to us unfamiliar and puzzling. For the last fifty years, following the seminal work of Martin Glaessner and Mary Wade, it has been the norm to seek out familiar animal prototypes and behaviours in the Ediacara biota, prior to the Cambrian explosion after 542 Ma. Such a uniformitarian approach is entirely natural and continues in places today. But current research, including laser-mapping and morphospace analysis, shows that few if any of these comparisons can stand up to critical analysis.

A contrasting view, explored by Hans Pflug and latterly by Dolf Seilacher, is that many have affinities with protozoans or even foraminiferan xenophyophores. But here again, comparisons with living forms encounter problems. A third and rising contention is that the Ediacara biota contains stem-group animal ancestors, lacking crown group characters such as a mouth plus anus, but having some fungal characteristics too.

In this talk, I will explore the bearing of some new Avalonian findings upon this dilemma of *Darwin's Lost World*. These include complex, slime-mould like colonies; bedding planes covered in paired grazing marks; bedding plane covered in complex linear traces at Mistaken Point; plus a host of other new and curious body fossils. We are only just beginning to appreciate the depths of our ignorance.

Concurrent abstracts

(in program order)

Monday 5 July 2010

SESSION 01RA (RESOURCES)

Controls on mineralisation at the Porgera gold deposit, PNG

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Fluid pathways and hence localisation of ore in intrusion-related hydrothermal systems, are controlled by the development of fracture networks and by ongoing competition between (1) fracture sealing processes and (2) stress-driven and fluid-pressure-driven opening of fracture permeability. The geometries and distributions of fracture-controlled fluid pathways are sensitive to the evolution of the stress field and differential stress. Here, we illustrate how stress fields evolve during gold mineralisation in the Porgera Intrusive Complex (PIC) and highlight the controlling role that changes in both stress field orientations and failure modes have on mineralisation styles. The Porgera gold deposit is located in the Enga province at 2500m elevation in the highlands of Papua New Guinea. Emplacement of the PIC occurred at 6.0 ± 0.3 Ma at a depth between 2–4km (Richards, 1997). Mineralisation occurred between 6.0 Ma and 5.6 Ma and regional uplift commenced around 4 Ma. Regional uplift of the Papuan highlands commenced at 4 Ma, after magmatism and mineralisation ceased.

On the basis of cross-cutting relationships, mineralisation at Porgera is separated into 4 main episodes: pre-stage 1, stage 1, stage 2 and post-stage 2. Only stage 1 and stage 2 are economically significant. Stage 1 vein mineralisation is characterised by weakly compositionally banded, fine to coarse grained pyrite-rich veins which can also contain sphalerite, galena, quartz and calcite. The veins can also contain trace amounts of gold, chalcopyrite, marcasite, arsenopyrite, freibergite, tetrahedrite and siderite. The bulk of the gold occurs as inclusions within pyrite. Stage 1 veins can contain up to 3.0g/t Au but on average contain 0.7g/t. Stage 1 vein mineralisation is hosted by widely distributed extension veins. Most veins are moderately to steeply dipping, but mutually overprinting relationships with a second population of gently dipping stage 1 veins indicates that there were repeated changes in the orientation of the near-field σ_3 from a gently plunging to steeply plunging attitude during Stage 1. Repeated reorientation of stress fields in the PIC during stage 1 is interpreted to be associated with either (1) magma inflation-deflation cycles in a deeper level magma chamber, or (2) inflation-deflation cycles driven by fluid leakage repeatedly interrupting accumulation and pressurisation of volatiles in a reservoir at the top of the magma chamber.

Stage 2 veins are typically compositionally and growth banded veins, breccias and cataclasites. Locally, stage 2 veins can also reactivate suitably orientated stage 1 veins. The gold is found in association with roscoelite (vanadium-rich white mica) and the veins also contain quartz, pyrite, tellurides, apatite and barite, with rare marcasite, chalcopyrite, tetrahedrite, sphalerite, galena, magnetite and haematite. Stage 2 veins can contain up to 200g/t Au but on average contain 7.5g/t. Stage 2 mineralisation occurs in fault-fill veins in the Romane Fault and its associated network of faults, vein breccia systems and extension veins. Stage 2 veins exhibit a broad single orientation cluster with veins striking NE-SW and steeply dipping to the SE. Many veins are sub-parallel to the Romane Fault.

The transition from stage 1, low grade, distributed mineralisation to stage 2 localised high grade mineralisation was associated with the growth of the Romane Fault network. This fault network accessed magmatic-hydrothermal fluids at depth and localised fluid flow through faults and their damage zones. Compositional banding in stage 2 veins indicates cyclic changes in fluid chemistry. The formation of implosion breccias is interpreted to indicate sudden fluid de-pressurisation associated with fault slip events. Microstructures indicating multiple episodes of opening and sealing of some veins and breccias suggest that episodic, fracture-controlled flow may have been controlled by co-seismic permeability enhancement and interseismic permeability destruction in the stage 2 fracture systems. Transiently high flow rates, large transitory fluid

pressure gradients, and large chemical gradients, during pulses of fluid redistribution, were associated with repeated breaching of the deep-level magmatic-hydrothermal fluid reservoir and are interpreted to be key factors promoting flow localisation and efficient gold precipitation during stage 2.

Reference

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Fluid-driven growth of fracture networks: experimental approaches and implications for fluid pathways in hydrothermal ore systems

Stephen Cox[1]
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Experimental deformation of dolomite rocks in the brittle field shows for the first time the difference between stress-driven growth of fracture networks and fluid-driven growth of fracture networks. Stress-driven fracture growth, in the absence of a pressurised fluid reservoir, is an example of an 'ordinary' percolation process characterised by distributed nucleation and growth of microfractures. Progressive linkage with increasing strain ultimately forms a connected fracture network. In contrast, fracture growth driven by a fluid pressure source is more akin to an 'invasion' percolation process that is characterised by preferential fracture growth occurring initially at the high fluid pressure part of the rock sample. Fluid-driven fracture networks propagate rapidly through the sample and away from the high fluid pressure reservoir. All components of the fracture network are connected to the fluid reservoir.

The growth of vein networks in overpressured hydrothermal ore systems, such as many intrusion-related systems, is expected to be dominated by fluid-driven enhancement of fracture permeability. Pulses of fluid migration in these systems are interpreted be triggered by episodic breaching of fluid reservoirs, with subsequent migration of a fluid pressure front within a propagating fracture network. Repeated cycles of fluid pressure build-up in reservoirs, followed by breaching and fluid pressure loss, in combination with hydrothermal sealing of fracture-controlled fluid pathways, requires that ore formation in such systems occurs within an episodic flow regime. Episodic propagation of fluid-driven fracture fronts favours rapid transit of fluids to environments where they are out of equilibrium with their host rocks.

STREAM 01EA (ENVIRONMENT)

Reconstructing past extreme events based on U-series dating of uplifted reef blocks and lagoon sediments

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Extreme events such as tropical storms, cyclones and tsunamis have a severe impact on human populations and economy and play an important role in coral reef development and biodiversity. The loss from extreme climatic events over the last decade has surged by 10 times relative to that of 1950s. For instance, the total damage caused by Cyclone Larry in north Queensland on 20 March 2006 alone amounts to nearly $1 billon. The total loss and death toss caused by Hurricane Katrina in August 2005 in the USA amounts to US$125 billion and 1836 lives, respectively. The recent IPCC Report (2007) predicts that through climate change there will be a likely increase in the intensity and frequency of tropical cyclones. If and how global warming affects cyclone activity is a topic of considerable interest. Assessing anthropogenic effects on variations of cyclones requires decoupling recent and future trends from longer-term periodicities/variability, as well as a better knowledge of cyclone occurrences over the past millennium. The available instrumental/historical record, however, is far too short (for Australia < 150 years) to document and understand the complex links within the climate system responsible for cyclones. Only through extending the records beyond the instrumental measurements by geological data, can we capture the full range of natural variability inherent to the climate system. Tropical cyclones play a significant role in ecological perturbation of reef communities by influencing coral reef

morphology and community compositions, much like bush fires in terrestrial systems. Understanding long-term variability in the occurrence of tropical cyclones is important for determining their role in ecological disturbances, for predicting present and future human vulnerability and for assessing whether changes in the variability of such cyclones are induced by climate change.

The frequency and magnitude of cyclones can be recorded in various archives, such as transported reef blocks, storm ridges/ramparts, lagoon and coastal sediments (sediment structure and grain-size distribution), near-shore lakes, sinkholes or swamps (fingerprints of sea-water surges), and even tree-rings and speleothems. Through dating and characterising such geological archives, cyclone activity in the Earth's most recent history can be reconstructed. Bearing this in mind, we have employed U-series dating of cyclone-transported reef blocks and reef-lagoon sediments to reconstruct past cyclone history in the South China Sea and the Great Barrier Reef.

In these studies, numerous cyclone-uplifted reef blocks, some a few meters across, were found to litter the outer reef flats of Yongshu reef in the southern South China Sea and Heron, Wistari and One Tree reefs in the southern Great Barrier Reef. Because many such reef blocks represent individual coral boulders transported from their living growth positions on the reef slope, the surface mortality ages of these boulders should closely approximate the times when the cyclones occurred. Using the TIMS U-series dating method, we have demonstrated that coral boulders of 10–1,000 years old can be dated with precisions of up to ±1–5 years [1,2]. The results obtained so far suggested that coral blocks on Yongshu reef were uplifted over the past 1000 years, whereas those on Heron, Wistari and One Tree reefs, over the past 300 years (most within the last century). These studies also demonstrated a clear correlation between the ages of cyclone-transported coral blocks on Yongshu Reef and increased lagoon deposition rates and elevated weight percentages of coarse-grained (>1 mm) sediments [3]. Based on this correlation, the variation in the weight percentage of coarse-grained sediments was interpreted as a proxy for storminess (i.e. frequency/intensity of cyclone events). On millennial scales, the grain-size distribution pattern reviews three extremely stormy periods centring around ~1200 AD, ~400 BC and ~1200 BC, respectively, which are reversely correlated with hurricane records in the Caribbean region [4]. On shorter timescales, the grain-size distribution pattern shows periodicities consistent with solar cycles. Overall, this study demonstrates that the combined use of transported coral blocks and the weight percentage of coarse lagoon sediments provides an excellent means for comprehensive reconstruction of past storm activity.

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Intensified massive coral mortality since 1860 AD In the southern South China Sea

Kefu Yu[1,2], Jian-xin Zhao[1], Qi Shi[2], Gilbert J Price[1], Tian-ran Chen[2], Huiling Zhang[2]

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The key to predicting the possible response(s) of coral reefs to hypothesised future global warming is the knowledge of coral reef response(s) to previous extreme climatic events. However, there is a general paucity of information concerning the long-term historic response of reefs to such events, primarily because our understanding of contemporary coral reef dynamics is based largely upon the recent period of ecological monitoring (i.e., post-1960s for most reefs worldwide). New developments in radiometric dating methods, such as U/Th dating, means that it is now possible to date well-preserved corals up to 500 years with precision of only 1–10 years. Such dating advancements mean that it is now possible to explore the longer-term history of reefs and their response(s) to previous ecological stresses such as warming-induced bleaching events. Here we targeted the U/Th dating (n=80) of dead massive corals (*Porities*) from the Nansha Islands, South China Sea, with an aim of understanding the long-term history, frequency and causes of local coral mortality. Massive corals, such as *Porities*, typically have strong tolerance to bleaching and other environmental stresses, and therefore, the occurrence of their mortality may serve as indicators of severe historical ecological or environmental stresses. Our results suggest that there were nine significant episodes of coral mortality since

1860, with a significant increase in frequency since 1930; a period coinciding with regionally and globally warmer temperatures.

STREAM 01SA (SOCIETAL RESOURCE SECRURITY)

Australia's Minerals Inventory: how it is compiled and how it ranks globally

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[1]Geoscience Australia

Australia's mineral resources are an important component of its wealth, and a long term perspective of what is likely to be available for mining is a prerequisite for formulating informed policies on resources and land management. The national resource inventory is quantified in the annual online publication: *Australia's Identified Mineral Resources*: http://www.australianminesatlas.gov.au/aimr/index.jsp. This provides Geoscience Australia's assessments using its national mineral resource classification system, which is based on the McKelvey resource classification system used by the United States Geological Survey (USGS). It defines known mineral resources according to two parameters: degree of geological assurance and degree of economic feasibility of exploitation.

Companies listed on the Australian Securities Exchange are required to report publicly on Ore Reserves and Mineral Resources under their control, using the Joint Ore Reserves Committee Code (JORC; see http://www.jorc.org/). Data reported for individual deposits by resources companies generally provide a relatively short term commercial perspective. They are compiled in Geoscience Australia's national mineral resources database and used in the preparation of the annual assessments of Australia's mineral resources. This involves aggregating JORC categories from company reports into larger categories in the national system.

Because of the specific use of 'Reserve' in JORC, this term is not used in the national inventory, where the highest category is 'Economic Demonstrated Resources' (EDR). In general terms EDR incorporates JORC Proven and Probable Ore Reserves and Measured and Indicated Mineral Resources. This is considered to provide a reasonable and objective estimate of what is likely to be available for mining in the long term.

By way of comparison between the national inventory and published JORC Reserves:

- JORC Ore Reserves for bauxite at June 2009 amounted to only about 35% of EDR, but 81% of EDR was in established mining areas; and
- JORC Reserves for gold at the same time amounted to 56% of EDR, but 80% of EDR was associated with existing or committed mines.

Australia has the world's largest resources of mineral sands (rutile and zircon), nickel, silver, uranium, zinc, lead and brown coal. In addition, bauxite, black coal, copper, gold, iron ore, industrial diamond, ilmenite, lithium, manganese ore, niobium, tantalum and vanadium rank in the top six worldwide. During 2008 Australia's EDR of copper, gold, iron ore, lead, manganese ore, nickel, zinc and uranium increased, indicating that production was more than compensated by discovery of new resources, mainly within existing mining belts. Bauxite and black coal EDR remained constant while EDR for mineral sands and diamonds decreased slightly.

EDR of most of Australia's major commodities can sustain current rates of mine production for many decades. The resource lives for black coal and iron ore have levelled off after the decreasing trend in the decade to 2007, which resulted from major increases in production and reassessments of resources. Resource lives based on ore reserves are lower, reflecting a shorter term commercial outlook.

The fact that resource life indicators appear generally healthy overall does not mean that Australia's position as a premier mineral producer is secure. In the increasingly globalised and competitive mineral commodity market, individual mine projects in Australia are ranked against the investment returns from other deposits worldwide. While many of Australia's iron ore, black coal, bauxite and mineral sands deposits are world class, a number of nickel and other base metal mines have closed recently.

When global competition is considered along with the paucity of major discoveries over the past two decades, it is apparent that Australia's continuing position as a premier mineral producer is dependent on continuing investment in exploration to locate new high quality resources and/or to upgrade known deposits in order to make them competitive on the world market, and investment in beneficiation processes to improve metallurgical recoveries. Successful exploration outcomes rely heavily on the continuing flow of pre-competitive geoscience data from government agencies. Integrated research efforts leading to state-of-the art geoscientific syntheses are also needed to reduce exploration risk in new mineral provinces in prospective frontier regions.

Peak resource production—does Australia have a problem?

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Australian oil and gold production has already peaked; oil in 2000, when 35.3 million tonnes were produced, and gold in 1997, when 82 tonnes were produced in the December Quarter.

It is probably not surprising that oil production peaked when the Gippsland Basin output started to decline. However, the situation with gold is not so obvious. From 1997 until the end of the first quarter of 2009, gold production has, on average, declined by approximately 0.52 ± 0.08 tonnes per quarter relative to the 1997 peak.

Surprisingly this decline appears to be independent of the price of gold or the levels of exploration expenditure devoted to search for it.

Production trends from other mature gold producers, such as South Africa, Canada and the USA, are similar and also indicate that 'peak gold' has been and gone in those countries. World gold production has peaked at approximately 2600 tonnes in 2001 and is likely to continue to decline.

However, the gold production curves (unlike Hubbert's curves for oil) are not symmetrical about the peak production and have a slower decay than the rise to the peak. Therefore, although Australia's gold production is likely to continue to decrease, it should still be significant for many years to come.

We will just have to work harder to find it.

Other resources such as coal and nickel will also be examined and the results will identify key commodities where new exploration techniques will have to be developed to increase production rates.

STREAM 01DA (DYNAMIC EARTH: GEODYNAMIC EVOLUTION OF AUSTRALIA)

Initiation of subduction on the Gondwanan continental margin in north-west New South Wales

Robert J Musgrave[1], John Greenfield[1], Phil Gilmore[1], Stephen Dick[1]
[1]Geological Survey of NSW, Industry and Investment NSW—Primary Industries and Energy

Cambrian convergence along the north-eastern flank of the Curnamona Craton, the Gondwana margin in far north-west NSW, resulted in the development of the Koonenberry Belt segment of the Delamerian Orogen. Interpretation and modelling of gravity and magnetic data has significantly aided our reconstruction of the 3D geometry and geological history of the Koonenberry Belt. A Neoproterozoic rifted margin, marked by the alkalic Mount Arrowsmith Volcanics, forms the substrate on which was built a NE-facing Cambrian arc, complete with a clearly delineated inner imbricate accretionary prism (the Wonnaminta Zone) and outer thin-skinned wedge (the Kayrunnera Zone).

Mature arc volcanism, represented by the calc-alkaline Mount Wright Volcanics, exhibits mixed arc–rift geochemistry. Interpretation and modelling of magnetic data reveals a chain of volcanic edifices of the Mount Wright Arc, now below 3 to 7 km of Devonian sandstones in the Bancannia Trough. Remarkably, a simple rotation around an Euler pole reconstructs the Wonnaminta Zone against the craton, and aligns structural

elements on the two sides of the trough. Arc volcanism evidently occupied a rift in marginal continental crust, and the geometry, geochemistry and geophysical properties of the Mount Wright Arc are closely analogous to the Taupo Zone of New Zealand. Rifting of the arc divided Delamerian structures, indicating that at least part of the Delamerian deformation developed in a subduction accretion setting, rather than in some terminal collision.

Below the Wonnaminta Zone, a 3 to 5 km thick body can be traced as a large magnetic source along the length of the zone. Overridden by the thrust stack of the accretionary prism, this body is mostly planar and dips towards the east, although it is deformed into a broad antiform in the central part of the zone. Modelled magnetic susceptibility and density suggest that this body may be a thick rift-volcanic pile equivalent to the Mount Arrowsmith Volcanics. In the southern part of the belt a re-entrant in the Wonnaminta Zone faces a large magnetic anomaly sourced in the basement of the Kayrunnera Zone. The geometry of the re-entrant, and the development of Silurian and Devonian basins over the surrounds, suggests analogy with structures observed in modern accretionary margins associated with the subduction of seamounts. Bounding the Kayrunnera Zone to the north-east is the Thomson Orogen, a Neoproterozoic to early Palaeozoic structural zone largely covered by Mesozoic sediments. Deformation by the Late Ordovician to Silurian Benambran Orogeny affects both the Kayrunnera Zone and the Thomson Orogen. Seismic reflection indicates overprinted NE and SE facing thrusts below the Kayrunnera Zone, and deformation features project both towards and away from the Thomson Orogen. A plausible explanation interprets the local expression of the Benambran Orogeny as an arc-arc collision between the Mount Wright Arc and a Thomson Arc. Propagation of the frontal thrust of the Thomson Arc resulted in capture of former Mount Wright fore-arc.

Preserved within the accretionary prism of the Wonnaminta Zone are basaltic volcanics and intrusives of the Bittles Tank Volcanics. Despite their forearc location and their chemistry, which suggests MORB and OIB characteristics with a small subduction signature, the Bittles Tank Volcanics are at least partly contemporary with activity of the Mount Wright Arc. Extensive MORB-like tholeiitic volcanism has recently been identified as the earliest stage of arc volcanism in the Izu-Bonin Arc, preceding the boninitic phase. Initial eruption in the forearc of the Bittles Tank Volcanics may similarly represent the very first stage of subduction along the Mount Wright Arc. Boninites appear to be absent, in contrast with the Cambrian arc systems of Victoria: this difference may reflect the contrast between development of a new arc on a continental margin (the Koonenberry Belt) and in an intraoceanic setting (the Victorian arcs and the Izu-Bonin Arc). Following this initiation of subduction on the Gondwanan margin in the Cambrian, repeated phases of slab rollback have maintained this subduction system in the south-west Pacific to the present day.

This abstract is published with the permission of the Director, Geological Survey of New South Wales, Department of Industry and Investment–Primary Industries and Energy.

South-directed oroclinal folding in the Lachlan Fold Belt: unravelling mid-late Silurian fold belt assembly to solve apparent Ordovician–early Silurian complexity

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Recent models for the Lachlan Fold Belt (LFB) attribute geometry (vergence changes between west, central and eastern portions), sedimentary relationships, width and magmatic history to either: (1) several coeval subduction zones of opposing polarity, or (2) large-scale horizontal movement along the mid to Late Silurian Baragwanath Transform. Aeromagnetic data shows that the Baragwanath Transform does not occur in western New South Wales, but compelling evidence that the Tabberabbera Zone was not contiguous with the Melbourne Zone until the Early Devonian remains. This is not addressed by multiple subduction models; a new explanation must be sought.

The model presented here provides a solution that involves mid to Late Silurian oroclinal folding adjacent to dextral strike-slip faults. This solves the geometrical puzzle and apparent great width of the LFB, and simplifies its Late Cambrian–Early Silurian configuration, allowing closer ties with the Ross Orogen along the east Gondwana margin.

At the onset of the Late Ordovician Benambran Orogeny, Tasmania and the Selwyn Block are located outboard of the Gondwana margin, separated by the undeformed proto-Bendigo Zone ocean basin. A continent-directed subduction system was active along the entire eastern edge of the LFB. The Benambran Orogeny involved

west-directed accretion associated with ongoing subduction that produced predominantly east-verging structures in the adjacent accretionary complex, including the Mallacoota Zone and Tabberabbera Zone. The Bendigo Zone, then along strike from the Tabberabbera Zone, was separated from subduction–accretion by the Selwyn Block.

The Late Silurian Bindian Orogeny marked the beginning of an interval where the evolution of the Lachlan and Ross orogens were markedly different. Bindian Orogeny movements in the LFB were south-directed and reminiscent of lateral escape tectonics, possibly in response to the southward movement of the Thompson Fold Belt. The LFB became progressively fragmented, with one portion, the western LFB, including the Selwyn Block, remaining attached to the Gondwana margin. A para-autochthonous portion—the Tabberabbera Zone, Hay-Booligal Zone and northern Stawell Zone—peeled away from the Delamerian margin and was oroclinally folded. An allochthonous portion comprising much of the central and eastern LFB, Wagga-Omeo Metamorphic Complex, and Macquarie Arc, detached from the margin and moved south along major strike-slip faults.

The main fault may be the Bootheragandra Fault, reinterpreted as a dextral strike-slip fault initiated in northern NSW. It propagated south-east, cutting across the Stawell Zone into the interior of the Lachlan Orogen. Dextral transtension along it was in hot weak crust west of the Macquarie Arc, leading to local crustal thinning and further heating: the Wagga-Omeo Metamorphic Complex. As the Bootheragandra Fault cut across the arc (as the dextral Kiewa–Kancoona strike-slip fault system) it began to founder in low-grade forearc terranes (Tabberabbera and Mallacoota zones). These regions deformed by oroclinal folding.

The Selwyn Block and the Macquarie Arc acted as rigid indentors. Their oblique convergence during the Bindian Orogeny controlled oroclinal folding of intervening zones. As the Macquarie Arc moved south-east past the Selwyn Block along the Bootheragandra Fault, the Tabberabbera Zone underwent more than 90° clockwise rotation to form the middle limb of a Z-shaped oroclinal fold of ~400km amplitude, arriving against the eastern margin of the Selwyn Block in the Early Devonian. This rotation reversed the apparent vergence of structures within the Tabberabbera Zone. There was concomitant clockwise rotation of the Hay-Booligal Zone and northern portion of the Stawell Zone as they were also peeled out from their former position along the Delamerian craton margin. The Hay-Booligal Zone may restore as part of the Macquarie Arc. The western limb of the Z-fold includes the Bendigo Zone. The eastern limb includes the Mallacoota Zone. Hinge regions are exposed in Victoria: the east–west trending portions of the northern and south-eastern Tabberabbera Zone, and the south-west Kuark Zone.

This is a powerful new model. It does not require multiple subduction zones to explain reversals in vergence and observed complex distribution of sedimentary packages, instead explaining them by subsequent oroclinal folding developed ahead of strike-slip faults. It also fits new aeromagnetic data, and explains the palaeogeographic relationships without need of the Baragwanath Transform concept.

STREAM 01LA (LIFE AND SOLAR SYSTEM: ARCHEAN AND PROTEROZOIC LIFE)

Early Earth

Therese Schneck[1]
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The presence of xenon isotopes from in-situ spontaneous fission of short-lived 244Pu has been confirmed in Hadean detrital zircons from Western Australia. ^{244}Pu was extinct within 600 million years of Earth's formation Hadean and meteoritic zircons can retain secondary overgrowths developed after primary crystallisation at 3.97–3.94 Ga years.

Xenon isotopes fractioned by accretion, nebular hydrodynamic processes and decay of Iodine I129 (beta decay) and Pu244 and U238 are indicators of atmospheric, crustal and planetary evolution,. Curium, heaviest known element with isotopes possess a geologically significant half life; Cm247 and isotope Cm248 decay to lead via U235. The estimated Pu244/Cm247 ratios of r-process heavy actinide synthesis is 0.64 to 49.3 with a mean of 5. Curium is one of a few elements that has a lattice structure stabilise by magnetism

Merrilite in lunar crust lithologies typically contains more Mg than Fe.

More than 70 per cent of the fission tracks studied in whitlockites in phosphates from chondrite meteorites are due to the decay of extinct Pu^{244}. Data on whitlockite crystal 14301 could be due to an early irradiation; The various petrologic units in the meteorite experienced the same cooling event which reequilibrated metal as well as reset the phosphate chronometers

.92Nb92Zr can provide new time constraints on early silicate differentiation processes in planetary bodies, Nb can be strongly fractioned from Zr during silicate melting in the presence of Mg perovskite. Mars had a perovskite layer at the base of its mantle. On the Moon the magnitude of Pollonium-210 to Radon-222 on the Aristarchus plateau spectrum indicates a past greater activity. Nb/Ta values in the bulk silicates Earth 14 and the Moon 17 are below the chondritic ratio of 19.9 in contrast to Mars which magnetosphere disappeared at the end of the Noachian at 3.9 Ga years; The opaque minerals observed in Lunar samples from Descartes site are Ti-chromite, ilmenite, traces of troilite and metallic FeNi. At 3.85 Ga years Nectaris basin and 3.9 Ga years Descartes sites the primordial crust consisted mainly of ferroan anorthosite and Mg-suite;. The evolution of Earth and Mars Planetary cores and The Earth Moon system from Nb/Ta systematics is consistent with a Moon iron core delayed until 3,9 Ga years Chemical reactions and albedo stabilise the Earth atmosphere abundance against the solar luminosity variations.

Sun → Earth → crust → biosphere → life: what do the elemental abundances tell us?

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The elemental composition of the planets, moons and asteroids in the solar system reflects to a large extent the composition of the Sun, except that relative to the Sun, all are depleted in the most volatile elements hydrogen, helium and the noble gases. When the Sun formed from the solar nebula, volatile elements were swept away by the solar wind from the region of the solar nebula where terrestrial planets formed. Rocky planets like the Earth, accreted from the fractionated nebular condensate whose composition in refractory (but not volatile) elements closely resembles the solar composition.

Input from chondritic material and a late-veneer of volatile elements due to the impacts of comets and other objects from beyond the snow-line led to a crust which exhibits elemental abundances more like solar abundances, depleted in volatile elements, than the abundances of the bulk Earth.

Life on Earth is based on elements such as hydrogen, oxygen, carbon and nitrogen which were added to the crust in the form of water, carbon dioxide and ammonia ice in the chondritic and cometary material. Indeed, molecules such as amino acids and hydrocarbons brought in by these early impactors on Earth could have been the pre-biotic precursors that reacted together to form the earliest metabolic systems.

Today, life on Earth is primarily composed of the chemical elements oxygen, carbon, hydrogen and nitrogen, which in humans and bacteria make up 96.8 ± 0.1% of the mass. Apart from these bulk elements, phosphorus and sulphur together make up 1.0 ± 0.3% of the mass. The remaining 2.2 ± 0.2% of the mass is dominated by potassium, sodium, calcium, magnesium and chlorine, while 0.03 ± 0.01% is attributed to trace elements such as iron, copper and zinc.

We present correlations between elemental abundances in life, the bulk Earth, the Earth's crust, and the Sun using the most recent and complete data sets in the literature and discuss the implications for life in the universe. Life on Earth is based on the most abundant elements in its environment. Life does not reside in the mantle or the core of the Earth and so its elemental abundances are more reflective of abundances in the upper crust (specifically the biosphere) than abundances in the bulk Earth.

The process of formation of a star like the Sun, out of a collapsing molecular cloud polluted by heavy elements from earlier generation of stars, is observed wherever there are molecular clouds. The associated process of terrestrial planet formation is probably common in the universe and it is likely that the elemental abundances of the surfaces of extrasolar habitable planets will also be similar to cosmic abundances as represented by the Sun.

Since, the abundance of most elements in life forms and their environments on Earth follow cosmic abundances, perhaps extraterrestrial life will also exhibit elemental abundances similar to those found in life on Earth. Alternatively, if extraterrestrial life is to be found on planets and moons with environments where

elemental abundances are different to those found on Earth, it may be possible to predict the elemental abundances and metabolic processes of the extraterrestrial life based on the observed elemental fractionation between: a) the Sun and the bulk Earth, b) the bulk Earth and the crust, c) the crust and the biosphere, and d) the biosphere and life.

SESSION 01TA (TOPICAL: PALEOMAGNETISM)

New Zealand marine magnetic signature over the last 50 ky

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Magnetic and paleomagnetic analyses of sediment cores collected from offshore South Westland NZ reveal a distinctive environmental magnetic signature over the past 50 ky. Cores were collected from the *RV Marion DuFresne* (Calypso cores) in 2006 and the *RV Tangaroa* (piston and kasten cores) in 2007. Remanent magnetism, magnetic susceptibility (κ) and anhysteretic remanent magnetism (ARM) were measured on U-channel samples from each of the sediment cores using the University of Otago 2G Enterprises long core cryogenic magnetometer. The Otago system also has an in-line Bartington susceptibility loop for measuring magnetic susceptibility, AF demagnetising coils and a solenoid loop for imparting ARM. Isothermal remanent magnetism (IRM), hysteresis parameters and step-wise temperature dependent susceptibility were also determined for a number of discrete subsamples from the cores as well as for a series of sea floor samples collected by grab sampling on earlier cruises to the region.

Demagnetisation, IRM and hysteresis data identify magnetite as the dominant magnetic mineral in both sediment core and sea floor samples with varying grain-size and domain state. Down-core susceptibility (κ) and ARM susceptibility (κARM) indicate varying magnetite grain-size, which mimics global climate variability over the past 50 ky as revealed by both terrestrial and marine oxygen isotope records. Chronology of the records is confirmed by radiocarbon dates obtained from foraminfera collected from discrete intervals in the cores. Inclination data (from AF demagnetisation) and paleointensity data (from ARM/NRM ratios in intervals with uniform grain size) reveal a number of geomagnetic field excursions including the Laschamp and Mono Lake in the older part of the records as well as younger excursions. The collective data set imply a water-depth control on magnetic grain-size variability in sea floor samples and by inference we interpret changing sea level to be the major control on down core measurements. The strong correlation between the environmental magnetic signature in the cores and the marine isotope record since marine isotope (MIS) stage 4 implies a dominance of ice volume control even for short order variability in the marine oxygen isotope record. Work is continuing on the older parts of the records but diagenesis is more problematic in the lower part of the cores.

SESSION 01RB (RESOURCES)

El Indio revisited—the secret life of enargite-gold deposits

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Enargite-gold (syn. 'high sulphidation') deposits, range from small, high-grade vein deposits such as El Indio, Chile to very large, low-grade deposits, such as Yanacocha, Peru. They differ significantly in form; low-grade, bulk-tonnage deposits typically occur in extensive, blanket-form zones of advanced argillic alteration developed in near-surface environments, whereas high-grade veins are tightly constrained by fracture arrays at paleo-depths of up to 1500 m. However they have in common a pre-ore alteration assemblage characterised by oxidised sulphur as alunite in association with quartz (±kaolinite, pyrophyllite, diaspore) and a subsequent, contrasting, sequence of ore-stage sulphide assemblages that typically include pyrite, enargite, a range of sulphosalt minerals, gold, and silver. Fluid inclusion and stable isotope data demonstrate that both deposit styles formed from low-salinity, low-density fluid of probable magmatic origin with very limited involvement of meteoric water. Paradoxically however, the widely accepted temperature range for sulphide

stage ore formation is about 250°±50° C. This is only about a third the temperature of magmatic fluid when it is released from epizonal intrusions. How may this temperature difference be accounted for?

New Field-Emission SEM analyses of sulphosalt mineral assemblages from the Copper Stage at El Indio, Chile, Summitville, Colorado and other deposits now provide clear evidence of much higher temperature deposition. Delicate doubly-terminated hexagonal quartz assemblages occur within complex sulphosalt (mostly Fe-tennantite) assemblages that contain abundant sub-micron scale vugs that host a range of discrete Sb-rich sulphosalt, quartz, feldspar and flourapatite minerals evidencing deposition from the vapour phase. The local preservation of symplectic sulphosalt + chalcopyrite textures is consistent with crystallisation of the sulphosalt assemblages from a primary arsenic-sulphur melt containing copper, gold, silver, iron, antimony etc., that coexisted with a vapour phase at temperatures above about 600°C. Combined, these observations are evidence of magmatic vapour expansion to pressures of only a few tens of bars within shallow fracture arrays that may be considered the feeder systems for higher level, low grade 'solfataric' gold-silver deposits. The lower temperatures indicated by careful fluid inclusion studies may record extreme expansion localised by dilations on controlling structures or secondary mineral-fluid reactions in the later, cooler stages of vein formation.

Another paradox is why, in these deposits, there is a 'switch' rather than a progressive change from sulphate to sulphide assemblages. In turn this is consistent with the history of brittle failure and the accompanying systemic changes in structural permeability that control heat transfer, phase behaviour and alteration at the scale of the controlling fracture array rather than with speculative changes in the chemical state of deep-seated source magmas. It is also consistent with the highly-localised occurrence of sulphate-sulphide oscillations at El Indio and Pascua Lama.

The key notes that arise from these new data are that a) enargite-gold deposits result from magmatic vapour expansion at higher temperatures than have been previously considered, and b) provide useful insights to the chemical dynamics of present day active volcanoes.

Ore formation as a primarily physical process—a new perspective on the mineral systems method

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In recent years, the Mineral Systems method has become an increasingly popular way of organising observations about ore-forming process. However, by and large the application of this approach tends to focus on the chemical, rather than the physical aspects of ore-forming systems. This has to date limited the predictive utility of this approach because there is generally a complex array of chemical processes observed in the study of ore deposits and it is seldom clear which of these are essential and which are incidental. Furthermore, even those chemical processes which might reasonably be considered essential may vary considerably between very similar deposits. For example, the process of precipitating metal sulphides from metalliferous brines in the fairly-well defined class of sediment-hosted base-metal deposits has been plausibly shown to be associated with all three of the following processes; reaction with reduced sulphides in the host rocks, reaction with sulphate transported in the same or another brine and reduction by a mobile hydrocarbon phase.

It is proposed instead that a much more productive way of analysing mineral systems is to focus on the physical processes of ore formation, which represent far more fundamental attributes of the system. Ultimately, any ore-forming process requires the mobilisation of metal from a large rock volume into a much smaller small rock volume via advective fluid and/or magma flux. This implies fundamental constraints on the ore-forming process such as conservation of mass and energy. These constraints very much reduce the parameter space of viable source-transport-trap combinations that might be proposed from a purely chemical perspective. For example, they suggest that it is unlikely that either metamorphic devolatilisation or basin dewatering (two processes historically invoked in ore formation) are physically viable mineralising processes.

A physical perspective on ore-forming systems has the power to unify our understanding of the fundamental controls on a large range of deposit types. This is because the most fundamental physical process, the concentration of advective fluid (including magma) flux is independent of the particular chemical processes that might occur. This has been empirically recognised in the mineral exploration industry for many decades as

explorers use essentially very similar regional-scale structural targeting criteria for most ore types. A very good example is the extremely well-established but still somewhat enigmatic relationship between large ore-deposits (of almost all types) and translithospheric structures, recognised at least since the 1950s.

Chemical processes of ore-formation are however not independent of their physical context and many ore-depositing processes that have been proposed historically do not pass the test of physical viability because they ignore fundamental physical constraints such as mass balance. Therefore, a focus on the physical processes of ore formation provides a powerful method for discriminating competing chemical hypotheses for ore deposition.

The two most important predictions that mineral explorers seek from the analysis of a mineral system is its relative productivity (ie compared to similar systems elsewhere) and the spatial location of ore formation. A chemistry-focused study of mineral systems is incapable of answering these questions. In contrast, a physical process perspective is much more useful. In particular, the degree of metal concentration must ultimately be a function of the amount of work (in a thermodynamic sense) done by the system. This in turn can be related to the energetics of the system and it is probably no coincidence that we commonly see a close association between giant ore-deposits and highly energetic geological systems. For example, the giant Sudbury Ni deposit is associated with the largest astrobleme observed in the terrestrial record and the giant Noril'sk Ni deposit is associated with the largest Phanerozoic flood basalt province. In more detail however, the story is more complex than total energy supply and there is a critical role played by local transient barriers to energy flow in organising concentrated fluxes of ore-bearing fluids or magmas.

Structural controls and timing of gold mineralisation and alteration in the Braidwood Granodiorite, NSW

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More than 40 tonnes of gold have been produced from the Braidwood-Majors Creek-Araluen goldfields. Most of this was alluvial gold derived from erosion of primary gold deposits within and immediately surrounding the Braidwood Granodiorite. Previous research has shown that the primary mineralisation was related to mesothermal, CO_2-bearing fluids that produced pyritic lode and related vein deposits with associated phyllic and propylitic alteration. Isotopic data and radiometric dates for the host rocks and alteration sericite are consistent with the gold mineralisation forming during hydrothermal activity related to late-stage magmatic processes during cooling of the host pluton.

This study examines the structural controls that have localised hydrothermal alteration and gold mineralisation in the Braidwood Granodiorite. Known gold deposits are concentrated in the roof zone of the pluton. This zone contains remnants of dioritic and monzodioritic phases that appear to have intruded and then been engulfed by more fractionated granodiorite. Observed fractures within the intrusion can be categorised into two distinct systems: (1) thermal joints and (2) brittle fractures. Thermal contraction joints/zones and later brittle fractures are both interpreted from geophysical imagery, ground based analysis, sampling of structures and sectioning for microstructural evidence of fractures. The first set of joints is a generally east-west trending system that has formed as a result of thermal contraction in an elongate pluton that can be approximated to a rectangle. The thermal contraction has formed zones of close spaced joints that in outcrop vary from a few metres to tens of metres apart. The second set is a conjugate north-east/north-west set of fractures that appear to have formed as a late-stage system related to continued tectonic activity within the Lachlan fold belt after the pluton cooled.

Alteration zones and accompanying gold deposits are hosted within the early thermal joint systems of the pluton. Alteration has been magnetite destructive and the alteration zones appear as magnetic lows in aeromagnetic data. Dyke-like inclusions within the granodiorite may have exerted some control on thermal fracture development and fluid focusing. Aplite and pegmatite dykes are also controlled by this joint pattern and in mineralised areas aplites show pyritic mineralisation and associated alteration, indicating that they pre-date the mineralisation. Some pegmatitic phases in the granodiorite contain miarolitic cavities (1–2 cm in diameter) indicating the development of a significant magmatic fluid phase. Observations of jointed and variably altered granodiorite indicate a sequence of alteration veinlets (chlorite-epidote-carbonate) initiated by micro-fracturing, commonly localised along grain boundaries, progressing to more pervasive alteration and replacement (sericite-calcite-albite±epidote-chlorite). Hornblende and biotite commonly show initial

pseudomorphic replacement by chlorite-epidote rich aggregates and chlorite respectively. Magnetite aggregates have been progressively pyritised. In weakly altered granodiorite, preserved micro-fractures appear to have formed by thermal contraction of solid grains. In more altered rocks the primary fluid channelways have been obscured by the alteration, but are indicated by linear domains of alteration minerals through weakly altered rock. The nature of the alteration textures suggests significant hydrothermal fluid over pressuring.

Improved knowledge of structural controls on the mineralising hydrothermal fluids in the Braidwood Granodiorite should aid exploration and the discovery of additional economic gold deposits in the area. The findings on this poorly known type of structural control may also be applicable in exploration for intrusion-related gold deposits in other terrains.

SESSION 01EB (ENVIRONMENT)

A novel technique for coupled stable-isotope and trace-element determination in single ostracod shells applied to a late Quaternary record from the Gulf of Carpentaria, Australia

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The use of ostracod geochemistry is a valuable tool to study the changing environments of marine and non-marine aquatic settings. In particular, stable-isotope and trace-element ratios are now commonly measured in ostracod shells extracted from sediment core material. Within the calcitic shell, the trace-element content reflects past water chemistry and temperature while the oxygen-isotope ratio integrates water origin, evaporation and water temperature. Those proxies are complementary and show their full potential when measured in combination within single ostracod valves. We present an innovative method for coupled stable-isotope and trace-element determination in individual ostracod valves that is less restrictive than previously published methods and should enhance the coupled trace-element and stable-isotope approach in future ostracod studies. The technique involves dividing each valve in two parts, one to be analysed for trace-element ratios and the other for its $\delta^{18}O$ and $\delta^{13}C$ values. For trace-element determination, we have precisely measured Na/Ca, Mg/Ca, Sr/Ca, Ba/Ca, Mn/Ca, Fe/Ca and U/Ca using an Agilent 7500ce ICP-MS. The oxygen and carbon isotopes were analysed on half valves of weights typically 20–30 µg of $CaCO_3$. To test the validity of the technique, we compared the stable-isotope or trace-element ratios of matching half valves. The $\delta^{18}O$ and $\delta^{13}C$ values and the Mn/Ca, Fe/Ca and U/Ca ratios were very similar for most pairs of half valves with typical differences in the order of the analytical precision. Small differences in Na/Ca, Mg/Ca, Sr/Ca, Ba/Ca ratios between half-valves and equivalent full valves were systematic given that the ostracod valves were cut in a similar manner and thus could be modelled and corrected easily. We applied the method on fossil valves of the geochemically well known ostracod species *Cyprideis australiensis* extracted from a sediment core retrieved from the centre of the Gulf of Carpentaria (MD-972132). Located between Papua New Guinea and Australia, the Gulf of Carpentaria was disconnected from both Pacific and Indian Ocean when global sea level was -53 m bpsl with sedimentological and geochemical evidences suggesting the dominance of a lacustrine environment from ~70 ka to 12 ka BP. During this time period, the lake extent underwent wide oscillation from a maximal covered area of 190,000 km^2 to totally empty with periods of subaerial exposure in the centre of the basin. Although the environment of the gulf has been previously characterised for the last glacial cycle, palaeoclimatic inferences using the lake sequence have remained a challenge due to episodes of marine water inflow and strong seasonality. For the purpose of this study we focused on sediment intervals of the core where the ostracod stable-isotope or trace-element ratios, individually, could not explain the origin of the environmental variability. We show that the method has the potential to resolve complex palaeoenvironmental records with pronounced short-term variability similar to that in palaeolake Carpentaria. The ostracod splitting technique could also be used to couple the measurement of other geochemical proxies of palaeoenvironmental interest such as the $^{87}Sr/^{86}Sr$ ratio.

Speleogenesis In Cainozoic limestones on a passive continental margin south-eastern Australia

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Extensive areas of Cainozoic marine and eolianite limestones occur on the passive continental margin of south-eastern Australia. The Lower South East of South Australia and a substantial part of south-western Victoria form the Gambier Karst Province in the western Otway Basin; this contains four relatively small areas of intensive karst development in Miocene marine limestone (Naracoorte, Glenelg River, Drik Drik and Mount Gambier), interspersed amongst extensive areas with limited karst. Syngenetic karst has developed in the dune ridges of the Pleistocene Bridgewater Group (Formation) dunes, and is widespread across the province where favourable conditions occur.

The development of the karst is closely related to the coastal location of the karst province. Although currently some areas are significantly inland from the coast, these areas were located on the coast during the time of initial and major karstification. The groundwater conditions of a coastal environment, combined with highly porous and permeable limestones, have resulted in a distinctive karst.

Across the karst province phreatic conduits formed in coastal environments on an upwarping continental margin, where specific localised conditions, such as the development of joint fractures associated with the Kanawinka Fault, created enhanced solutional conditions over relatively short time periods in the early to mid Pleistocene. Falling sea levels throughout the rest of the Pleistocene controlled subsequent modification of this karst. Superimposed over the cave development in the marine limestones, is the development of syngenetic karst in the Pleistocene carbonate strandline ridges of the Bridgewater Group (Formation) eolianites.

Cave formation at Naracoorte occurred after the Early Pliocene uplift on the Kanawinka Fault zone, but before sea level fell between ~750 and 800 ka when the West Naracoorte Range was deposited. The main phreatic conduit formation occurred between ~1.1 Ma and 800 ka when sea level was at ~70 m above present. Prior to 1.1 Ma, the area was flooded by the sea and karstification was minimal. Cave formation occurred in a flank margin situation, either near the top of the watertable and/or along the freshwater/seawater halocline. Maximum conduit development occurred ~400 to 500 m inland from the coastline, probably in estuarine or coastal dune backswamp conditions associated with the mouth of Mosquito Creek. Two levels of cave occur at ~61 m and ~70 m above present sea level; they formed during two sea level stillstands. Large phreatic solutional chambers crossing both levels, e.g. Wet Cave (U 10) and Cathedral Cave (U 12), formed under phreatic conditions and solution may have been enhanced by CO_2 rising from depth from nearby eruption of Newer Volcanic basalts. When sea levels dropped between ~800 ka and 750 ka and the West Naracoorte Range was deposited, Mosquito Creek incised, collapse occurred and the caves sequentially drained. Although the caves were never completely flooded again, they were further modified by solution and collapse. The cyclical wet and dry conditions of the Mid to Late Pleistocene resulted in solution pipe formation, deposition of fossiliferous clastic sediments, precipitation of calcite speleothems, further collapse and the weathering of cave walls. Localised flooding deposited mud in the lower sections of a few caves. Minor modification continues to the present day.

Many karst features are similar to those seen in carbonate island karst elsewhere in the world, such as The Bahamas. However, the passive continental margin setting of southern Australia throughout the Pleistocene is significantly different from tectonically stable platforms in the tropics, resulting in some significant differences in the karst environment. The features, processes of formation and timing of the karst of the western Otway Basin bring new insights into coastal karst conditions that have consequences for the overall understanding of speleogenetic concepts in coastal settings.

The Quaternary geological record of southern Australia—more than just dead rocks and old kangaroo bones

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Although the Australian continent remained essentially ice free during successive Quaternary glaciations (apart from the Snowy Mountains and the Central Plateau of Tasmania) and thus might intuitively be regarded as not preserving evidence for significant environmental changes, the continent is imbued with a rich legacy of Quaternary environmental changes. Key elements of the southern Australian record reveal repeated changes in relative sea level, alternating influences of ocean-boundary currents in enhancing climate changes, repeated transitions from pluvial to more arid climatic conditions, 'hot region' volcanism and subtle but quantifiable neotectonism in discrete geotectonic domains.

In its passive, intra-plate setting, the Australian continent continued its northerly course during the Quaternary. During that time, temperate carbonate sedimentation resulted in a rich record of marginal marine sediments producing one of the world's largest cool water carbonate provinces, extending from south-western Western Australia to western Victoria. Coastal landforms within this region include laterally persistent barrier shoreline complexes of mixed quartz-skeletal carbonate affinity (aeolianites) that formed during successive sea level highstands on the open ocean coastlines and peritidal carbonate successions within the protected gulfs.

Fossil marine molluscan and foraminiferal faunas provide testimony to some of the more dramatic long-term climate changes that have occurred in the later Quaternary in southern Australia. The contraction in the biogeographic range of the arcoid bivalve *Anadara trapezia* reflects a reduction in suitable estuarine habitats, a response to the progressively increasing continental aridity since late middle Pleistocene time.

Perspectives of landscape and environmental changes in Australia are dominated by nuance. The subtleties of long-term environmental change reflect the predominantly slow process rates that typify the continent and the biases in the preservation of evidence for environmental changes within the geological record. For example, the epeirogenic uplift of the Coorong Coastal Plain in southern South Australia, one of Australia's more neotectonically active settings is only 0.07 mm/a in a line of section from Robe to Naracoorte. In a similar manner, sedimentary successions of the last interglacial shoreline (MIS 5e, c. 130 to 118 ka) in southern Australia reveal only modest rates of tectonic uplift in a global context and intertidal facies of late Pleistocene interstadial successions (e.g. MIS 5c, 5a and 3) do not occur above present sea level, further highlighting the general tectonic quiescence of the continent. Other distinctive aspects of the southern Australian Quaternary record, when considered in global terms include the lateral persistence of many landscape features over distances of hundreds of km, their remarkable preservation and lengthy duration. Developments in geochronology and geochemistry have provided quantitative frameworks to open a window on the distinctively Australian notion of landscape change. That vision shows that it is considerably more than just 'dead rocks and old kangaroo bones'.

SESSION 01SB (SOCIETAL: GEOLOGICAL HAZARDS)

Validation of the impacts of the 2004 Indian Ocean tsunami on Geraldton, Western Australia

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In response to the devastating Indian Ocean tsunami (IOT) that occurred on 26 December 2004, Geoscience Australia (GA) developed a framework for tsunami risk modelling. The outputs from this methodology have been used by emergency managers throughout Australia to prepare the community for such an event. For GA to be confident in the information that is provided to the various stakeholders, validation of the model and methodology is required.

While the huge loss of life from the tsunami was tragic, the IOT did provide a unique opportunity to record the impact of a tsunami on the coast of Western Australia. Eight months after the tsunami a post-disaster survey was conducted at various locations along the coast and maximum run-up was determined from direct

observational evidence or anecdotal accounts. In addition, tide gauges located in harbours along the coast also recorded the tsunami and provide a time series of tsunami wave heights from which we obtain frequency information.

This study employs the tsunami hazard modelling methodology used by Geoscience Australia (GA) to simulate a tsunami scenario based on the source parameters obtained from the Indian Ocean earthquake of 2004. The model results are compared to observational evidence from satellite altimetry, inundation surveys and tide gauge data for Geraldton, a community on the Western Australian coast. The Western Australian coast provides a suitable location to validate the tsunami models for distant tsunami and compliments other work conducted at Geoscience Australia that has validated the models for near-source regions such as Patong Bay in Thailand.

Results show that the tsunami model provides good estimates of wave height in deep water and run up in inundated areas. Importantly, the model matches the timing of the first wave arrivals. However, the model fails to reproduce the time series data of wave heights observed by a tide gauge in Geraldton harbour. The model does, however, replicate the occurrence of a late arriving (16 hours after first arrival) wave packet of high frequency waves. This observation is encouraging since this particular wave packet was observed elsewhere in the Indian Ocean and caused havoc in harbours many hours after the initial waves had arrived and dissipated. This result has implications for tsunami warnings and response, as the initial waves may not be the most damaging in marine areas.

The results from this study demonstrate that GA's current methodology for modelling the hazard of tsunami for Australia is robust and credible. GA and its various stakeholders can be confident that the run up estimates are reliable, however precaution must be taken in interpreting waveform information in harbours which is less reliable.

Overturned cliff-top mega-boulders at Little Beecroft Head, Jervis Bay, NSW, Australia: a mega-tsunami or aboveground bolide impact about 20 ka BP?

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The largest of several detached boulders on top of the 33 m high cliffs at Little Beecroft Head measures 3.5 x 2.1 x 1.6 m and weighs ~31 tonnes. Sedimentary structures (cross-bedding) show that this boulder has overturned. The boulder and the nearby cliff are pebbly quartz sandstone of the Permian Snapper Point Formation in the southern Sydney Basin. A comparison with the local stratigraphy indicates that the boulder was detached from the nearby north-east facing cliff face, in which a bed of identical lithology crops our at a lower elevation. A Holocene tsunami has been invoked by other authors for emplacement of the boulder onto the cliff top.

Using the isotopes ^{10}Be and ^{26}Al, we determined the cosmogenic exposure ages of (a) the currently exposed upper surface of the mega-boulder; (b) the lower surface which is in partial contact with the cliff-top platform upon which the mega-boulder rests; and (c) the cliff-top platform surface itself, ~3 meters landward of the boulder. ^{10}Be and ^{26}Al exposure ages for all three samples are consistent. Simple age modelling (zero-erosion case) shows that today's lower surface of the boulder was exposed for ~63 ka prior to the overturning event and that today's upper surface has been exposed for ~19 ka, which represents the detachment age or the elapsed time since the overturning event exposed the top surface of the boulder. The adjacent platform surface has a zero-erosion exposure age of 84 ka.

At the time of global Last Glacial Maximum, 20–22 ka, sea level was 120–130 m lower than at present and the land-ocean boundary lay some 20 km east of the site. This precludes boulder emplacement and overturning by a storm wave or even by a 'normal' tsunami wave. We suggest that the event which dislodged the boulder from the vertical cliff face, lifted and overturned it and emplaced it ~2 meters further inland could be (1) a mega-tsunami resulting from a large bolide impact in the distant ocean; or (2) a mid-air cometary explosion similar to that which is thought to have occurred at Tunguska, Russia, in 1908.

Earthquake location using coda waves

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Traditional approaches for locating earthquakes in a cluster use early onset body waves in the form of arrival times and/or travel time differences between pairs of events. Uncertainty from these techniques increases dramatically when only a few stations are available or azimuthal coverage is poor. In intraplate regions such as Australia, the density of seismic stations leads to earthquake locations with uncertainties of a few kilometres. In general these uncertainties are too large for the kind of detailed imaging necessary to understand fault structures.

The tail of the seismic waveform contains coda waves that have departed the source in all directions and been scattered by heterogeneities in the Earth. These coda waves represent the majority of the recorded waveform and are typically discarded in earthquake location studies. In this presentation we show how they can be used to estimate separation between pairs of events and in turn provide new independent constraints on earthquake location. Unlike the travel time based approaches, our coda wave techniques do not require multiple stations and are not susceptible to poor azimuthal coverage. This makes coda waves attractive for estimating earthquake locations in intraplate regions where they provide valuable additional constraints to travel times. We introduce examples from the Kalannie region in Western Australia and the Calaveras Fault, California to demonstrate how coda waves can achieve relative locations with uncertainties of the order of a hundred metres.

Major earthquakes in Oceania: how well do we understand them?

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Earthquakes represent an increasing threat to Oceania because of increasing concentration of populations in built environments that are vulnerable either to ground shaking or to landslides or tsunamis generated by earthquakes. The estimated impact of earthquake shaking is strongly dependent on details of the earthquake rupture such as stress drop, depth and rupture extent. For example, the magnitude 7.5 South Sumatra earthquake, 60 km from the city of Padang (30/09/09), killed over 1100 people, while the much larger South Sumatra earthquakes of magnitude 8.4 and 7.9 (12/09/07), only 130 km from Bengkulu and 190 km from Padang, respectively, collectively killed only 12 people. Similarly the ability of earthquakes to generate tsunamis that impact coastal populations is strongly influenced by the up-dip extent of fault rupture and its orientation with respect to population centres: the tsunami generated by the magnitude 8.1 Samoa earthquake (29/09/09) killed over 180 people, while that generated by the magnitude 7.8 Vanuatu earthquake (7/10/09) killed no one. Our ability to forecast the potential impacts of future earthquakes on a population centre is therefore dependent not only on our knowledge of the occurrence probability for an event of a certain magnitude, but also on our understanding of the different styles of rupture that may occur. Rapid estimate of impact, for purposes such as tsunami early warning or early assessment of post-disaster response requirements, is dependent on our ability to rapidly and reliably estimate not only magnitude and epicentre, but also details of earthquake rupture.

But how well do we understand the rupture properties of major earthquakes in our region, and how rapidly and reliably can they be estimated? In the last decade new observation systems, and improvements in old ones, have made it possible not only to more rapidly estimate earthquake source properties, but also to assess how reliable the estimates are. These observation systems include more extensive networks of broadband seismometers and GPS instruments, as well as seafloor and satellite observation platforms, including ocean bottom pressure sensors (aka DART buoys or tsunameters), and Synthetic Aperature Radar (SAR) and multispectral satellite systems. This talk will survey the methods available for assessing earthquake rupture characteristics, focusing particularly on techniques useful for the large, offshore earthquakes typical of Oceania.

4D crustal-scale geological systems modelling in western Victoria and its implications for crustal accretion, strain partitioning and fluid flow

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3D geological modelling is now as ubiquitous a tool to the field or exploration geologist as the compass or map. The value of 3D models for visualising complex geometries, unravelling structural histories and planning drilling or mining programs is undeniable and has been discussed in detail before. The real value in these models however is not realised until they are used to help us understand how geological systems have (or will) evolved through time, *i.e.* by adding the fourth dimension. CSIRO and GeoScience Victoria have recently taken crustal-scale 3D model outputs from GeoScience Victoria's 3D program and used them to constrain numerical simulations of the evolution of the Western Lachlan Orogen through time. These simulations have implications for the evolution of gold systems across Victoria, the distribution of Devonian granites and the development of the Otway Basin and associated petroleum resources during Cretaceous spreading.

Crustal-scale 3D modelling of central and western Victoria and recent 2D onshore deep crustal seismic transects highlighted the asymmetric nature of the basin which must have existed between the Delamerian margin of Gondwana and the continental fragment known as the Selwyn Block, which was located in the proto-Pacific during Ordovician time. Oblique closure of this basin during the Late Ordovician and subsequent accretion of the Selwyn Block onto eastern Gondwana would have resulted in complex strain partitioning within the oceanic sediment trapped between the two continental blocks, resulting in the formation of the major fault systems of the 'Golden Triangle' enhancing the localisation of gold bearing fluids.

In order to better understand these early, crustal-scale structural controls on mineralisation a series of simulation models were run using the Gale particle-in-cell finite-element modelling code at CSIRO, using iVEC supercomputer facilities. These simulations tracked a number of physical properties including stress and strain rate during the collision/accretion process. Large high-strain zones formed at the continental margins representing the Moyston and Mt William Fault Zones. A series of smaller faults also formed in the intervening region which reasonably matches the distribution and orientation of known faults in the field. These simulation results have allowed investigation into the spatial relationship between Victoria's world-class orogenic gold deposits and the asymmetric basin which contained their host sediments. In particular this relationship has implications for explorers looking in the northern parts of the gold belts under shallow cover.

Another outcome of the simulation work was the identification of a series of deeply penetrating WNW and ENE striking transfer faults that formed within the Delamerian and Selwyn Block basement respectively as a result of this collision. These structures are intriguing as similarly oriented structures have been identified in potential field datasets, proposed as the conduits for Devonian granite emplacement and also (rarely) identified in the field. Given that the locus of this collision lies to the north of Cape Otway, the point at which Cretaceous spreading related normal faults change strike from NW to NE orientations, it is also possible that this spreading geometry is controlled in part by these enigmatic structures. Additional Gale modelling is being conducted at GSV to test whether the change in orientation of the Otway Basin normal faults is more likely to be related to refraction associated with changes in crustal strength (as previously proposed) or whether this could also be related to the transfer faults predicted by the simulation modelling to the north.

This work highlights not only the value of building full crustal 3D models when investigating mineral and resource systems, but also shows that value-add projects such as 4D tectonic simulations can significantly impact our understanding of the development of resource systems and the tectonic evolution of the region in general.

Earliest Permian non-collisional orogeny and basin formation in the southern New England fold belt sector of the Terra Australis Orogen

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Around the Carboniferous–Permian boundary, between 305 and 295 Ma, the Tablelands Complex along the east Australia section of the Terra Australis Orogen experienced a major tectonothermal event that we term the Tablelands Orogeny. This involved widespread deformation, associated HT/LP metamorphism rising to amphibolite grade at Wongwibinda and Tia, and the onset of S-type granite emplacement. Deformation was almost immediately followed by the onset of clastic sedimentation and local arc-related volcanism in the extensional Barnard Basin, and the rise of serpentinite bodies to the surface. S-type granite emplacement continued through the early stages of basin evolution, mostly in basement rocks, and at the same time the earliest I-type granite pluton was emplaced. U/Pb zircon SHRIMP dating augmented by earlier determined ages and detailed field studies, allow these phenomena to be ordered chronologically, a closer correlation of surficial and deeper crustal processes to be established and their relationship to local and far-field plate reorganisation assessed.

The youngest detrital zircons so far identified in the accretionary rocks are about 320 Ma, there are concentrations of inherited grains in S-type granites as young as 306 Ma, and the youngest rocks related to the associated western magmatic arc are 304 to 300 Ma providing an estimated upper age limit for subduction-related activity of ca. 305 Ma.

Deformation and associated HT/LP metamorphism had commenced by 297 ± 2 Ma and possibly earlier on the basis of monazite EMP ages from metamorphic rocks at Wongwibinda (S.Craven and N. Dazco *pers. com*.). An age for the syn-D5 Tia Granodiorite indicates deformation here was on the wane by ca.296 Ma. In the western Tablelands Complex deformation at this time is indicated by large-scale sinistrally verging steeply plunging folds. These folds deform accretionary structures but are transgressed by granite of the Bundarra Suite of age ca.293 Ma. They may have folded earlier emplaced serpentinite bodies and were possibly generated by early sinistral movement of the Tablelands Complex ascribable to the Tablelands Orogeny. In the eastern Tamworth Belt Devonian strata show similarly oriented folds, also of sinistral vergence, that may be of similar age which has important implications for the regional NNW trending structures is this area, which pre-date the sinistral folds but have previously been considered of Late Permian age.

A major stratigraphic break has been identified in the Tamworth Belt in the latest Carboniferous and deformation at this time was probably responsible for the removal of several thousand metres of Middle Devonian – Carboniferous strata prior to the Early Permian in the upper Barnard River district.

SHRIMP dating of volcanic rock close to the base of the Permian sequence at Halls Peak, where an unconformity separates accretionary rocks from rift-basin fill, indicates that basinal sedimentation commenced shortly before 292 Ma. Unconformable relations between basinal rocks and serpentinite demonstrate that serpentinite bodies were exposed at the time of opening of the Barnard Basin.

New SHRIMP zircon granite dates indicate that the two New England S-type granitic suites, the Bundarra and the Hillgrove Suite were essentially contemporaneous and overlapped in time with Barnard Basin rifting. SHRIMP dates also confirm that the I-type Kaloe Granodiorite was emplaced at about 292 Ma, contemporaneous with S-type magmatism.

Orogenesis occurred in an active convergent plate margin setting immediately following the ending of long-established subduction-related magmatic arc activity in western New England and ca. 5 Ma before the development of a new arc and penecontemporaneous extensional basin within the accretionary complex related to the earlier arc. There is no evidence that deformation was related to the collision of the convergent margin with a major lithospheric mass and the widespread development of extensional basins in the eastern third of Australia in the early Permian indicates control by phenomena acting on a continental scale, probably changing plate kinematics associated with the amalgamation of Pangea.

The Wongwibinda Complex: a HTLP metamorphic terrain

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The Late Carboniferous Wongwibinda Complex (WC) is a region of high temperature low pressure (HTLP) metamorphic rocks that occur in association with granites of the Hillgrove Plutonic Suite within the Tablelands Complex of the southern New England Fold Belt. The WC exhibits a metamorphic progression from relatively unmetamorphosed sedimentary rocks to high-grade schists with migmatites abutting the Abroi Granodiorite/Gneiss. This project aims to understand the tectonic processes that generate HTLP terrains by studying the evolution of the WC. An interdisciplinary approach is being employed studying the interaction between deformation, metamorphism, partial melting and magmatism.

The Wongwibinda Complex is composed mainly of the Girrikool Beds and their metamorphic equivalents, the Ramsbeck schists and associated migmatites. The Girrikool Beds are a thick (15–20 km) turbidite sequence of interbedded, siliceous, intermediate- to fine-grained psammites and pelites. In order to better confine the age and character of this sequence, U-Pb and Hf-isotopes were measured from zircon separated from rock samples and a TerraneChron drainage survey from the Complex. The survey identified well-defined populations at ~40 Ma, ~250 Ma, and ~290 Ma and a broad population at ~330 ± 20 Ma. Respectively, these populations reflect known ages of Tertiary Basalts, I-type plutons, S-type plutons and the ~310–350 Ma broad peak is interpreted as provenance for the sedimentary rocks being an Early to Late Carboniferous volcanic arc. A small number of grains yielding Proterozoic and Archean ages are likely to have been inherited by the magmatic/volcanic rocks from which the Girrikool sediments were derived.

Detrital zircon grains from a weakly metamorphosed metapsammite (333.7± 3.6 Ma), an unfoliated metapelitic cordierite hornsfels (330.6±7.5 Ma) and a migmatite (325.9±6.4 Ma) adjacent to the Abroi exhibit a U-Pb age distributions similar to the TerraneChron alluvial samples and suggest deposition of the sediment at ~320 Ma. A second migmatite sample yields a younger age (306.9±8.6Ma) probably reflecting lead loss due to metamorphism.

EMP monazite chemical dating of an unfoliated cordierite hornfels (311 ± 8.4Ma), a cordierite augen schist (292 ± 2.8 Ma) and the migmatite (297 ± 4.3 Ma) suggests the peak of metamorphism shortly followed deposition of the sedimentary protoliths at ~320 Ma.

Two zircon concentrates from strongly foliated/gneissic and relatively unfoliated samples of the Abroi Granodiorite/Gneiss were analysed and returned U-Pb ages within error: 291.2 ± 2.3 Ma and 293.6 ± 3.5 Ma respectively. Each sample has few inherited grains. Zircon grains show no evidence of metamorphic effects such as overgrowths of new zircon or dissolution of igneous zircon. The Hf data for these samples indicate a mix of juvenile and crustal components with an average Hf model age of 1.8 Ga. The disparity in age data between emplacement of the Abroi at ~293 Ma and early metamorphism of the metasediments at ~311 Ma suggests that metamorphism largely pre-dates the emplacement of the Abroi Granodiorite/Gneiss by at least a few million years and possibly up to 15 million years.

These data will be integrated with structural and metamorphic data to compile a complete temporal and spatial history of the Complex. The further research planned for the Wongwibinda Complex will provide important information about the New England Fold Belt, the geological evolution of the Australian Plate and contribute to wider geodynamic interpretations.

Crossing the Tasman: tracking Torlesse Terrane rocks from New Zealand into the New England Orogen

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Throughout New Zealand, the Torlesse Supergroup forms an extensive Permian to Cretaceous accretionary wedge of rather monotonous, greywacke-dominated turbidites. In contrast to contemporaneous rocks in neighbouring terranes within the accretionary wedge, the turbidites have less intermediate-volcaniclastic compositions, and show more quartzose, continent-derived, plutonic rock provenances Petrographic, geochemical, isotopic and detrital mineral age characteristics all indicate that they did not originate at the

contemporary Gondwanaland margin in New Zealand, but rather, constitute a suspect terrane (Torlesse Terrane), having sediment sources elsewhere along the margin. This latter subject has been controversial, with sediment sources suggested in Antarctica, southern South America and north-east Australia, but detailed Torlesse detrital mineral (zircon and mica) age data and bulk rock Sr-isotope patterns can be best matched for the most part with Carboniferous, Permian and Triassic sources in the New England Orogen, and the remainder with Cambrian and Ordovician sources in its hinterland.

Torlesse Supergroup rocks are poorly fossiliferous but, in general, are Jurassic and Cretaceous in the North Island and Triassic and Permian in the South Island. The oldest horizons, Late Permian, are close to the southernmost edge of the terrane, in Otago, South Island, where there are also a few tiny (tectonic) limestone enclaves, occasionally with Late Carboniferous faunas. These probably represent oceanic seamount and pelagic seafloor assemblages upon which the Torlesse was later deposited. The apparent stratigraphic gap, almost 70 million years, is surprisingly large however, and there remains the possibility that the Torlesse Supergroup could extend into the Early Permian and/or Late Carboniferous. Preliminary detrital zircon data suggest that Middle Permian (c. 270 Ma) horizons might be present, but no older rocks have yet been found. These oldest horizons of the Torlesse have detrital zircon age patterns dominated by Carboniferous and early Paleozoic/Precambrian sources, and unlike the Triassic and Jurassic Torlesse, have proportionally lower zircon inputs from contemporary volcanic activity. A possibility thus arises that some 'missing' Torlesse rocks might still remain close to their suggested source in eastern Australia.

Recent detailed geochemical, Sr-isotope and detrital mineral age studies of major sedimentary complexes within the New England Orogen now allow some comparisons with Torlesse Supergroup rocks in New Zealand. Late Paleozoic metasedimentary rocks dominate in the southern part of the New England Orogen, with those in the accretionary wedge including Late Carboniferous, Wandilla Formation (south-east Queensland) and Coffs Harbour Block (north-east New South Wales). These have intermediate-volcaniclastic compositions, low initial Sr isotope values (<0.706), and low proportions of continent-derived detrital zircons that do not fit comfortably with the Late Permian-Jurassic evolution patterns of the Torlesse. In contrast, more quartz-rich sandstone successions of the Shoalwater Formation (south-east Queensland) and Beenleigh Block (north-east New South Wales) have more radiogenic Sr-isotope compositions (>0.708) similar to the Torlesse, but are probably too old (mid-Carboniferous), and have far higher proportions of early Paleozoic and Precambrian reworked zircons.

In north-east New South Wales, the Nambucca Block metasedimentary successions (probable Early Permian) represent a period of extension between the Late Carboniferous formation of the accretionary wedge/volcanic arc phase and emplacement of major Late Permian and Triassic magmatic arcs. These metasediments provide the best comparison with the oldest Torlesse, having bulk Sr-isotope values and detrital zircon age characteristics that fall at the older age extremity of the evolution patterns of Permian-Triassic, Torlesse in New Zealand. Therefore, the oldest Torlesse sedimentary rocks record the initiation, in mid-Permian times (c. 270 Ma) of a major Late Permian-Triassic accretionary phase, which was stimulated and supplied by rapid development and erosion of contemporaneous magmatic arcs in eastern Australia.

SESSION 01LB (LIFE AND SOLAR SYSTEM: ARCHEAN AND PROTEROZOIC LIFE)

Oxygenating the Earth: were Archaean stromatolites constructed by cyanobacteria?

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It is almost universally accepted that the oxygenation of the previously anaerobic Earth was driven by the oxygenic photosynthesis of cyanobacteria. But there are inconsistencies of hundreds of millions of years in the various lines of evidence for the timing of the oxygenation process. Disputed evidence from organic geochemical biomarkers indicates the presence of cyanobacteria by at least 2.7 Ga. Suggestive evidence from microfossils and stromatolites supports that interpretation. However, geochemical evidence seems to indicate that the 'Great Oxidation Event' (GOE) occurred at about 2.45–2.32 Ga when the atmosphere and shallow hydrosphere became oxic. Some geochemists postulate early 'whiffs' of oxygen in the atmosphere some 50 Ma prior to the GOE. Yet others have a radically different view and see evidence of oxic environments back to 3.5 Ga.

The geological record of stromatolites extends back to 3.5 Ga. Almost all extant stromatolites are constructed predominantly by cyanobacteria so it is not unreasonable to postulate that this record allows the possibility of the evolution of cyanobacteria a billion years before the GOE. That would pose a major dilemma for most geochemists.

A way to deal with this issue is to ask what are the biological processes that lead to the construction of stromatolites and are those processes restricted to cyanobacteria. A subset of those questions relates to whether any fossil stromatolites are demonstrably cyanobacterial. I contend that at least some 2.7 Ga stromatolites are probably cyanobacterial, some 3.0 Ga examples are possibly so, and those at 3.5 Ga need not be.

Two possible sulphur metabolisms preserved in a 3.4 billion-year-old sandstone

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A sandstone from the 3.4 Ga Strelley Pool Formation of Western Australia contains pristine μm-sized pyrite intimately associated with organic material coating framework quartz grains. A syn-sedimentary to early diagenetic origin for this pyrite is indicated by its occurrence in both black, bedded sandstone at the base of the formation, and reworked black clasts higher up in the formation. High resolution multiple sulphur isotope analysis (^{32}S, ^{33}S, ^{34}S) using secondary ion mass spectrometry (NanoSIMS and large-radius ion microprobe) reveals $\delta^{34}S_{V\text{-}CDT}$ values between c. –12 and +6‰, and $\Delta^{33}S$ values between –1.65 and +1.43‰, from pyrite grains within a single thin section. A large spread of $\delta^{34}S$ values over only 5–10 μm, together with a spatial association of pyrite with carbon and nitrogen strongly suggests biological processing of sulphur. The presence of both $+\Delta^{33}S$ and $-\Delta^{33}S$ signals overprinted by significant mass-dependent $\delta^{34}S$ fractionation in this pyrite population indicates for the first time that both microbial sulphate reduction of aqueous sulphate ($-\Delta^{33}S$), and microbial disproportionation of elemental sulphur ($+\Delta^{33}S$) were co-occurring in an open-marine, sedimentary-hosted ecosystem in the early Archean.

Identification of carotenoid breakdown products in the 1.64 Ga Barney Creek Formation, McArthur Basin, northern Australia

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Microbial communities are often highly pigmented due to organic compounds known as carotenoids. All photosynthesising organisms utilise carotenoids as accessory pigments in various stages of photosynthesis. In order to study the occurrence of carotenoids in the geological record as molecular fossils (biomarkers), the effect of burial and heat on their molecular structure must first be determined. Burial diagenesis reduces functionalised and unsaturated organic molecules to their saturated hydrocarbon equivalents. However, compounds that undergo diagenesis often retain structural information about their biological precursors and may contain information about depositional environment and biological communities. Biomarkers are ideal for the investigation of life in the Precambrian where body fossils are often poorly preserved and not informative.

Carotenoids are often difficult to study in the geological record because of their low preservation potential. Preservation of the hydrocarbon equivalents of carotenoid molecules is rare due to their tendency to break into smaller units or undergo complex aromatisation and rearrangement reactions, e.g. [1]. Generally, biomarkers are only preserved under specific conditions, for instance in reducing, low energy environments where oxidation and recycling by microorganisms is less severe. In rare instances where intact C_{40} carotenoid hydrocarbons are preserved by suitable diagenetic conditions, they are often subsequently cleaved into smaller fragments by increasing temperatures during burial of the host sediment (catagenesis). Catagenesis can be simulated in the laboratory using a method called hydrous pyrolysis [2], which involves heating organic matter submerged in water in a sealed vessel for several days.

The aim of this study was to synthesise a standard to investigate the thermal breakdown of the C_{40} carotenoid hydrocarbon, β-carotane from precursor β-carotene, as it would occur in nature. This experimental

investigation involved pyrolysing β-carotane in a sealed quartz vessel under a cold-seal pressure apparatus. The ideal conditions that generated systematic cleavage products of β-carotane were determined to be heating β-carotane for 1 day at 360°C under hydrous conditions.

To validate the standard that we synthesised, we looked for the occurrence of these β-carotane breakdown products in the 1.64 billion-year-old (Ga) shales from the Glyde River (GR-7) drill core of the Barney Creek Formation (BCF) in the McArthur Basin, Northern Australia. β-Carotane had previously been reported from the BCF [3], and a comparison of BCF mass chromatograms with the pyrolysis standard demonstrated that a full series of β-carotane breakdown products are also present. These results confirm that our pyrolysis experiments adequately simulate the breakdown of carotenoids under geological conditions.

To apply the carotenoid breakdown products standard to a new system, we analysed yet older and more mature samples from the BCF where intact β-carotane was not present. We were able to detect a partial series of β-carotane breakdown products representing the oldest evidence for saturated carotenoids in the geological record.

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SESSION 01TB (TOPICAL: PALEOMAGNETISM)

An improved radiocarbon chronology and calibration over the Laschamp event: ^{14}C – ^{10}Be cross synchronisation

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The production rate of cosmogenic isotopes ^{10}Be and ^{14}C is influenced by variations in the primary cosmic ray flux and by changes of the Earth's magnetic field, which has experienced a number of significant perturbations during the late Quaternary (e.g. Lashamp/Mono Lake excursion, circa 41 ka BP). Understanding these changes and synchronising variations in palaeomagnetic intensity derived from various marine sediment cores can often help constrain the quality of ^{14}C dating, particularly in the interval between 20 and 50 ka ago, and establish reliable chronologies for ocean sedimentation rate changes. A common often used proxy for these palaeomagnetic changes is atmospheric fallout of ^{10}Be in marine sediments. We are investigating the Core MD – 982167, which was recovered from the Scott Plateau in the Eastern Indian Ocean at latitude of 13°S. The MD-982167 already has an established stable isotope stratigraphy and a high sedimentation rate of 10 to 20 cm per ka. A series of ^{14}C and ^{10}Be determinations in foramifera and fine fraction of the core sediments as a function of core depth have been obtained. Palaeomagnetic measurements with the aim to determine the position of geomagnetic disturbances like Laschamp and Mono Lake as recorded in the ocean sediments were also done on the samples from the same core. Synchronisation of palaeomagnetic, ^{10}Be and radiocarbon records together with the application of ^{10}Be pulse as a global chronostratigrafic marker is discussed. An improved chronology for this high resolution core that has recorded brief, less than one thousand year duration, climatic events during the studied time interval will allow much better correlation between marine sedimentary records and the detailed chronologies established from the ice cores.

Late Carboniferous-Early Permian paleomagnetic poles from regolith in cratonic Australia

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A paleomagnetic study of weathering profiles throughout Australia was undertaken to determine the timing of chemical remanence acquisition. Most sites yielded Late Cretaceous-Cenozoic paleomagnetic poles by

comparison with the Australian Apparent Polar Wander Path. However, several sites yielded Late Carboniferous-Early Permian poles.

A characteristic feature of the Late Carboniferous-Early Permian poles is that they are comprised exclusively of reversed polarity remanence directions, consistent with acquisition during the Kiaman Reversed Chron, a long interval of reversed polarity between about 320 and 260 Ma.

Such ancient weathering ages, from weathering profiles up to 100 m deep, are consistent with the long-held view of Australia as an ancient continent, exposed to subaerial processes for hundreds of millions of years. However, the persistence of regolith more than 300 million years old, at or near the surface, is inconsistent with long-term denudation rates based on cosmogenic nuclides and apatite fission track thermochronology (AFTT).

At two sites, in the northern Yilgarn and central NSW, reconciliation between paleomagnetic ages and AFTT implies kilometre-scale burial and exhumation since the Late Carboniferous.

Carboniferous and Permian palaeomagnetism in New South Wales

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Two aspects of the late Carboniferous to Permian palaeomagnetic record from New South Wales are noteworthy: steep palaeomagnetic inclinations indicate that this region lay within about 30° of the geographic pole, and the global phenomenon of the reversely polarised Kiaman Superchron resulted in uniformly positive remanence inclinations through most of this interval. Two recent studies have focused on these characteristics.

Glacial varves from the Seaham Formation at Abercrombie Quarry in the Hunter Valley of New South Wales afford an opportunity to examine secular variation from the Kiaman Superchron on a yearly to centennial time-scale. This high-palaeolatitude record from the early part of the Kiaman provides a valuable counterpoint to red-bed studies from the low-palaeolatitude Dôme de Barrot site in France, which were dated to late in the Kiaman. Thermal and AF demagnetisation thoroughly remove the Cretaceous normal overprint that is problematic in many Palaeozoic sequences in eastern New South Wales; the low permeability of these very fine grained, siliceous varves appears to have minimised invasion of fluids responsible for the chemical remanence that carries this overprint. Rock-magnetic parameters indicate magnetite in its pseudo-single to single domain state as the magnetic carrier in the varves, qualifying them as likely to preserve a stable depositional magnetisation. Although a fold test is not available, the characteristic remanence averages close to the expected late Carboniferous pole after removal of bedding tilt, supporting the inference that the remanence is depositional. Remanence measured in clasts of the varves ripped up while still soft and incorporated in sandy members is scattered, suggesting very early locking-in of the remanence, at the instant of deposition or very soon after.

A series of ten sites, each grouped over about 10 to 50 yearly varves, and spanning a total of about 800 years, yield virtual geomagnetic poles. These form a systematic arcuate track around the late Carboniferous palaeopole, similar to historic secular variation records. Inferences about the geodynamo, specifically the support for active outer core convection during superchrons, can now be extended on this basis into the early phases of the Kiaman Superchron.

In contrast to the direct measurement of palaeomagnetism, remanence can also be determined by inversion of magnetic anomalies, provided that the magnitude of the remanence compared to the induced magnetisation (the Königsberger ratio) is high enough, and that the geometry of the source can be constrained. Extending over a swath for nearly 250 km in south-western NSW, a suite of more than 500 bullseye anomalies contrast strongly with the low-amplitude regional magnetic response to early Palaeozoic basement and Murray Basin cover. High Königsberger ratios and the presence of reversed remanence in at least some of the sources are indicated by a significant proportion of negative anomalies. Modelling the sources as diatremes with an assumed vertical or steep plunge, and inverting on remanence, yields two remanence populations, one normal and the other reversed. Restricting the sample to those where remanence clearly dominates the induced magnetisation gives antipodal directions for the means of the normal and reversed directions, suggesting that a stable palaeoremanence has been isolated. The

corresponding palaeomagnetic pole falls near the Permian part of the Australian apparent polar wander path: the presence of both normal and reversed polarity remanence restricts the age to the late Permian, after the end of the Kiaman Superchron. Burial below Murray Basin sediments has prevented sampling of any of the sources in this suite: however, the sources of similar anomalies from another large suite of diatremes in the north-west of NSW have been sampled, yielding late Permian (about 260 Ma) radiometric ages. The existence of two extensive areas of diatreme intrusion of similar age attests to substantial heat input below western NSW in late Permian times.

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Paleomagnetic investigation of the Late Devonian reef complexes of the Canning Basin, Western Australia

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The reef systems in the Canning Basin, Western Australia perhaps are the best exposed and least deformed examples of ancient reef systems known in the world. The recently commenced multi-disciplinary research project in the Devonian reef complex of the Canning Basin is a broad investigation of the depositional history of a carbonate platform using paleomagnetic, stable isotope geochemistry (inorganic and organic), sedimentology, and biostratigraphy. By focusing on the world-class exposures in the Canning Basin, this project seeks to provide a global stratigraphic reference frame for key intervals in life history such as the Frasnian-Fammenian mass extinction event, as well as providing a useful analogue for resource models of other carbonate reef systems elsewhere in the world. This reference frame will consist of a high-resolution magnetostratigraphic profile to supplement the presently sparse Global

Polarity Timescale for the Devonian, as well as a chemostratigraphic profile (chiefly carbon isotopes) to identify possible shifts in the global carbon budget associated with biotic crises and/or climate change. Additional goals include identification of the conditions leading up to, and possible causes of the mass extinction event, and testing for a possible mid-Paleozoic episode of True Polar Wander.

The work reported here mainly focuses on paleomagnetic aspects to address the goals mentioned above. Paleomagnetic core samples were collected from an outcrop section in the Guppy Hills area of the Canning Basin, with ages ranging from Middle Givetian to Early Frasnian. A total of over 400 paleomagnetic core samples were collected. Paleomagnetic analysis reveals that magnetite and goethite are the two major magnetisation carriers, and hematite is present in only a few samples. ChRM directions can be easily obtained for most of the samples (>60%), which yield a total of 13 normal and 13 reversed polarity zones. The calculated mean direction (Dec = 41.0°, Inc = -31.2°) yields a paleopole of 51.0°N and 220.6°. This, and other Mid-Paleozoic cratonic Australia poles, suggests the presence of an ocean between Gondwana and North America.

STREAM 01RC (RESOURCES)

The Spinifex Ridge 3.3 Ga porphyry-style Mo-Cu deposit, East Pilbara, Western Australia, the world's oldest

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The Spinifex Ridge (Coppins Gap) Mo-Cu deposit is located north of the Mount Edgar batholith in the 3.52–2.85 Ga East Pilbara granite-greenstone terrane. The Mo-Cu mineralisation (650 million tons at 0.05% Mo and 0.08% Cu) is associated with a suite of magnetite-bearing, high-level quartz-plagioclase porphyries and porphyritic granodiorites intruded into 3.45 to 3.32 Ga basalts and rhyolites. The mineralisation consists of a complex series of multiphase stockwork veins. Quartz-potassium feldspar-carbonate veins with molybdenite

and chalcopyrite are most abundant where both granodiorite and quartz-plagioclase porphyries are present. Although regional and contact metamorphism partly overprint early magmatic-hydrothermal alteration at Spinifex Ridge, potassic alteration is preserved as potassium feldspar veins and replacement of plagioclase by potassium feldspar within the high-grade core of the deposit, and as pervasive biotite alteration of both porphyries and basalts at the periphery of the high-grade core. Both phyllic and propylitic alteration are also associated with the mineralisation. Re-Os dating of molybdenite samples confirms the timing of mineralisation at Spinifex Ridge. Molybdenite ages of 3298 ± 11 and 3284 ± 11 Ma are indistinguishable within their 2-sigma uncertainties, and agree with SHRIMP U-Pb zircon ages for granodiorites in the Mount Edgar batholith (3314 ± 13 Ma, Coppin Gap suite; 3304 ± 10 Ma, Boodallana suite). Multiple sulphur isotope analyses of molybdenite also confirm a magmatic-hydrothermal source for sulphur. Together these observations confirm that Spinifex Ridge is an Archaean porphyry-style Mo-Cu deposit and the world's oldest world-class ore deosit.

Phanerozoic porphyry-style magmatic-hydrothermal metal deposits are typically associated with hydrous, volatile- and metal-rich inermediate to silicic magmas at convergent plate margins with Mesozoic and Cenozoic porphyry Cu deposits showing the strongest link to the subduction of ocean crust. Mineral deposits formed at high levels in modern active convergent margins have very limited chances of preservation. Most modern porphyry-style Mo-Cu deposits are associated with crustally derived silicic magmas in weakly extensional settings at either convergent or rifted plate margins and consequently have a slightly higher chance of preservation. These magmatic-hydrothermal systems are also characterised by lower oxygen fugacities than those associated with magmatic-hydrothermal Cu-Au deposits. Petrogenetic studies indicate that the 3.3 Ga granodiorites and rhyolites in the East Pilbara formed by crustal melting of an older intermediate TTG suite during the late stage of a major period of arc and/or plume magmatism. Ore zone geometry suggests that the intrusive-mineralisation system was emplaced during an episode of mild extensional deformation and subsequently strongly tilted during the deformation that accompanied the uplift of the Mount Edgar batholith into its present position. The regional geology supports formation of the Spinifex Ridge Mo-Cu deposit in a weakly extending regime at ~3.3 Ga, similar to magmatic-tectonic conditions that produce Mo-Cu porphyry-style deposits today. Regardless of the interpreted tectonic setting for the East Pilbara 3.3 billion years ago, it is not surprising that the oldest world-class, high-level, magmatic-hydrothermal ore deposit is a Mo-Cu porphyry-style deposit.

Doriri Creek Pd-Pt-Ni prospect, an unusual low temperature hydrothermal platinum group element occurrence, south-eastern Papua

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The Doriri Creek hydrothermal Pd-Pt-Ni lode is located in a northern tributary of the Ada'u River, Mt Suckling district, about 180km ESE of Port Moresby. It contains the highest platinum group element (PGE) grades known in Papua New Guinea. Mineralisation is confined to massive magnetite-mica rock hosted in Jurassic-Cretaceous gabbro. Sulphides are rare or absent. Ni-arsenides may be present, along with the green oxidation product annabergite. Bismuth, antimony and tellurides are associated with the PGE mineralised zones, but mineral species have yet to be identified. The Doriri Creek system has a strike length in excess of 520 m and the mineralised zone an average width of 10–15 m. The prospect is localised within the 7–8 km wide trace of the Keveri Fault Zone, a prominent regional structure that marks the boundary between continental rocks of the Australian plate and rocks of an island arc affinity of the Pacific plate. More than 8 km of vertical movement across the fault during the past 5–8 million years attests to the fundamental nature of this active structure and its potential to channel and focus circulating hydrothermal fluids.

Best exposures of PGE-Ni mineralisation are in Doriri Creek, where rapid down-cutting of the stream has exposed a 75 m vertical interval through the deposit's interpreted upper levels. Here, the steeply dipping Pd-Pt-Ni mineralised lode passes upwards/is overlain by a hydrothermal clay cap. The section clearly illustrates the hydrothermal features of the deposit:

- Mineralisation is characterised by relative enrichment of more mobile PGE, typically with Pd:Pt ratio >8:1. This ratio is typical of other hydrothermal PGE deposits worldwide, and is indicative of the relative mobility of Pd with respect to Pt in low temperature (300°C) hydrothermal conditions. Rh, Ru, Ir, Os concentrations are very low.

- Abundance of coarse 'pegmatoidal' alteration mica in the Doriri Creek mica-magnetite mineralised zone is indicative of (1) wholesale hydration facilitated by good porosity/permeability along the Doriri Creek structure and (2) time and space to grow.

- Zonation of hydrothermal alteration laterally to and above the main PGE-Ni mineralised zone is typical of a hydrothermal vein.

- Hydrothermal brecciation is locally abundant in the lowermost exposed intervals. Hydrothermal veining and stockworking of mica-magnetite rock occurs throughout the PGE-Ni mineralised lode and in the clay cap developed above it. Veining, stockworking and brecciation are hallmark textural features of low-temperature hydrothermal deposits such as epithermal gold deposits and Au-Cu porphyry deposits.

- Marcasite, a low temperature epithermal dimorph of pyrite, is present in the deposit.

The wholesale hydration of gabbro wallrock, coarse mica books, vein and breccia textures and the presence of trace marcasite indicate migration of large volumes of low temperature hydrothermal fluid along a relatively narrow, near vertical structure that has been held open for a considerable time period.

High PGE and Ni grades are contained in the zone of massive mica-magnetite rock and surface grades average 10–15 m @ 1.3% Ni, 1–2 g/t 2PGE. Narrow intervals (0.46 cm) contain up to 14.7 g/t Pd, 3.4 g/t Pt and 2.58% Ni. PGE and Ni concentrations decrease at higher levels in the deposit as the lode splinters and inter-fingers with stockworked argillised gabbro. Au is present in the stockworked zones overlying the main mica-magnetite mineralised zone.

The patterns of wallrock alteration and PGE-Ni mineralisation are unknown in any other example described worldwide. Doriri Creek is a unique example of hydrothermal, oxide-dominant (sulphide-poor) Pd-Pt-Ni mineralisation. Other hydrothermal PGE deposits, such as New Rambler, Wyoming, are of low tonnage and are regarded as mere geological curiosities. Textural indications are that the Doriri Creek structure has been held open for a considerable time period, and thus the lode is expected to have a reasonable lateral and depth extent.

The pre-1.8 Ga tectono-magmatic evolution of the Kalkadoon-Leichhardt belt—implications for the crustal architecture and metallogeny of the Mt Isa Inlier, north-west Queensland, Australia

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New geochemical, U-Pb zircon and Nd-Hf isotope data for felsic and mafic components of the Kalkadoon-Leichardt Belt in the Mt Isa Inlier of north-west Queensland confirm that the evolution and tectonic make-up of this belt prior to 1.8 Ga was closely aligned with that of the Western Fold Belt. Like pre-1.8 Ga magmatic rocks of the Western Fold Belt, those in the Kalkadoon-Leichardt Belt are characterised by late Archaean to Palaeoproterozoic crustal residence ages (T_{DM} *ca.* 2.3 to 2.6 Ga) but the geochemical data suggest stronger within-plate affinities, implying that the Kalkadoon-Leichardt Belt intrusions underwent a greater degree of crustal assimilation and/or were emplaced further inboard of the active subduction margin. A new SHRIMP U-Pb zircon age of ca. 1.86 Ga from a felsic intrusion in the northern KLB confirms earlier age constraints for the main phase of the Kalkadoon Granite. Nd isotope patterns for intrusions in the Western Fold Belt and the Kalkadoon-Leichardt Belt are distinct from those of *ca.* 1.7 to 1.5 Ga intrusions in the Eastern Fold Belt. This isotopic discrepancy suggests the Eastern Fold Belt underwent a separate evolutionary history and was accreted to the Western Fold Belt and the Kalkadoon-Leichardt Belt at some stage prior to, or during, the *ca.* 1.86 Ga Barramundi Orogeny. The occurrence of widespread, isotopically homogeneous *ca.* 1.72 Ga magmatism (Argylla Event) across the entire Mt Isa Inlier implies that amalgamation of the allochthonous Eastern Fold Belt with the North Australian Craton was completed by that time. The significantly elevated metallogenic potential of the Eastern Fold Belt for ca. 1540–1500 Ma iron-oxide-copper-gold, relatively low endowment of the Kalkadoon-Leichhardt Belt, and predominance of ca. 1650–1550 Ma base metal occurrences in the Western Fold Belt, are all consequences of the tectonic interplay and lithospheric processes that controlled the evolution of the Mt Isa Inlier prior to *ca.* 1.8 Ga.

Hyperspectral remote mapping of Archaean lithologies and hydrothermal alteration mineralogy in the Eastern Goldfields superterrane, Australia

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Airborne hyperspectral (HyMap) data covering an area of about 2500 km^2 in the Kambalda area within the 2.8 to 2.6 Ga Norseman-Wiluna greenstone belt (Yilgarn Craton, Australia) were collected and processed to generate seamless mineral maps potentially of value for mineral exploration. The study area, centred on the Kambalda Dome, is highly prospective for both Archaean Au as well as komatiite-associated Ni sulphide mineralisation. The structurally controlled Au mineralisation is hosted by a variety of rock types including mafic and ultramafic rocks, granitoids, porphyries and metasediments. Controversy remains whether fluid-rock or fluid-fluid interactions were critical in depositing Au or whether there were one, two or even three 'synchronous' fluids from different sources (magmatic, mantle, metamorphic, meteoric?) involved in Au mineralisation. However, there is general agreement that gold deposition developed at sites where there existed fluid pathways intersecting steep physicochemical gradients and that mapping/tracking these pathways/gradients is of exploration value.

Tracking the level of Tschermak substitution in white micas has proved useful in defining the chemical gradients associated with mineralisation for Au(Cu) mineralisation across the Kalgoorlie and Mount Isa region. This white mica chemistry is interpreted to be related to the relative activities of Si and Al in K- rich hydrous fluids. However, Archaean CO_2-rich fluids were also present in greenstone belts generating distinctive talc-carbonate alteration mineral assemblages in ultramafic rocks. These contrast with serpentine-magnetite alteration in ultramafic rocks related to hydration reactions of the primary olivine/pyroxene. Amphibole (tremolite-actinolite, hornblende) is also a common mineral developed in Archaean mafic/ultramafic rocks. Amphibole, as well as talc and serpentine in theory can all be generated through regional metamorphic dehydration/decarbonation reactions. Indeed, workers have used changes in amphibole mineralogy to define regional metamorphic temperature isograds for the Kalgoorlie region.

The collected airborne hyperspectral imagery spans a >15 km wide zone covering the entire Boulder-Lefroy Fault from Kalgoorlie in the north to Tramways in the south. The 126 channels (from 450 to 2500 nm) of HyMap imagery were processed using the same methods developed for the public geosurvey data releases for north Queensland, Broken Hill and Kalgoorlie (http://c3dmm.csiro.au). The SWIR (2000–2500 nm) is particularly sensitive to absorption by AlOH, MgOH and FeOH-bearing sheet silicates (e.g. muscovite, talc, chlorite) as well as amphiboles and epidotes.

The results show that a number of mineral mapping products are providing new geological/alteration information not apparent in other exploration data (including geological mapping, airborne magnetics/radiometrics). For example, the published amphibole-defined temperature isograd that separates the <400°C domain to the north (actinolite-tremolite) from the >400°C domain to the south (hornblende) is well defined in the processed HyMap imagery by a change from white mica developed in mafic/ultramafic rocks in the north and no white mica developed in mafic/ultramafic rocks in the south. In addition, there is a hyperspectral pattern of biotite-chlorite and other MgOH minerals (talc-amphibole) being well developed in the south. Also, although related to weathering, it is notable that there is a pronounced change in the Al-clays across this isograd with dominantly kaolin (of variably crystallinity) in the north and Al-smectite (+kaolin) in the south, which could be a function of the feldspar mineralogy sensitive to temperature of formation.

All of the open pit Au mines in the region show some Si-rich (long 2200 nm wavelength) white mica (phengite), though for some mines this is restricted to only the felsic porphyry dykes as other Au-host rocks exposed by mining have biotite as their main K-bearing mica (indicative of higher temperatures). Within these open mines as well as extensively developed in natural exposure, are mapped talc, amphibole and chlorite-biotite. This provides more within-unit detail compared with the existing large-scale company solid geological mapping, based on analysis of fresh rock drill core, including multi-element geochemistry. This greater within-unit details enables the opportunity to target for example, talc (-carbonate) alteration along specific faults (e.g. those parallel to or intersecting/splaying from the Boulder-Lefroy Fault) that intersect ultramafic rocks.

This was examined for the Tramways area where a number of known NNW-SSE trending faults could be assessed for possible CO_2-rich fluid movement. Of the mapped seven faults, only a pair of side-by-side paralleling faults 200 metres apart show talc developed between/along their length for some distance. These

same faults are associated with chlorite-biotite in the underlying mafic unit, which is not developed elsewhere in the same unit. The airborne radiometrics show some relative enrichment in K also in this area. All of these provide evidence for metasomatic fluids moving along brittle pathways at high angle to the stratigraphy. Whether these fluids were Au-bearing and intersected physicochemical conditions of sufficient contrast to deposit Au are other issues to be considered.

Assessment of mineral prospectivity of the northern Flinders Ranges, South Australia, using GIS analysis

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The northern Flinders Ranges region in South Australia is underlain by rocks belonging to two contrasting geological provinces: the metamorphic and igneous Palaeoproterozoic to Mesoproterozoic Mount Painter and Mount Babbage Inliers, and the sediments of the Neoproterozoic to Cambrian Adelaide Geosyncline. Each geological province has a distinct suite of mineral deposits and corresponding mineral potential (prospectivity).

The area displays a unique coincidence of abundant mineralisation (and therefore high mineral prospectivity), well-exposed and unusual rocks of value for research into the geological and mineralisation history of the State, and high environmental sensitivity and scenic and tourism interest.

As part of a study aimed at refining the management of these frequently conflicting values, a comprehensive and scientifically-based assessment of the mineral prospectivity was carried out. PIRSA geoscientists established the relevant mineral deposit styles (43 in all), categorised by dominant commodity (copper, uranium, rare earths, gold, base metals and tin, industrial minerals, construction materials, gemstones and coal), and identified the key genetic ingredients which could be spatially analysed, such as stratigraphic units, diapirs and faults, and intersections of these.

A knowledge driven, index overlay methodology of GIS analysis was applied to the mature geological and mineral deposit databases compiled by PIRSA over many years. Geoprocessing was performed in the ArcGIS Model Builder environment which allowed the process to be automated and easily updated with new information or processing steps. Maps of predicted prospectivity for each commodity, and for all commodities combined, were generated.

Each modelled commodity occurs as one or more mineralisation styles. Prospectivity maps of each mineral style were modelled in turn, by assigning prospectivity scores to geological units, linear structure and diapir geology which were additively combined. Commodity level prospectivity maps were then computed by additively combining sets of mineral style prospectivity maps and show higher prospectivity where there are a number of spatially coincident mineralisation styles. Finally, all commodities were weighted, additively combined and reclassified to produce a prospectivity map of the northern Flinders Ranges region. Weighting of commodities assigned highest weight to uranium, rare earth elements and copper; moderate weight to base metals and gold and low weight to gemstones, coal, industrial minerals and construction materials. The final mineral prospectivity map can be used in high level land use decision making within the northern Flinders Ranges and clearly shows areas of high, moderate and low mineral prospectivity.

The study has confirmed and, importantly, spatially delineated the high level of mineral potential of the northern Flinders Ranges, particularly for copper and base metals in the Adelaide Geosyncline, and for uranium and rare earths in the Mount Painter and Mount Babbage Inliers.

Statistical and visual analysis confirmed the robustness of the predictive methods used, as spatial comparison of predicted mineral prospectivity with known mineral occurrences and geochemical assay results showed a high level of correlation (72–100% correlation for mineral occurrences and 68% to 100% correlation for geochemical samples). This process has also highlighted anomalies which require follow-up to ground-truth their prospectivity, possibly leading to undiscovered mineral systems or previously unrecognised mineral styles. For example, radiometric data over Adelaide Geosyncline sediments suggest elevated levels of uranium which are unexpected and require further investigation.

A complementary and novel GIS analysis of exploration activity and geoscientific values added to the documentation of the region's importance to the economic and research sectors.

This study has outlined a work flow and range of GIS procedures which are adaptable to other regions in South Australia and beyond, with differing geology, mineral occurrences and styles, degree of exposure and level of knowledge. An existing GIS analysis can be easily re-run with the collection of new data, or where previously unrecognised or overlooked mineral styles can be considered to apply to a given area. A different commodity focus or emphasis can be accommodated in response to new technologies, changed market conditions or improved infrastructure.

STREAM 01EC (ENVIRONMENT)

δ^{18}O-derived temperature records from the Australian flat oyster, *Ostrea angasi*

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As with many other biogenic carbonates, stable isotope analysis of bivalve shells can impart valuable environmental information. As bivalve carbonate has been found to precipitate in equilibrium with the ambient water with respect to δ^{18}O, the shell δ^{18}O signal can be used as a temperature archive. The accretionary growth structure of the shell also permits recovery of seasonal scale temperature records through high-resolution sampling.

To calibrate the δ^{18}O signal in modern specimens of the Australian flat oyster, *Ostrea angasi*, monitoring experiments were conducted at two locations on the east coast of Australia—Pambula Lake, New South Wales and Little Swanport, Tasmania. Specimens were collected, measured and labelled, then returned to their natural habitats for a period of 12 months, along with data loggers that recorded water temperature at 30-minute intervals. Water samples were collected fortnightly for stable isotope analysis. Four shells from Pambula Lake and three from Little Swanport were sampled at a resolution of 80 to 200µm. Instrumental temperatures were then compared with temperatures reconstructed from the δ^{18}O signal of the shells using the δ^{18}O-temperature equation developed for biogenic carbonates by Epstein *et al*. (1953).

Each of the Pambula Lake shells produced a clear δ^{18}O signal spanning 1.5 years, with the three shells from Little Swanport producing records covering 8, 5 and 2.5 years. Comparison of the δ^{18}O-derived temperatures with instrumental temperatures shows that the shell of this species contains a good record of ambient water temperature, albeit with some caveats.

The estuarine environment of the species can present some challenges to accurate temperature reconstructions, as fluctuations in salinity can disrupt the otherwise temperature-dependent nature of the δ^{18}O signal. Indeed, the Pambula Lake *O. angasi* clearly show an overestimation of temperature corresponding to periods of high rainfall and thus increased freshwater flows to the estuary. This can also be compounded by the intolerance of *O. angasi* to low salinity, as when *O. angasi*'s salinity threshold (preferred salinity is 25 to 35 ppt) is breached, the oyster will 'shut-down' and thus not precipitate any carbonate, interrupting the otherwise continuous time record.

It can also be seen that biological influences can affect the δ^{18}O signal in *O. angasi*. Two shells from Little Swanport were significantly older than the other shells studied, and the range of variability in δ^{18}O during their later years of growth (from the age of approximately two years onwards) is somewhat dampened due to underestimation of summer temperatures. Winter extremes are still well represented; hence we deduce that the onset of sexual maturity and subsequent annual spawning in the summer months disrupts growth during the summer time, causing a truncation of maximum summer temperatures.

Two *O. angasi* shells from an Aboriginal midden site at Severs Beach, on the Pambula River, down-river from Pambula Lake, were also analysed. Interestingly, the midden shells' δ^{18}O signals do not exhibit higher amplitudes in their earlier years of growth, but show comparatively consistent summer maxima and winter minima throughout their lifetime. It is not known why these shells, being of comparable age to those analysed from Little Swanport, do not show the same 'dampened' signal after their first two years of growth.

Reconstructed temperatures from the two midden shells are identical within error and show a seasonal range comparable, but not identical, to modern day temperatures. Winter minima are consistent with temperatures

recorded during the Pambula Lake monitoring experiment, but results indicate significantly cooler summers in the past.

Reference

Epstein S, R Buchsbaum, HA Lowenstam and HC Urey (1953), Revised carbonate-water isotopic temperature scale, *Geol. Soc. Am. Bull.*, *64*, 1315–1326.

Morphological variation, composition and age of submerged reefs on the Great Barrier Reef

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Coral reefs are powerful indicators of environmental changes, such as sea level, salinity and sea surface temperature fluctuations. Many sites within the Indo-Pacific and the Caribbean have been investigated, yet the Great Barrier Reef (GBR) remains largely under-represented in early deglacial, Late Pleistocene records. IODP Expedition 325 Site Survey (Proposal 519) returned with 4200 km^2 of high-resolution multibeam bathymetry of submerged reef features on the shelf edge, revealing extensive terraces, barrier reefs, lagoons, pinnacles and palaeo-channels. Fossil coral reef specimens were collected from these features (*in situ* and loose) at depths ranging from 45–160 m and dated using ^{14}C AMS and U-Th. Preliminary results suggest the morphology of the features and the timing of drowning are influenced by a number of complex factors, possibly including, but not limited to variations in sea level, latitude, shelf width, local weather patterns and reef community composition.

Sea level and ice volume during the last interglacial

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Paleoshorelines and coral reefs associated with the last interglacial, ~125,000 years ago, have persistently been recorded at 4 to 6 m higher than present sea level at many localities around the globe. Because there is also evidence that the last interglacial was globally warmer, approximating temperature conditions that have been predicted for late in the 21st century, the last interglacial represents a valuable case study for understanding the response of ice sheets and sea level to future warming. Several recent studies suggest that the last interglacial sea level highstand more unstable than previously thought, including a brief sea level fall of several meters followed by a later rapid rise, and reaching a maximum eustatic sea level 6 to 9 m above present mean sea level.

The difference between sea level position at +4 or +9 m relative to present is significant: most of the 4 meters can be accommodated with melting from the Greenland ice sheet, but additional sea level rise would have to come from Antarctica. Collapse of the unstable, marine-based portion of the Western Antarctic ice sheet has been invoked to explain rapid rates of sea level rise and high eustatic sea levels above +4 m postulated to occur during the last interglacial. We have set out to evaluate published rates of sea level rise, interpretations of rapid sea level oscillations, and estimates of maximum eustatic sea level using a combination of an extensive literature review, new field and analytical work, and glacio-hydro-isostatic modelling.

Our modelling of the last interglacial focuses on (1) assessing the eustatic sea level signal, which is essentially a reflection of the continental ice volume at that time, and (2) determining whether evidence for sea level instability during the last interglacial is representative of fluctuations in eustatic sea level or whether these observations are attributes of the spatial variability of the isostatic response to changes in ice sheet and water loading that occur on glacial-interglacial timescales. The field work we have undertaken focuses on improving the quality and resolution of sedimentologic and geochronologic data in far-field localities that play a key role in the process of modelling the eustatic sea level function. Finally, we have compiled coral U-Th age-elevation data from around the globe to assess the temporal evolution of last interglacial sea level, as recorded by the maximum height of coral reefs that grow near the sea surface. The database assembled comprises >600 data points from 14 globally-distributed sites, only 6 of which are considered tectonically stable.

At all locations the response of last interglacial sea level to changes in surface ice loading is a function of: (1) the ice model consisting of the ice margins and thickness of the ice—both before and after the last interglacial, (2) the rheological model of the mantle which determines the rate, magnitude, and wavelength of the response to the ice sheets, and (3) the eustatic sea level function, or volume of continental ice volume and ice grounded on the shelves. In principle, it is possible to separate out these three contributions given an observational dataset that has good geographic and temporal distribution in an analogous way to analyses of post-last glacial maximum sea levels.

This presentation will focus on the advances we have made in our understanding of last interglacial eustatic sea level, including results from recent field work in Western Australia and the Seychelles. Modelling results for key last interglacial sites in far-field and intermediate field positions will be discussed as well as the implications for interpreting data from these sites in the context of eustatic sea level changes during the last interglacial.

Lead isotopic evidence for an Australian source of aeolian dust to Antarctica at times over the last 170,000 years

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Systematic analysis of Pb, Sr and Nd isotopes of 32 fluvial clay samples (<2µm fraction) from many of the major tributaries of the vast (1.10^6 km^2) Murray Darling Basin (MDB), located in semiarid south-eastern Australia, display similar isotopic values between some MDB clays and dust from several ice core samples from the EPICA Dome C in Antarctica. Close scrutiny of several ratios of the four Pb isotopes, and in particular $^{208}Pb/^{207}Pb$ versus $^{206}Pb/^{207}Pb$, show that several samples from the Darling-sub-basin of the MDB display similar values for the same isotopes for Dome C samples from different ages, and more particularly during wet phases in Australia [Marine Isotopic Stages 5e, 3 and 1]. The combination of Nd and Sr isotopic ratios from the same MDB fluvial clays clearly eliminates the Murraysub-basin, and supports the Darling sub-basin as a potential source of aeolian material to Antarctica. Overall, the Australian dust supply to Antarctica predominantly occurred during interglacial periods.

The work presented here shows that aerosols generated in south-eastern Australia can travel to parts of West Antarctica and this is supported by atmospheric observations and models. In addition, evidence of Australian dust in Antarctic ice cores further implies dust deposition in the Southern Ocean would have occurred in the past. Current meteorological observations also imply that the western Pacific and Indian Ocean sector of the Southern Ocean would frequently receive aeolian dust components originating from south-eastern Australia.

Southern high latitude record of the first glacial events of the Cainozoic

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The early Cainozoic earth was dominated by greenhouse conditions in the absence of permanent ice caps. Declining CO2 levels in the atmosphere and cooling in the late Eocene culminated in East Antarctic Ice Sheet expansion by the earliest Oligocene (Oi1 *ca.* 33 Ma). This marked the onset of more global icehouse conditions.

Records of Oligocene glacio-eustatic events are primarily based on C and O isotope excursions in deep sea sections and northern hemisphere records like the New Jersey margin in the USA. Early Oligocene records of these events are rare in the Southern Hemisphere, confined mainly to poorly sampled subsurface sections or attenuated sub/outcrop in Antarctica. Here we present for the first time the results of a detailed microfossil and facies analyses of a subsurface cored section (Groper-1) of early Oligocene age from 55°S palaeolatitude, in the offshore Gippsland Basin, south-east Australia.

Foraminiferal and facies analyses suggest that the marl and limestone in this section were deposited in low energy shelfal to upper slope environments from 28 Ma to 32 Ma. The presence strong metre scale cyclic alternations of dysoxic to suboxic middle shelf marl and oxic outer shelf to upper slope chalk are interpreted as eccentricity (100 ky) driven glacio-eustatic events.

Two shallowing events superimposed on this cyclicity are associated with benthic dysoxia and strong surface ocean productivity. These two events are evidence of glacial events Oi2 (*ca.* 30 Ma) and Oi2* (*ca.* 29 Ma) predicted from global Oxygen isotope data.

Facies and seismic evidence suggest minor subaerial exposure and strong subsidence during deposition. Hence, it is probable that Groper-1 preserves one of the best high latitude proxy records of early Oligocene glacio-eustacy in the Southern Hemisphere. However, evidence of Oi1 the first and biggest Oligocene glacial event is not preserved.

STREAM 01SC (SOCIETAL: GEOLOGICAL HAZARDS)

Natural hazards risk research in a changing world

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Increases in natural disasters worldwide are presenting new challenges for natural hazard risk research. Natural disasters are more likely than ever to have global impact in a world where catastrophic risk is shared across national and international boundaries and between the public and private sector. Climate change is the popular scapegoat for the increase in disasters; but exponential growth in human population and assets as well as increased exposure of populations in coastal areas and megacities are equally to blame. Interest in natural hazard risk is widespread among the public, in all levels of government, in international relations and across the private sector. This presentation explores how these issues and interests are manifest in the evolution of natural hazards risk research, including the role of geoscientists in this process.

30 years ago, natural hazard research was narrowly confined to the development of hazard maps, which were used primarily for input to building codes and the design of major infrastructure or critical facilities. Today, solutions require multi-hazard information and the development of a wide range of analyses about the exposure and vulnerability of communities. Further, it is not enough to just quantify the problem; results also require solutions in the form of options for mitigating the risk. These new demands require inter-disciplinary teams of hazard scientists, engineers, economists, social scientists, mathematicians, geographers and more. The development of solutions also requires the involvement of a wider range of stakeholders and clients in order to ensure that products are fit for purpose.

The drivers for better natural hazard risk information are now evident in Australia in the form of significant new national policies. The new National Security policy issued in 2008 recognises that natural hazards can pose catastrophic risk for Australia. In 2009, the Australian Agency for International Development issued a Disaster Reduction Policy as a foundation of its capacity building programs overseas; natural hazards are a key element of this policy, which has resulted in significant investments in natural hazard risk research in the region.

Geoscientists have a major role to play in meeting the demand for information on natural disasters and in assessing natural hazard risk. First of all, there is greater demand for information to describe the processes that lead to natural hazard events. This includes better understanding of the causes and probabilities of these events, as well as descriptions of events in a physical and spatial context. Hazard or risk models based solely on statistical methods are no longer sufficient. Natural hazard science is moving to physically-based models which are driven by an understanding of Earth dynamics, with increased computing power and improved simulation tools critical to this evolution. In terms of climate change hazards, there is an increasing demand for earth scientists to contribute to our understanding of the potential increases in coastal erosion, storm surge, riverine flooding, and sea-level rise, all of which require fundamental geological and geophysical input.

Interferometric synthetic aperture radar for natural hazard monitoring: case studies in Western Australia and Papua New Guinea

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Satellite Interferometric Synthetic Aperture Radar (InSAR) is a unique observational technique capable of high resolution and high precision measurement of surface deformation. InSAR has been widely used to study many geophysical phenomena, including volcanoes and earthquakes, but the technique is not without its limitations and is adversely impacted by both atmospheric artefacts and signal decorrelation associated with steep topography and vegetation. However, new time series analysis approaches can in part mitigate these limitations. In this study, we review two recent investigations of Australian earthquakes and volcanic deformation in Papua New Guinea (PNG) and demonstrate how InSAR can make unique contributions to natural hazard monitoring. In the first case study, we use InSAR to investigate two intraplate earthquakes in a stable continental region of south-west Western Australia. Both small-magnitude events occur in the top 1 km of crust and their epicenters are located with an accuracy of ±100 m (1σ) using observations from the ALOS and ENVISAT satellites. For the Mw 4.7 Katanning earthquake (10 October 2007) the average slip magnitude is 42 cm, over a rupture area of approximately 1 km^2. This implies a high static stress drop of 14–27 MPa, even for this very shallow earthquake, which may have important implications for regional seismic hazard assessment. For the Mw 4.4 composite Kalannie earthquake sequence (21–22 September 2005), we use a long-term time series analysis technique to improve the measurement of the co-seismic signal, which is a maximum of 27 mm in the line-of-sight direction. These earthquakes are some of the smallest magnitude seismic events to have been investigated using InSAR and demonstrates the capability of the technique to provide important constraints on small-magnitude coseismic events in stable-continental regions. In the second case study, we demonstrate how time series analysis can be used to improve InSAR's application in the highly vegetated and actively deforming Rabaul Caldera, PNG. We used 16 ALOS PALSAR scenes from January 2007 to March 2010 to infer subsidence, which is a maximum of 80 mm yr^{-1} at Matupit Island and Vulcan, at a precision typically better than ±2 mm yr^{-1} (1σ). This suggests that despite the limited application of InSAR in PNG to date its use would significantly complement volcano monitoring activity.

Risk monitoring and maintenance programs at Falls Creek Alpine Resort—linking hydrogeological understanding to risk management

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Falls Creek is Victoria's largest alpine resort and a major tourist destination in North East Victoria. Since 1999 GHD Pty Ltd has been working closely with Falls Creek Resort Management Board (FCRM) on extensive on-going geotechnical risk management programs. The geotechnical stability of land at Falls Creek is an important environmental and safety issue and together FCRM and GHD have designed monitoring and maintenance programs which take into consideration the landform, climate changes and the resort's potential exposure to geotechnical hazards.

This presentation looks at the new tools, maintenance programs and methods implemented at Falls Creek to manage geotechnical stability of land, building upon the continued understanding of the geotechnical risks and hydrogeology and adopting these to our improved technology and changing environment.

Background

The allocation of geotechnical funds provided through the Department of Sustainability and Environment's Alpine Risk Mitigation Program has enabled FCRM to deliver a recurrent works program that includes groundwater monitoring, a groundwater maintenance program and emerging hazard identification. In addition, an auditing process is in place to review previously addressed sites, and together has reinforced the fact that the geotechnical status of land in this area is subject to change over time due to various influences.

The Risk Mitigation program was established as an extension to the desktop investigations and visual inspections conducted by SMEC Victoria Pty Ltd (SMEC) for all Victorian Alpine Resorts during a period extending from late 1998 to mid-1999. The groundwater monitoring program was initiated at the request of FCRM. A series of piezometers were initially installed at locations indicated as high risk during the original

SMEC or subsequent GHD risk analyses. Further instrumentation was installed as part of GHD's Ancient Landslide Investigation, Hydrogeological Model, and recommendations contained in annual groundwater monitoring reviews.

Following the 2009 program of works, there are 68 monitoring bores (37 installed with vibrating wire piezometers, 55% coverage) and 50 horizontal drains. Over the life of the monitoring program selected piezometers have been upgraded to vibrating wire instrumentation in an effort to improve the efficiency of the groundwater monitoring data collection phase and accuracy of the data. The monitoring program has developed from a purely manual monitoring system to an integrated real time continual logging system with integrated flow monitoring.

In addition to improving the piezometer network, a key aspect has been the importance of continued rehabilitation and maintenance on horizontal drains and monitoring bores during the life of the program. Quarterly and annual monitoring reviews indicate that the continual flushing and rehabilitation of the horizontal drains are critical to accurate reporting and ability to effectively mitigate risk.

Hydrogeological understanding and approach to higher risk sites

Between 2000 and 2009 the monitoring program at Falls Creek provides water levels, as levels of free water or seepage in the standpipes or piezometers recorded at the given time of measuring as part of the agreed monitoring program. The groundwater levels recorded in the observation bores generally exhibit a seasonal trend expected in the alpine village although individual bores do show slight variations. The groundwater levels generally decrease during the summer months, with the lowest levels recorded in early autumn. A slight elevation in groundwater levels is observed during the winter period and a dramatic rise occurs in late spring (September/October) as a consequence of snowmelt and heavy rainfalls.

The trend observed from the seepage rates from the horizontal drains is similar to those of the observations bores. Many of the observation bores and horizontal drains in the village are sensitive to high rainfall events as small increases in levels and rates have been observed immediately following the event. This understanding of changes in groundwater levels due to rainfall and snowmelt in conjunction with the presence of weathered low strength materials, increase the pressures in the slope where groundwater flow is concentrated, leading to the development of zones of highly saturated, low strength materials forming potentially unstable slope conditions.

To reflect the importance of recording such variations, a new logging system approach has been implemented at higher risk or at risk sites, enabling continual logging of piezometer water levels and horizontal drain flow. The system is powered via a solar panel, which connects to a terminal cabinet located one of the bore sites. The system has been designed with the intention of using telemetry, which allow instant access to groundwater levels, and consequently provide a larger dataset for interpretation.

An enhanced understanding of the hydrogeological controls in the village area is a proactive approach to identification and management of slope stability hazards throughout the larger village area. The combination of deeply weathered, low strength materials and periodically elevated groundwater levels may lead to decreased stability in certain areas. Thus, to obtain a more accurate representation of the groundwater regime at Falls Creek, the improvement in groundwater monitoring data together with mitigation measures such as horizontal drains are essential to the risk management at Falls Creek.

Precusory signals of the Sumatra-Andaman earthquake: what could we have known?

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In the past decade a large number of very large earthquakes have occurred, resulting in significant destruction and devastation from both the ground movement and from the tsunamis generated by some of the earthquakes. Scientists were 'caught unawares' by the Sumatra-Andaman earthquake in December 2004 and much investigation of historical data has been undertaken as a result in an attempt to learn how and why the scientific community was not expecting that this Great earthquake would occur. This soul-searching process has led to the realisation that there were indicators that the whole region was undergoing a slow but significant deformation which led to a massive rupture of the Earth's crust, but also that large tsunamis had actually occurred in the past. Given the cyclic nature of such Earth processes, it was inevitable that such an

event would occur again. This paper describes some of the precursory signs of large earthquakes that we now know can exist as well as how they can be detected. That this is possible provides hope for the future that the scientific community can be better informed and can therefore provide better information to communities about the natural hazards with which they coexist.

STREAM 01DC (DYNAMIC EARTH: INTRAPLATE AND PASSIVE MARGIN PROCESSES)

Geochronology and geochemistry of post-collisional Cenozoic alkali-rich porphyries in Eastern Tibetan Plateau, Yunnan, China

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The 1,000-km-long, north- and northwest-striking, Jinshajiang-Ailaoshan alkali-rich magmatic belt runs from the south-eastern margin of the Tibetan plateau to the plateau interior parallel to a major fault zone. The belt contains numerous hypabyssal, alkali-rich porphyries with ages ranging between 40 and 30 Ma, and numerous Cu (-Mo,-Au) deposits are spatially and temporally associated with the porphyries. The porphyries apparently formed in a post-collisional continental setting, post-dating continental collision between India and Asia (ca. 55 Ma). This magmatic belt thus can not be related to oceanic slab subduction, as in the traditionally interpreted typical circum-Pacific setting for the formation of porphyry Cu (-Mo, -Au) deposits. Here we report the geochronology and geochemistry of the alkali rich porphyries in the Dali-Jianchuan area, the middle segment of the Jinshajiang-Ailaoshan magmatic belt, in NW Yunnan province, and discuss their tectonic settings.

SHRIMP zircon U-Pb dating of the porphyries shows that alkaline magmatism was initiated at 36.93 ± 0.32 Ma and persisted until 33.06 ± 0.39 Ma, with a major peak at 35.5–35.0 Ma. The quartz syenite porphyry intrusion associated with the Beiya gold deposit was emplaced between 36.93 ± 0.32 and 36.35 ± 0.37 Ma. The granite porphyry associated with the Machangqing porphyry Cu-Mo (-Au) deposit formed at 35.0 ± 0.2Ma. The syenite porphyry associated with the Yao'an gold deposit formed at 33.43 ± 0.32 Ma. The porphyries intrude the non-metamorphosed sedimentary sequences outside or well away from the Ailaoshan-Red River shear zone, which has been proposed to be responsible for the magmatism. In fact, 40–30 Ma alkaline magmatism is widely distributed throughout northern and eastern Tibet and is not confined to major lineaments. Therefore, our geochronological and geological data support the view that there is no direct link between the alkaline magmatism and the strike-slip faulting. Rather, geochemical data require a regional lithospheric extension setting involving mantle processes (see below).

The Beiya intrusion consists mainly of quartz syenite porphyry, the Machangqing intrusion consists mainly of granite porphyry, and the Yao'an intrusion consists mainly of syenite porphyry. These intrusions are characterised by enrichment of total alkalis, especially potassium. Geochemically, the Beiya quartz syenite porphyry is equivalent to a shoshonitic rhyolite, the Yao'an syenite porphyry to an alkaline trachydacite, and the Machangqing granite porphyry to a high-K calc-alkaline rhyolite. They are all enriched in LREE and LILE (such as Rb, Ba, Sr, Th, U, and La), depleted in HFSE (such as Nb, Ta, Ti) and HREE, have high Rb/Sr, La/Nb, LREE/HREE ratios, with no obvious Eu anomalies. The initial $^{87}Sr/^{86}Sr$ ratios are high and ε_{Nd} values are low, close to enriched mantle (EMII). We consider these intrusions were derived from partial melting of the metasomatised lithospheric mantle (most likely the metasomatised, phlogopite-bearing peridotite source) beneath the western margin of Yangtze craton which had been previously subjected to the Paleo-Tethys oceanic subduction in the Triassic. However, the tectonic trigger for the upwelling of asthenosphere which caused the partial melting of the metasomatised lithospheric mantle remains unclear. Although these intrusions share similar features in tectonic setting, age and source region, they show differences in lithology and chemical compositions, which was probably due to differing degrees of partial melting of the source region. The Au mineralisation is considered to be associated with the intrusions of shoshonitic to alkaline series while Cu mineralisation with the intrusions of high-K calc-alkaline series in the Jinshajiang-Ailaoshan alkali-rich magmatic belt.

Experimental phase and melting relations of metapelite in the upper mantle—implications for the petrogenesis of intraplate magmas

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Recent experimental work and studies of natural ultra-high pressure rocks indicate that much of the sedimentary components of subducting slabs escapes significant geochemical modification during deep subduction into the mantle. These rocks may then comprise part of heterogeneous mantle domains that may be the source of some intraplate magmas (e.g. Jackson et al. 2007). To examine the melting behaviour and phase relations of sedimentary rocks at upper mantle conditions, we have performed a series of piston-cylinder experiments on a synthetic pelite starting material over a pressure and temperature range of 3.0 to 5.0 GPa and 1100 to 1600 ºC. The anhydrous pelite solidus is between 1150 and 1200 ºC at 3.0 GPa and close to 1250 ºC at 5.0 GPa, whereas the liquidus is likely to be at 1600 ºC or higher at all investigated pressures, giving a large melting interval of over 400 ºC. The subsolidus paragenesis consists of quartz/coesite, feldspar, garnet, kyanite, rutile, ±clinopyroxene ±apatite. Feldspar, rutile and apatite are rapidly melted out above the solidus, whereas garnet and kyanite are stable to high melt fractions (>70%). Clinopyroxene stability increases with increasing pressure and quartz/coesite is the sole liquidus phase at all pressures. Feldspars are relatively Na-rich (K/(K+Na) = 0.4–0.5) at 3.0 GPa but are nearly pure K-feldspar at 5.0 GPa. Clinopyroxenes are jadeite and Ca-eskolaite rich, with jadeite contents increasing with pressure. All supersolidus experiments produced alkaline dacitic melts with relatively constant SiO_2 and Al_2O_3 contents. At 3.0 GPa, initial melting is controlled almost exclusively by feldspar and quartz, giving melts with K_2O/Na_2O ~1. At 4.0 and 5.0 GPa, low-fraction melting is controlled by jadeite-rich clinopyroxene and K-rich feldspar, which leads to compatible behaviour of Na and melts with K_2O/Na_2O >>1.

Our results indicate that sedimentary protoliths entrained in upwelling heterogeneous mantle domains may undergo melting at greater depths than mafic lithologies to produce ultrapotassic dacitic melts. Such melts are expected to react with and metasomatise the surrounding peridotite, which may subsequently undergo melting at shallower levels to produce compositionally distinct magma types. This scenario may account for many of the distinctive geochemical characteristics of EM–type ocean island magma suites. Moreover, unmelted or partially melted sedimentary rocks in the mantle may contribute to some seismic discontinuities that have been observed beneath intraplate and island-arc volcanic regions.

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Post rift thermal evolution of Tasmania and the South Tasman Rise: insights from low-temperature thermochronology

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Evolution of south-eastern margin of Australia has been strongly influenced by rifting between Australia and Antarctica, and the eastern Australian margin and the Lord Howe Rise. Tasmania, along with two continental fragments, the South Tasman Rise (STR) and East Tasman Plateau (ETP), which are located at a rift junction, offers a distinctive opportunity to study the post rift geodynamic evolution of this tectonic setting.

Low-temperature thermochronology applies temperature-sensitive geological dating methods, most notable the $^{40}Ar/^{39}Ar$, fission-track and (U-Th-Sm)/He methods, to reconstruct the thermal history of rocks. The latter two methods applied to apatites (AFT and AHe respectively) record patterns of geological cooling through approximately 120°–60°C and 80°–40°C respectively, characteristic of the upper few kilometres of the Earth's crust. Here, we report the first AHe studies on Jurassic (~175–180 Ma) Tasmanian dolerite, together with previous AFT data from other lithologies, further constrains the post rifting thermal evolution of south-east Australia. We have focused on the dolerite particular because it is widely-distributed over Tasmania and is considered to be a precursor to the initiation of Gondwana break-up, and therefore forms an ideal geological 'marker' to document the post rifting thermal history.

Single-grain AHe results from dolerites yield ages ranging from ~70–115 Ma (mostly 87–101 Ma), while most of the previously reported AFT data yield ages <120 Ma. These AHe ages are not directly related to post-intrusion cooling and support previously published AFT results strongly supporting a rapid mid-Cretaceous cooling episode in Tasmania. AHe and AFT ages in this time range have also been reported from offshore Tasmania (STR) and the south-eastern Australian margin (NSW and Victoria). Combined AFT and AHe results suggest that most of the surface rocks currently exposed in eastern and central Tasmania cooled from >110°C to 40–50°C within 20 Myr (~3°C/Myr). This period corresponds to the early formation of Tasman Basin (95–83 Ma) and rifting of Lord Howe Rise from the eastern Australian margin, as a consequence of East-Gondwana break-up. Our AHe results suggest that Tasmanian dolerites have remained at a near-surface level since Late Cretaceous time. Further, the data also imply that the Tasmanian dolerite was either intruded at crustal depths of ~3–4 km or that following its intrusion it has undergone a significant phase of burial between Late Jurassic to Early Cretaceous time. In addition, in south-east Tasmania, AHe ages reveal a slight younging trend from inland towards the coast, which may suggest a greater degree of cooling/denudation along the Tasman Sea rifted margin after ~80 Ma.

Geomorphic tracers of mantle flow beneath the Australian continent

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Deciphering the subtle surface deflections (amplitude 100 m, wavelength 100–1000 kms) caused by small-scale convection in the upper mantle has proved difficult because they are small compared those associated with isostatic compensation of loads within or on the lithosphere. In the Australian continent, extraordinarily flat landscapes, combined with low rates of lithospheric deformation, extremely inefficient fluvial regimes, and the absence of widespread glaciation, have meant that it ideally suited to seeking such dynamic signals. Transient dynamic surface deflections of appropriate spatial scale and characteristic timescale of ~1–10 million years, are indicated by tracking the record of past megalake and marine shorelines, thereby providing geomorphic tracers of the growth and detachment of convective instabilities from the upper thermal boundary layer beneath the northward moving Australian plate, as well as the relative direction of mantle flow. Understanding the subtle pattern of landscape alteration, that has caused significant rearrangement of drainage patterns helps explain hitherto enigmatic biodiversity of Australia's inland faunas, and provides new cluses to understanding distribution of strategic metal reserves such as sedimentary U-deposits.

STREAM 01LC (LIFE AND SOLAR SYSTEM: ARCHEAN AND PROTEROZOIC LIFE)

Opening the phosphate window onto early life—the 1900 Ma Gunflint Chert

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Evolving patterns of phosphorus recycling have been fundamental to major biosphere revolutions in Deep Time. In this paper, we report on our recent discoveries and studies of phosphorites from the Gunflint Chert of Canada, about 1900 Ma, and compare them with younger Proterozoic through to upper Cambrian and younger examples.

These findings allow us to test the Mixed Layer Model put forward by Brasier and Callow (2007, Memoirs of the Association of Australasian Palaeontologists, 34, 377–389) and in Brasier (2009, Darwin's Lost World, Oxford University Press) which predicted the following taphonomic changes from the Proterozoic to post-Cambrian times:

- a departure from high-fidelity cellular (and possibly sub-cellular) preservation observed in the Proterozoic, towards the lower-quality preservation of organic materials generally seen in the Phanerozoic
- a change in the locus of phosphatisation from near-shore microbial mats in the Proterozoic towards outer shelf and slope environments after the Cambrian

- a change in the locus of phosphogenesis from the sediment-water interface in the Proterozoic towards greater depths below the surface of the sediment after the Cambrian

- a change in the objects that are themselves phosphatised and preserved, from mainly photoautotrophic organisms in the Proterozoic towards faecal matter and heterotrophic remains after the Cambrian.

Our Mixed Layer Model is here revised and updated to link observed patterns in phosphogenesis to stepwise biological and biogeochemical innovations, notably the emergence of sulphate reduction + oxygenic photosynthesis after c. 2400 Ma; multicellularity after c. 1000 Ma; and bioturbation and grazing, leading to greater oxygenation, after c. 560 Ma.

The origin of biomarkers (molecular fossils) of eukaryotes and oxygenic cyanobacteria in Archean and Proterozoic rocks

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A study from 1999 reported the discovery of traces of hydrocarbon biomarkers (molecular fossils) in 2.7 to 2.5 Ga old, mildly-metamorphosed shales from the Pilbara Craton in Western Australia[1]. Based on the typical Precambrian composition and high thermal maturity, the biomarkers were characterised as 'probably syngenetic' with the Archean host rocks[2]. The findings lead to far reaching conclusions about the Archean biosphere. 2α-methylhopanes were interpreted as evidence for the existence of oxygen producing cyanobacteria more than 300 million years before the atmosphere became widely oxygenated[1, 3], and the presence of steranes suggested that ancestral eukaryotes existed 2.7 Ga ago, 800 million years before the first eukaryotic body fossils appear in the geological record[1]. However, here we present evidence that the biomarkers entered the Archean rocks at a much later point in time. Furthermore, we demonstrate that not only Archean but a substantial fraction of Proterozoic biomarker assemblages was tainted with younger hydrocarbons.

In a recent study, Rasmussen and co-workers[4] detected microscopic spherules of pyrobitumen (thermally solidified bitumen) in Archean shales and compared their carbon isotopic composition with liquid bitumen and kerogen in the same rocks. The indigenous pyrobitumens had approximately the same carbon isotopic composition as co-occurring kerogens, but were depleted in ^{13}C by 10 to 20‰ relative to extractable biomarkers. The isotopic discrepancy between solidified and liquid bitumens indicates that the liquid hydrocarbon phase entered the rock after peak-metamorphism 2.2 Ga ago, either in the form of migrating petroleum, or during drilling and storage.

If the hydrocarbons were indeed later additions, then they should have left a distinct spatial distribution in the Archean rocks. In the simplest case, recent contaminants should be entirely surficial, while syngenetic hydrocarbons should be homogeneously distributed throughout the rock. However, liquid contaminants might also diffuse into fissures and pore space creating distinct concentration gradients[5]. Similarly, an indigenous oil is not necessarily homogeneously distributed in its host rock. Hydrocarbons might be driven to rock surfaces by pressure release when the core is recovered from great depths after drilling, leading to an accumulation on rock surfaces. To study these phenomena in the Archean rocks, we determined the spatial distribution of biomarkers in drill core material. Rock samples were cut into millimeter thick slices, and the molecular content of each slice was quantified. In the drill core, saturated and aromatic hydrocarbons of low molecular weight had gradually increasing concentrations from the surfaces to the center of the rock while the abundance of higher molecular weight hydrocarbons decreased with distance from the outer surfaces.

We propose two mechanisms that may have caused the inhomogeneous distribution: diffusion of petroleum-based contaminants into the rock ('contamination model') and leaching of indigenous hydrocarbons out of the host shales driven by pressure release after drilling ('condensate-escape model'). To test these models, we compared the hydrocarbon distribution in the Archean shales with artificially contaminated rocks, and with younger mudstones where leaching of 'live-oil' had been observed after drilling. Although the condensate-escape model is consistent with some of the observed patterns in the Archean shales, the observed relative migration depth of different hydrocarbon classes is only consistent with chromatographic effects caused by diffusion of contaminants from the surfaces of the rock towards the centre. The results confirm that the biomarkers are not of Archean age and probably entered the samples during years of storage.

We applied the same methodologies to re-appraise the Proterozoic biomarker record. The results show that biomarkers of eukaryotic algae are, in general, rarely detected in the Precambrian and, if present, very distinct from the Phanerozoic. Although the record of sedimentary sequences with demonstrably indigenous biomarkers is still exceedingly patchy, an evolutionary pattern emerges that is, for the first time, broadly consistent with microfossil evidence.

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Organic geochemical evidence of a microbial ecology in the 2.7 Ga Tumbiana Formation from stromatolitic outcrop samples, Fortescue Basin, Western Australia

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The Tumbiana Formation (2.7 Ga) records Earth's transitional period prior to the Great Oxidation Event in a 2–20m stromatolitic carbonate succession in the Pilbara craton, Western Australia. Outcrop samples are from across the 400km wide NW Pilbara Sub-basin. Previous organic geochemistry studies of the Pilbara utilising drill cores have been hampered by low volumes of sample, contamination by drilling fluids, and sampling of unknown stromatolite morphologies. The Tumbiana Formation stromatolite outcrops present a unique opportunity for hydrocarbon extraction as they are remote, display primary sedimentary features and detailed stromatolite morphologies and have undergone only very low grade metamorphism. This study follows the highly challenging search for Archaean chemical fossils in drill core, which have been hampered by low volumes of sample, contamination by drilling fluids, and sampling of unknown stromatolite morphologies.

The fossil stromatolites are composed of Fe-rich calcite and are commonly laminated and infilled with volcanic tuffs. They range in size and morphology from millimetre scale smooth-lamina bulbous structures, decimetre scale columnar forms, and low synoptic relief-elongate domes of over 3m in length with wavy laminae. The conical stromatolites have a characteristic axial zone, uneven column margins and do not branch; by comparison with extant analogues construction by phototactic, filamentous bacteria, perhaps cyanobacteria, is likely.

Outcrop samples lack anthropogenic contamination and give us the ability to examine samples within the geological and stromatolite morphological context. Analysis demonstrates mature hydrocarbons are present in the calcite of the stromatolites, with *n*-alkanes, monomethylalkanes, acyclic isoprenoids ($<C_{21,}$) cyclohexylalkanes, cheilanthanes, hopanes, steranes and aromatic steroids, consistent with the results of Brocks et al. (2003) on drill cores and inconsistent with any recent organic matter overprint. Hydrocarbon signatures vary with each stromatolite locality. It is therefore unlikely that widespread oil migration in the Archaean, prior to metamorphism and closure of the porosity at 2.2 Ga (Macfarlane et al. 1994), was responsible for the hydrocarbons. Slice-style experiments demonstrate the absence of biomarkers in the outer section of the stromatolite samples, with a suite of biomarkers present in the inner slices. These lines of evidence suggest that the Tumbiana Formation stromatolites contain syngenetic hydrocarbons that will help constrain the timing of the origin of oxygen production prior to the Great Oxidation Event.

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The evolution of sterol biomarkers in the Proterozoic

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Molecular fossils are organic compounds that can be extracted from sedimentary rocks and traced back to a specific biological source. The most common biomarkers for eukaryotic organisms in bitumen and oils are the sterane homologues cholestane, ergostane and stigmastane that possess 27, 28 and 29 carbon atoms, respectively. Steranes are the fossil analogues of sterols that function as membrane rigidifiers. Steranes are stable in geological systems for millions of years and their presence in sedimentary rocks can provide information on the abundance and diversity of eukaryotes through geological time, particularly in strata where conventional microfossils are absent or poorly preserved.

Previous studies have shown that the relative concentration of different steranes changes systematically throughout the Phanerozoic (< 542 Ma), a trend probably caused by the radiation of successive groups of primary producers such as diatoms, dinoflagellates, and coccolithophorids in the oceans [1]. However, in the late Neoproterozoic (~635–542 Ma) sterane ratios are generally significantly different from the Phanerozoic and appear to be diagnostic of their age [2]. This shift in relative lipid abundances is expected as the fossil assemblage of eukaryotic organisms changes dramatically across the Precambrian-Cambrian boundary (542 Ma). It is unusual however, that published sterane ratios from even older rocks (~1,700–635 Ma) are almost identical to Phanerozoic values, despite the fact that eukaryotic microfossils from this interval are rare and unusual [3].

Proterozoic rock samples are usually more mature than Phanerozoic samples and indigenous steranes are less abundant. Therefore, even traces of contamination may mask indigenous components, providing potentially misleading results. Petroleum products used in the drilling and storage process such as lubricants, plastic liners, drilling fluids and diesel fuel may contain phanerozoic hydrocarbons such as *n*-alkanes and steranes which may contaminate the surfaces of drill core [4]. We hypothesised that surficial contamination from Phanerozoic hydrocarbons may have altered previously published sterane distributions. To test this hypothesis, 23 Proterozoic samples (~1.9–0.54 Ga) which had been reported in the literature to contain steranes were reanalysed using an RSES-developed microablation system that separates potentially clean rock interiors from exterior surfaces.

To assess whether steranes are indigenous, the interior extract of each sample was compared with the hydrocarbon distribution on the exterior. Steranes that are exclusively detected on rock surfaces, but not in the interior, are evident contaminants. However, we have observed that hydrocarbons can infiltrate even compact rocks, and so the removal of rock surfaces is commonly not sufficient to eliminate allochthonous molecules. We tested the permeability of rock samples to hydrocarbon infiltration by looking for branched alkanes with Quaternary carbon centres (BAQCs) in the rock's interior. These molecules do not occur naturally and are derived from polyethylene sample bags [4]. All rocks analysed in this study had trace amounts of BAQCs on the surfaces, and ~75% had been infiltrated by anthropogenic hydrocarbons. Less than 25% of all samples had a clean interior, and from these we were able to extract clearly indigenous steranes. The results of this study indicate that micro-ablation is an efficient method of removing surficial contamination from rock surfaces, and the assessment of BAQCs is an effective tool to recognise and eliminate samples that were infiltrated by contaminants. This emphasises that the study of low-concentrated biomarkers in organically lean or thermally highly mature samples is only possible after comprehensive evaluation of contaminants.

The ratios of steranes in the samples that yielded indigenous signals were entirely different to the distributions described previously in the literature. Instead of Phanerozoic-like distributions which describe environments dominated by algae and plant debris, the indigenous Proterozoic sterane record suggests that eukaryotes did not play a significant role until the late Neoproterozoic. In contrast to the previously published record, the new sterane ratios and concentrations appear to be compatible with the Proterozoic body fossil record. Simple eukaryotes are only present in low abundance in the mid-Proterozoic (~1.2–0.85 Ga) and begin to diversify and increase in number during the middle of the Neoproterozoic to the beginning of the Phanerozoic.

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Assessing microbial diversity during the deposition of a Neoproterozoic (c.800 Ma) saline giant: evaporites as an archive for Precambrian halophiles

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We present the first molecular investigation of the biotic composition and biogeochemistry of an evaporitic, hypersaline environment from the mid-Neoproterozoic (c.800 Ma). Through detailed analyses of both sedimentary textures and their lipid biomarkers, we provide the oldest evidence of organisms that could exist at extremely saline conditions. In addition, we provide confirmation for the syngeneity of these molecules and demonstrate the ease with which hydrocarbon contamination can alter the indigenous biotic signal. Such research is timely, since the discovery of evaporite deposits on Mars highlights the need to understand their capacities as biological archives.

Samples for this study were derived from evaporitic sediments of the Neoproterozoic Bitter Springs Formation, Amadeus Basin, central Australia. Due to the broad shallow nature of the basin and a tenuous connection with the ocean, the water was characterised by elevated salinity levels during that time. As a result, very thick (100 m to >2000 m) evaporite units were deposited [1]. All samples for this study were derived from drill cores held at Geoscience Australia (Canberra) and at the Northern Territory Geological Survey at Alice Springs.

We extracted biomarkers from evaporitic sediments composed of dolomite, anhydrite and/or halite. The dolomite layers commonly assume the shape of microbial mat-like formations that exhibit roll-up structures and tearing. Pyrite was commonly associated with the dolomite. Full scan gas chromatography-mass spectrometry (GCMS) of the saturate fractions revealed high ratios of mono- and dimethylalkanes relative to *n*-alkanes. Such a pattern is typical of Precambrian and Cambrian samples and observed in a number of facies settings. However, indigenous biomarker signals both hopanes and steranes are absent in these samples. This observation is in direct contrast to previous studies of Neoproterozoic sedimentary rocks from the Amadeus Basin [2], where these molecules are purported to be present.

An outstanding characteristic of these evaporites are the presence of several pseudohomologous series of both regular (to C_{25}) and irregular (to C_{40}) acyclic isoprenoids. The relative concentrations of these molecules vary and depend on the mineralogy of the host rock. Indeed, concentrations of these molecules were observed to vary within millimetre scales, depending on the textural characteristics of the sedimentary rock. We interpret the isoprenoids as the oldest evidence of haloarchaea in the geological record, which can be developed into salinity proxies.

Based on these results, we present an ancient and extreme, saline environment dominated by prokaryotes. Furthermore, we show that the presence of exceptionally well preserved biomarkers in anhydrite ($CaSO_4$), despite the fact that sulphate and biomarkers are thermodynamically not stable together, raises the prospect of finding biomarkers in sulphate deposits on Mars.

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STREAM 01TC (TOPICAL: PALEOMAGNETISM)

How does Chinese loess become magnetised?

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The laterally extensive and thick Chinese loess deposits represent one of the world's most outstanding terrestrial archives of paleoclimate change. These deposits have also been extensively studied to obtain high-resolution records of geomagnetic field behaviour. Despite nearly three decades of paleomagnetic research on the extensive Chinese loess deposits, a convincing explanation has yet to be developed for how Chinese loess

becomes magnetised. To address this problem, we conducted re-deposition experiments using weakly consolidated Holocene Chinese loess that was disaggregated in the laboratory, and we compare our results with published paleomagnetic data. We simulated a depositional remanent magnetisation (DRM) associated with dry deposition of eolian sediments, and a post-depositional remanent magnetisation (PDRM) in which the sediment was water-saturated after deposition. The simulated DRM faithfully records the declination of the applied field, but with systematic inclination flattening. Addition of minor water slightly improves recording of the applied field, but inclination flattening persists. Reliable recording of the applied field occurs for PDRM simulation in water-saturated sediment. Our synthesis of paleomagnetic data from Chinese loess indicates that time-averaged paleomagnetic directions are often indistinguishable from the expected geocentric axial dipole (GAD) field, but in many cases inclinations are shallower than for a GAD field. We conclude that the Chinese loess is magnetised by a combination of DRM and PDRM mechanisms, with water content providing the dominant control on which mechanism aligns the detrital mineral fraction. Where pedogenesis causes neoformation of magnetic minerals, an additional chemical remanent magnetisation (CRM) will occur. The magnetisation of Chinese loess therefore appears to be controlled by a complex time-varying combination of DRM, PDRM and CRM mechanisms. This potentially complex interplay among paleomagnetic recording mechanism(s) reinforces the need for caution when interpreting paleomagnetic records from the Chinese loess.

A heretic view of the Alice Springs Orogeny: Australia-Asia collision and tectonic extrusion

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Paleomagnetic results from the ignimbrite-rich Carboniferous succession of the western and south-western Tamworth Belt, Southern New England Orogen (SNEO), eastern Australia, show a northward excursion over about 30E of latitude with a middle-late Visean peak. The excursion can be seen also in paleomagnetic data from the Australian craton and the Tasman Orogenic System (TOS) and may have started in Early Devonian. By middle-late Visean, the promontory of the Australian craton in central New Guinea reached latitudes of 30E-40EN, well within the paleolatitudinal range of the Central Asian Orogenic Belt (CAOB) of southern Laurasia. Devonian-Carboniferous convergence and collision of Australia, as part of north-eastern Gondwana, with the CAOB and closure of the Paleoasian Ocean, is proposed as the cause of contemporaneous, Variscan, tectonism throughout the ocean's northern and southern margin and hinterlands. That is throughout the CAOB of southern Laurasia and throughout Australia, as exemplified by the Alice Springs, Quilpie and Kanimblan Orogenies and probably also the Tabberabberan Orogeny. Convergence-related compressional deformation of Australia was confined to a 'compression box', extending southward from the central New Guinean cratonic promontory and bounded by the Lasseter Shear Zone in the west and the future East Australian Rift System in the east. Convergence-driven north-south compression, weak, heated, crust in the Larapintine Graben and in the oceanic basement of the TOS, and the 'free' oceanic boundary of the Paleopacific, constituted Variscan Australia-Asia conditions that were comparable to the Cenozoic India-Asia indentation and extrusion process. Tectonic extrusion of ductile lower crust and partial melt from the Larapintine Graben caused eastward displacement of the Thomson Orogen and the Northern New England Orogen (NNEO), perhaps in association with Paleopacific rollback. Upper crustal displacement was bounded in the north by the Diamantina River Lineament-Clarke River Fault Zone, and in the south, more complexly, by the Darling River/Cobar-Inglewood Lineaments and Cato Fracture Zone, and by the Lake Blanche-Olepoloko Fault Zones and Lachlan Transverse Zone. The tectonic extrusion hypothesis offers new avenues for interpreting the Late Paleozoic evolution of Australia: (i) Different tectonic grains of the Alice Springs Orogeny (E-W) and the Quilpie and Kanimblan Orogenies (N-S) represent different effects of the Australia-Asia convergence and collision on the brittle upper crust and on the ductile lower crust. In the upper crust, direct transmission of north-south compression led to the Alice Springs Orogeny of east-west tectonic grain. In the lower crust, hydraulic fanning out of north-south compression toward alignment with the east-west pressure gradient near the free boundary of the Paleopacific led to the Quilpie and Kanimblan Orogenies of north-south tectonic grain; (ii) Surface wave tomography shows continental-like velocities and east-west fanning of azimuthal anisotopy in the lower crust/upper mantle of the internal TOS, interpreted to trace lower crustal tectonic extrusion from the Larapintine Graben; (iii) Prominent negative magnetic anomalies in the Larapintine Graben and the TOS are interpreted to represent hematite-residing 'Kiaman' reverse polarity remanences in the lower and upper crust that outline the lower crustal flow; (iv) The extent of the latter may be outlined further by mapping the extent of seismically highly reflective lower crust, assuming that its planar anisotropy reflects horizontal ductile flow rather than vertical magmatic underplating; (v) The widespread Namurian sedimentary lacuna may represent

thermal expansion resulting from lower crustal ductile flow, with denudation products transported from the elevated 'compression box' into the non-elevated New England Orogen (NEO) and western Australian basins; (vi) Formation of the Kanimblan Highlands during Late Carboniferous may reflect this thermal expansion process, with latest Carboniferous and Permian thermal relaxation leading to its demise; (vii) A Late Carboniferous heat flux may explain the fission track and low-temperature isotopic disturbance record, without a requirement for extensive burial and denudation; (viii) A Stephanian change to clockwise rotation of Gondwana caused northward telescoping of the SNEO against the eastward-displaced buttress of the NNEO. Telescoping was facilitated by structural detachment of the SNEO from the Lachlan Orogen along the East Australian Rift System and led to formation of the Texas-Coffs Harbour and Manning Oroclines.

Magnetic overprinting of the Brachina Formation/Ulupa Siltstone, Southern Adelaide Foldbelt, prior to Delamerian deformation

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The Proterozoic sediments of the Adelaide Geosyncline were deformed and metamorphosed during the Ordovician Delamerian Orogeny. In the Flinders Ranges, the relatively unmetamorphosed sediments, though iron-rich, are only weakly magnetic. In the Mount Lofty Ranges, where peak metamorphic grades were reached, the Brachina Formation and its equivalent, the Ulupa Siltstone, are extremely magnetic and cause prominent linear magnetic anomalies with amplitudes of 100 to 500 nT that can be traced for 50 km or more. The higher metamorphic grades are accompanied by the growth of metamorphic magnetite parallel to sedimentary layering. These magnetic markers have been used to trace the macrostructure of the Southern Adelaide Foldbelt and have been especially useful where outcrop is limited. The amplitude and character of the magnetic anomaly change significantly along strike. This is basically a function of varying metamorphic grade as anomalies at lower grades can be successfully interpreted assuming induced magnetisation only (since both depth and dip are often known). At the highest grade, where the rocks are andalusite schists, the magnetic anomalies are inconsistent with magnetisations in the direction of the present magnetic field, and remanence causes the greater component of the anomaly. The results of a rock magnetism study show a close correlation between metamorphic grade and the variation in magnetic mineralogy and natural remanent magnetisation. The rocks display multiple components of NRM including a weak primary detrital component acquired during deposition and a much stronger thermal or chemical component acquired prior to deformation due to the Delamerian Orogeny. This secondary NRM component is similar to that of the nearby Black Hill Norite which is believed to have intruded during the waning phases of the Delamerian Orogeny. We therefore have magnetic signatures that bracket the Delamerian Orogeny.

The preliminary mean NRM direction for the Ulupa Siltstone, corrected for tilt, from 40 samples is Dec = 228.1°, Inc = 39.5°, α_{95} = 5.8° and the corresponding pole position is latitude λ_p= 46.5°S, longitude ϕ_p = 45.5°E, dp = 4.1°, dm = 6.9°. No directions of opposite polarity were found. The results of the rock magnetism study have been interpreted in terms of the geologic history of the Ulupa Siltstone and have been used in the interpretation of the aeromagnetic anomalies it causes. The study demonstrates the application of rock magnetism to aeromagnetic interpretation.

Magnetic characteristics of the Hiltaba Suite granitoids and volcanics: Late Devonian overprinting and thermal history of the Gawler Craton

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The ~1590 Ma Hiltaba Suite Granitoids (HSG) and comagmatic Gawler Range Volcanics (GRV) occur in the central Gawler Craton of South Australia. The HSG and GRV can be divided into an oxidised Olympic Dam type containing hematite and magnetite, and a less oxidised Kokatha type that tends to contain ilmenite and titanomagnetite. Magnetic properties of the HSG and GRV have been investigated using standard rock magnetic and palaeomagnetic methods to assist in mineral exploration. The predominant magnetic phase is pure end-member magnetite, in both the Olympic Dam types and the Kokatha types, except for a minor amount of titanomagnetite present in the Kokatha type Black Yardea Dacite. The most prevalent characteristic remanent component observed in the GRV is directed upward to the north-east. A palaeomagnetic fold test applied to the western flat lying volcanics and steeply northward dipping volcanics at Uno, to the south east, is

strongly negative, indicating that this characteristic remanence is an overprint. Rock magnetic properties indicate that the remanence of both types of GRV is carried by sub-optimal multidomain magnetite particles. Such grains are not capable of retaining primary remanence when subjected to even mild reheating on burial. The magnetisations have been reset as the crust cooled after peak temperatures probably due to the Alice Springs Orogeny. The *in situ* mean direction, not corrected for tilt, from 69 samples is Dec = 22.6°, Inc = -44.9°, α_{95} = 6.9° and the corresponding pole position is latitude λ_p= 69.5°S, longitude ϕ_p = 36.1°E, dp = 5.5°, dm = 8.7°. No directions of opposite polarity were found. No consistent remanence was found in either type of the HSG.

The pole position from GRV is consistent with other Australian palaeopoles from rocks of about 360–370 Ma. The GRV and many other rock units of the Gawler Craton have been remagnetised during the Late Devonian. Fission track studies have yielded a mean age of 331 ± 30 Ma for 13 apatites from the Gawler Craton, leading to the conclusion that the Gawler Craton was at an elevated temperature in the late Palaeozoic, before rapid exhumation that cooled the craton, blocking the magnetic remanence, after the Alice Springs Orogeny. A slightly younger age for apatite fission tracks (AFT) of ~330 Ma is consistent with the magnetic remanence being blocked earlier, ~360–370 Ma, at somewhat higher temperatures (> 200°C) than the apatite track retention temperature (100 ± 20°C).

SESSION 01RD (RESOURCES)

Alunite: internal textures, compositions, and their implications for exploration and alteration—mineralisation processes

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Lithocaps are characterised by advanced argillic alteration blankets above progenitor intrusions. Lithocaps have attracted a lot exploration attention, as lithocaps may host high-sulphidation (HS) epithermal mineralisation and the causative intrusions typically also have associated porphyry-style mineralisation. Lithocaps are typically large, some over 40 km^2. Their large size makes lithocaps easy to find and the large volume of alteration indicates large hydrothermal systems, which entice explorers to spend capital and time on them. However, exploration within big lithocaps has been very difficult, largely due to the lack of recognised mineralogical, textural or geochemical zoning patterns.

Alunite is a common mineral in lithocaps and it can contain many major and trace elements, therefore it has great potential for exploration and for revealing the underlying alteration-mineralisation processes. In this study, we investigate the internal textures and compositions of alunite samples from the Mankayan district, Philippines, where the genetic relationship between the Lepanto lithocap—HS mineralisation and the Far South-east porphyry has been well studied. Research methods applied include backscattered electron (BSE) imaging, cathodoluminescence (CL) imaging, energy-dispersive spectrometry (EDS), microprobe, PIXE imaging and quantification, and laser ablation—inductively coupled plasma—mass spectrometry (LA-ICP-MS) trace element analysis.

The alunite samples studied are coarse-grained (>120 microns) and most of them have flaky, euhedral shapes, indicating they are hypogene. BSE and CL imaging revealed that regular oscillatory zoning is common in alunite. The zoning is mostly due to variations in Na and K contents. Some alunite grains have cores with chaotic patchy zoning patterns, which may indicate early rapid growth. The outer zones of some grains are partially obliterated or have cross-cutting patterns, indicating minor post-formation modifications or dissolution-redeposition. Both BSE and CL imaging show the same textures, although some features are better illustrated by one type of imaging. Sub-micron holes are present locally, in some cases confined within certain zones or in other cases unrelated to zoning, as revealed by BSE imaging. Such locations are blurry and lighter on CL images. These holes are interpreted to represent fluid inclusions. Solid inclusions are also present in some alunite grains; they are mostly fine-grained (< 5 microns) quartz, rutile and pyrite. One enargite inclusion was found by PIXE using 3 MeV protons, which can penetrate beneath the sample surface; it was related to a fracture in the host alunite. Aluminium phosphates sulphate (APS) minerals up to about 50 microns are present in some alunite grains; they are typically but not always in the cores.

Despite zonation, the overall composition variation in a single grain or in grains from the same sample is typically small compared with the differences between samples from different locations; the latter vary from near end-member alunite to natroalunite compositions. PIXE studies revealed zones of elevated Pb (up to ~4000 ppm), Sr (up to ~5000 ppm), Zn, As, Ga and Ba in alunite, confirming that anomalously high values of these elements obtained in LA-ICP-MS analyses are intrinsic to alunite, not from inclusions. Zones rich in Pb and Sr are common and are typically mutually exclusive, but in zones with elevated P contents, both may be higher. Some APS grains also have high concentrations of both Pb and Sr. Concentrations of Cu and Au in alunite are very low, either at background level or below detection limits.

Alunite forms under acidic conditions and hypogene alunite has been interpreted to be related to acidic hydrothermal fluids caused by the condensation of magmatic vapours (e.g., HCl, SO_2). The lack of Cu and Au in the alunite indicates that these elements were not present in significant concentrations in magmatic vapours at Mankayan. Some elements, e.g., Pb, Zn and Sr, are not typically transported in vapours and are believed to have sourced from the dissolution of pre-existing rocks by acidic fluids. The presence of Pb, Sr, Zn, As, Ga and Ba in the alunite lattice, particularly Pb and Sr, indicates that these elements may be used as vectors towards the intrusive source. At Mankayan, it has been found that Sr in alunite increases in samples closer to intrusive centre whereas Pb decreases.

Pyrite-based LA-ICPMS trace element and sulphur isotope delineation of a sidewall convection system at the Hellyer VHMS deposit, Tasmania

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The well preserved Cambrian Hellyer VHMS orebody has received substantial geological and geochemical study, showing that the deposit formed as a discrete body overlying a narrow fault system within coherent andesite flows. The lead-zinc sulphide ores are topped with silica-barite, which is strong evidence that the overlying water column had a redox state buffered by sulphate. Unsurprisingly, this geological situation resulted in a narrow highly zoned alteration pipe, collectively known as the SEZ (Stringer Envelope Zone) which extends at least 700 m below the ores, and which has a stable ~7‰ $\delta^{34}S$ composition, similar to the ore values (Gemmell & Large, 1993). Gemmell & Large (1993) and Solomon (unpublished data) recognised the presence of isotopically heavy footwall sulphur (20–30‰) immediately beyond the SEZ, in propylitically altered volcanics. This is widely acknowledged to have resulted from local hydrothermal seawater sulphate reduction, implying a local circulation system in the region of the high temperature focused hydrothermal discharges. Our study examined the nature and extent of this circulation system.

A 1.5 km long, footwall section (10500N) based on 6 drillholes was obtained to the west of the Hellyer Pb-Zn-Ag deposit, at right angles to the feeding Jack Fault. The sulphur isotope sampling consisted of wholerock, conventional and LA-based analyses, and a smaller group of samples were chosen to obtain a pyrite trace element section (~140 analyses). The section is dominated at its western (most distal) end by pyrite interpreted to have grown during seafloor weathering ($\delta^{34}S$: -10–+5‰), grading eastwards at ~700 m (from ore) to pyrite in propylitic alteration with $\delta^{34}S$ > 15‰. A third key pyrite type ($\delta^{34}S$ = 6–9‰; Gemmell & Large, 1993) occurs in the core of the visible Hellyer alteration pyrite. The highest $\delta^{34}S$ values (>25‰) occur in a 100 m wide rib that parallels the form of the stringer envelope and occurs ~80m from the SEZ.

Pyrite within 500 m of ore is strongly enriched in Sb and depleted in Bi compared to pyrite in distal seafloor weathered rocks. Sb/Bi > 2 in pyrite places explorers within 500 m of the Hellyer ore zone, and increases towards ore, so that it is a tool that appears to be useful within the 15‰ S isotopic anomaly. Increasing Tl, and decreasing Ag, Mn, Pb and Cu, provide vectors towards ore within the propylitic alteration zone. Sb and Tl are positively correlated with $\delta^{34}S$ value, and most likely formed directly from heated seawater adjacent to the Hellyer pipe. Bi, Cd, Pb, Zn, U, Mo and Ag are all preferentially concentrated in the seafloor weathering-related pyrite, with a very sharp increase in their values in pyrite with $\delta^{34}S$ < -4‰. Although some of these elements (Pb, Ag, Zn) are also very enriched in some ore pyrite, all other criteria indicate that these pyrites are not close to an ore zone. Overall, these geochemical patterns are interpreted as the results of gradually stripping convecting seawater of chalcophile elements during heating and inorganic seawater sulphate reduction. The convection system is theorised to have been driven by conductive heat from the main hydrothermal discharge, transecting the porous andesite package.

Combined sulphur isotope and LA-ICPMS pyrite data appear to provide very robust tools to explore regionally altered seafloor rocks that have very minor pyrite concentrations, that otherwise attract little attention from explorers. The key point is that such rocks up to 1.5 km away from a major VHMS system can contain geochemical data that is diagnostic of the presence of a hidden orebody. In contrast, major element chemical vectors at Hellyer (typically used by explorers in VHMS terrains) extend only ~250m laterally from the alteration pipe.

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Reduction of oxidised arc basalts: a new model for magmatic sulphide genesis in arcs

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Magmatic sulphide deposits are generally considered to be the product of continental rifting. However, there are a number of small deposits found in arcs. Because there have been few deposits found in these regions, the possibility of magmatic sulphide formation in this environment has received little attention. The perceived lack of magmatic sulphide deposits these regions feeds back into industry exploration strategy such that there is no targeted exploration in these regions, which in turn confirms the premise, since no new deposits are found. However, we do know that arc magmas are metal rich, because porphyry Cu-Au deposits form in association with intermediate arc magmas, and some of these contain elevated concentrations of PGE. So one might ask the question as to why magmatic sulphide deposits are not found in arcs; or, perhaps they are more common than we thought.

It is well known that sulphur saturation in silicate magmas causes exsolution of immiscible sulphide melts, which partition and concentrate chalcophile elements as segregation progresses. Many intrinsic melt properties affect sulphur solubility in silicate melts: temperature, pressure, SiO_2 content, and FeO content are among the most well characterised. Oxygen fugacity (fO_2) also has the potential to affect sulphur solubility, but has not yet received the same attention. Recently it has been found that the solubility of sulphur in mafic magmas changes from ~ 0.15% to ~1.5% (an order of magnitude) between melts with $fO_2 \leq$ FMQ + 1 and those with $fO_2 \geq$ FMQ + 1, respectively (Jugo et al., 2005). This solubility gap is thought to represent the change from sulphide to sulphate stability, with sulphate more soluble than sulphide (Jugo et al., 2005). Arc basalts are, in many cases, oxidised and sulphur-rich. The 1991 Pinatubo eruption, for example, discharged the largest SO_2 gas cloud ever measured and the sulphur in this eruption has been linked to highly oxidised magmatic sources (Kress, 1997). We therefore hypothesised that if it were somehow possible to take an oxidised arc basalt, with very high concentrations of dissolved sulphur as sulphate, and reduce it into the sulphide stability field, this would cause extreme sulphide oversaturation, possibly leading to ore deposit formation. To investigate this hypothesis we studied the Hidaka Metamorphic Belt in south eastern Hokkaido, Japan. Here, a near-complete cross section of arc crust is exposed, with large mafic igneous complexes preserved at deeper levels. Magmatic sulphide mineralisation is developed within one of these complexes (the Opirarukaomappu Gabbroic Complex; OGC) at the southern end of the Hidaka Belt, which preserves a record of crustal contamination of mafic magmas via assimilation and magma mixing involving introduction of tonalite. Estimates of the proportion of assimilant added were obtained by AFC modelling, ternary mixing, and Nd isotope systematics, which generally offer similar mixing percentages. The ternary mixing and Nd isotope estimates place mixing at 15–30% and 20–37%, respectively. AFC modelling estimates combined mixing and fractional crystallisation at 25%. Magmatic sulphides and associated gabbros at this locality contain graphite (which would set the oxygen fugacity at the C-CO buffer), with a carbon isotope signature identical to that of the surrounding partially melted carbonaceous shales, indicating that graphite was added through the assimilation process. Sulphur isotope data suggest sulphur was also added from crustal sources during assimilation and magma mixing. The magmatic processes that occurred in the OGC show that input of oxidised sulphur-rich arc basaltic magma into a segment of deep arc crust that contains carbonaceous metamorphic rocks can drive partial melting of that crust, allowing subsequent mixing with felsic magmas with high reducing potential. Addition of graphite to the mafic magma by this mechanism can potentially lead to a dramatic drop in oxidation state causing extreme sulphide oversaturation and onset of ore deposit formation. Magmatic sulphide deposits that form by this

mechanism are more likely to be developed in the deep arc crust where magma mixing and mingling is thought to be a widespread phenomenon.

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The behaviour of chalcophile elements in evolving back-arc basins

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The spatial relationship between Au-Cu-rich sulphide deposits and convergent margin magmatism is well established, however the reason for this association is unclear. The study of Au ores themselves has given little clue to the earliest stages of the concentration process. Previous studies have shown that during melt evolution in a crustal magma chamber, the concentrations of Cu and Au increase with increasing SiO_2 until 60 wt. % SiO_2, at which point they suddenly decrease (Sun et. al., 2004). The cause was suggested to be Au loss in a fugitive volatile phase triggered by magnetite saturation and accompanying redox changes in an evolving crustal magma chamber, but this hypothesis remained untested by other observations. We present a more comprehensive geochemical data set for volcanic glasses from the Eastern Manus back-arc basin, including Ag, Pt, and the key element Se and compare this information with our data base of MORB analyses.

Se, a proxy for S, whose magmatic concentrations are not disguised by syn-eruption, late-stage degassing, shares the abrupt decrease with Au, Cu, and Ag. Petrologic modelling reveals the amount of magnetite fractionation is sufficient to convert most of the S originally dissolved in the magma as sulphate to sulphide, triggering saturation in a Cu-rich crystalline sulphide mineral, probably bornite (ideally, Cu_5FeS_4). The Cu-rich sulphide mineral sequesters Au and Ag, elements with the same valence as Cu in sulphides, but not other traditionally chalcophile elements such as Ni, Re and Pt. This mechanism of Au concentration requires specific conditions, the occurrence of which provides a pre-enrichment step to the formation of economic Au-Ag-Cu provinces. The ore-metal abundances in the mantle source of the parental Eastern Manus basalts are similar to the sources of mid-ocean ridge basalt (MORB), so the Cu-Au-rich characteristics of the province requires no enrichment from subducted material. Instead, the association of major Cu-Au deposits with convergent-margin magmatism results from a specific enrichment event during magmatic evolution under oxidising conditions.

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SESSION 01ED (ENVIRONMENT)

Coral and speleothem reconstructions of ocean-atmosphere dynamics in southern Indonesia during the 8.2 ka event

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A variety of natural archives have been interpreted as indicating major changes in the strength of the Australasian monsoon and ENSO through the Holocene. Geochemical tracers in coral skeletons are particularly well suited for reconstructing coupled ocean-atmosphere climate systems at seasonal to interannual timescales. The high temporal resolution offered by corals is especially important to study the variability of parameters such as sea surface temperature (SST) and the hydrological cycle on ENSO-monsoon timescales.

However, most coral studies have focused on the past millennium because coral aragonite is prone to diagenesis, and it is difficult to find pristine corals in the early to middle Holocene when the monsoon and ENSO may have been quite different from what we know today.

Here, we present preliminary results from the analysis of several well-preserved massive *Porites* corals from Alor (southern Indonesia), with U-series ages of 8.5 to 7.9 ka (thousand years ago). These corals have the potential to help resolve outstanding questions about the mechanisms and drivers of changes in the Australasian monsoon and ENSO before, during and after the so-called 8.2 ka 'cold event'. Therefore, the principle goal of this study is to explore how the climate of southern Indonesia changed in response to the 8.2 ka event.

In the first instance, we performed stable isotope ($\delta^{18}O$, $\delta^{13}C$) analysis of the corals at 5-year resolution to detect any changes in the mean climate state. Our records show a double cool/dry-snap with SSTs reaching minima at 8.3 and 8.0 ka. These rapid coolings (2–3°C in 30 years) are synchronous in time, length and strength with sharp increases in the $\delta^{18}O$ of speleothems from the nearby island of Flores.

Based on this result, specific periods have been targeted for high-resolution isotope analysis to document how ENSO and monsoonal rainfall change in response to abrupt changes in the mean climate state. With these high-resolution analyses, we were able to reconstruct the annual $\delta^{18}O$ cycle for several time periods during the modern time and the early Holocene (mean climate state, onset of the cold snap and the cold snap). These results show that during the early Holocene, the Australasian monsoon was weaker than today, but there is no real evidence for a weaker monsoon during the 8.2 ka event.

Thus, it appears that the 8.2 ka event in the Australasian region would have been only a cold event and not a dry one as suggested by previous studies.

Tropical western Pacific surface ocean circulation variability (1920–1984) as inferred from a high-resolution radiocarbon record of a Marshall Islands' coral

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The seasonal $\Delta^{14}C$ history of surface waters in and around Enewetak Atoll (RMI) in the tropical western Pacific has been reconstructed from a radiocarbon time-series of a coral. The water-masses that are part of the major regional climate-systems have diagnostic ^{14}C signatures. Corals directly record the ^{14}C signature of the water they grow in and therefore information about ocean circulation. Enewetak is located in an important transition zone between the tropics and subtropics and on the edge of the Western-Pacific Warm Pool. This record aids understanding of the El Niño-Southern Oscillation and Pacific Decadal Oscillation climate systems and the influence of surface ocean circulation on those systems.

During the 1940–60s large quantities of radiocarbon formed in the atmosphere as a result of nuclear testing in the Pacific. Interactions between the ocean and the atmosphere transmitted the 'bomb-pulse' to surface waters. The variation in ^{14}C levels of global water-masses after the 'bomb-pulse' provides valuable information about how the ocean and atmosphere have interacted since this time. Enewetak Atoll was a major nuclear testing ground during the 1940–50s and this is the first coral-radiocarbon record from within kilometres of a nuclear test site.

Did Port Phillip Bay nearly dry up between 2700 yr BP and 1000 yr BP—seabed channelling evidence, seismic and core dating

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Port Phillip covers an area of 1930 km^2 with a maximum depth of 24m. It has a large central muddy basin. In the south it connects to the ocean through narrow channels across the Nepean Bay Bar. Three new 1–7 km^2 PoMC multi-beam surveys of the bay floor reveal *in-situ* high-sinuosity 100m wide river-channel-like features recessed ~5m deep in the bay floor at -18 to -25m below present water level. This late Holocene channelling is demonstrably connected to the Yarra and Werribee Rivers. Where sub-bottom seismic lines cross these young channels, there appears less than 0.5m of marine? mud infill. Nearby C^{14} dated vibro-cores and sub-bottom

seismic data indicates the bay floor channels incise into older channel fill comprising > 4.0m of middle to early Holocene marine to non-marine mud grading down into non-marine late Pleistocene muddy sand, related to former courses of the Yarra and Werribee rivers during the last glacial low stand. In turn this late Pleistocene channelling incises more then 24m into sub-bottom acoustically refractive stiff clay of the mid-Pleistocene Fishermans Bend Silt.

Twelve new C^{14} shell dates indicate the top 5.0m of channel infill ranges from <423 to >8473 yrsBP, but a hiatus in the dates occurs at around the 0.5 m level between shell dates < 959 yrs BP and >2778 yrsBP. From seismic, the hiatus corresponds to the period when the younger channelling occurred, since ~1000 yrBP, 0.5m of shelly marine mud has been deposited over the central basin, and this post-1000 yrBP mud appears to veneer the bottom of the young channels. Therefore with a channelling age sometime between 2700–1000 yrsBP, the central basin down to -22m must have been sub-aerially exposed during the late Holocene, at a time when sealevels outside the bay were stabilised around the present level. Because >20m of subsidence in the last 1000 years seems unlikely, then alternatively the bay water became separated from the ocean over this period. This could happen if the shallow Nepean Bay Bar channels filled with sand blocking oceanic exchange. Because there is a high evaporation rate over the whole bay area (1980 figures quote -2.3 km^3/yr) compared to comparatively low river/rain input (1980 figures quote 2.7 km^3/yr) a 15% reduction in input would see evaporation and input equilibrate. Further reduction in input could see a net loss to bay water levels, if the disconnect to the ocean was maintained. Port Phillip would become an evaporating lake, the Yarra and Werribee rivers would meander and incise their courses across a progressively exposed muddy lake floor.

The abundance of fresh water dinoflagellates in core samples between ~8500–7000 yrBP indicate early Holocene fresh-water lakes existed in the bay when standard Holocene sealevel curves would indicate the bay should have been flooded by marine waters. Therefore the Nepean Bay Bar channels must have been initially blocked, delaying marine transgression into the bay by some 1000 years. Based on foraminiferal data in core, these channels eventually cleared and full marine conditions extended throughout the bay between 6000–4000 yrsBP. Towards the end of this period, bay levels appear to peak up to +2.0 m above present ocean level, inundating the swamplands of the Yarra delta. Between 2700–1000 yrBP the Nepean Bay Bar channels must have again blocked converting the bay into a receding lake falling to -22m. The diminished lake, if originally filled with saline marine water, may have become hypersaline. Palynology evidence for dinoflagellate blooms just before this period supports this view.

This history of differences between salinity and water levels in Port Phillip and the outside ocean would not be sustainable were it not for the aerially large and thick package of Pleistocene Bridgewater Formation aeolianite limestones that forms the 'bedrock' divide between the Nepean Bay Bar-Nepean Peninsula and the open ocean. Evidence for a 'fluctuating bay levels' scenario has widespread implications on Port Phillip's water balance, salinity, pre-European climatic events, aboriginal occupation their tribal boundaries and legends of bay flooding. Water inputs today are at present 15–20% lower than in 1980 as a result of the last 10 years of drought. This presents compelling support for maintaining bay connections to the ocean.

A 1,000 year rainfall record for SE Australia using speleothem hydrological proxies

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Cave drip water studies at Wombeyan Caves (34°19'S, 149°59'E) demonstrated a marked hydrochemical response to wet/dry (McDonald et al., 2004; 2007). Three 20th Century coeval active speleothems (WM4, WM6 and WM20) were geochemically analysed and changes in trace element and stable isotope values were related to the instrumental record. These climate-geochemical relationships were interpolated to two long-record speleothems (WM7 and WM9) which grew deeper within the same cave system.

Two major difficulties were encountered. Unlike other sub-annual/annual climate records derived from speleothems using trace elements (Treble et al., 2003; Johnson et al., 2006); stable isotopes (Treble et al., 2005; Johnson et al., 2006) and annual laminae (Borsato et al., 2007) where annual cycles were shown to be consistent, at Wombeyan frequent droughts perturb predicted rainfall patterns and rainfall variability is high. Here, droughts can span several years, or extend over winter, diminishing or obliterating the expected winter

recharge signal. Alternatively, wet summers can sustain 'unseasonal' high discharge and lessen the expected prior calcite precipitation (PCP) signal. Thus an annual wet/dry geochemical signal is often absent.

Secondly, due to the young age of the speleothems and very low uranium concentrations (~10 ppb) the use of U-series disequilibrium dating was ineffective to produce a robust chronology. Trace element cycle counting only gave the minimum age due to the non-expression of many cycles. The 14C bomb pulse was successfully defined in two modern stalagmites (WM4 and WM6) and maximum 14-C activity was around 134 per cent modern carbon (pMC) for both speleothems, indicating rapid transfer of 14-C from atmosphere, to soil, to drip water during the bomb-pulse period. A dampened 14C bomb pulse was detected in WM7 (where pMC_{max} was 112 per cent modern carbon) reflecting the greater degree of mixing within the thicker bedrock. Carbon-14 AMS analyses were utilised together with trace element cycle counting to obtain preliminary chronological control.

Despite these difficulties, palaeohydrological records using multiple proxies: Mg/Ca (aridity), P and Y (wet), $\delta^{18}O$ (dominant air mass and rainfall amount signals), and based on 14C ages were constructed for the longer-record, slower growing stalagmites. Over the last 1,000 years there have been several sustained episodes of wet/arid or highly variable phases. A sustained wet phase occurred ~ 900–1300 AD and followed by ~ 200 years of highly variable wet/dry conditions. From ~ 1500 to 1800 AD a dry phase is indicated. The last 150 years support a drying phase, but the negative IPO (1944–1978 [wettest period in 20thC]) is not indicated by a negative anomaly and further, sustained positive $\delta^{18}O$ anomalies in this period suggest that other factors maybe influencing this part of the record (temperature?). The $\delta^{18}O$ record indicates changing frequency from ~ centennial to pentadecadal time-scales in the longer-time scale oscillations. Within the longer-time scale oscillations, higher resolution (~ 2–5 years) variability is evident replicating the trend shown by modern annually resolved stalagmites at this site.

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SESSION 01SD (SOCIETAL: GEOLOGICAL HAZARDS)

Quantifying the risks of geological storage of CO2

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The majority of authoritative assessments of carbon capture and storage (CCS) agree that this technology will be an essential bridge to a sustainable energy mix and the avoidance of dangerous climate change. CCS is considered suitable for large, fixed sources of CO2 such as coal-fired power stations. Currently the major societal obstacles to the deployment of CCS are cost (largely associated with capture) and risk (largely associated with long-term storage, although transport of CO2 is also of concern).

The perceived geological risks of storage cover a wide range of scenarios, ranging from rapid, fatal leaks of large magnitude (the 'Lake Nyos' scenario), through damage to groundwater or hydrocarbon assets over a timescale of years, unwarranted issuing of carbon credits, and finally, on the longest timescales, the gradual

loss of CO2 back to the atmosphere. This is a concern because the construction of CCS infrastructure together with the capture, transport and injection of CO2 requires energy, and hence generates extra CO2. This factor limits the leakage rate that is climate-neutral for a fixed energy consumption scenario. Integrated CCS and climate models suggest that the leakage rate of geologically-stored CO2 has to be below approximately 0.1% per annum of the total stored volume and preferably an order of magnitude lower than this value.

With CCS in its infancy, and relevant data exiguously sparse, it is imperative to identify methodologies to proceed with risk assessment at CCS sites. This paper provides examples of the various mechanisms of concern, though all are hypothetical. The main geological risks include unidentified leaking faults, unforeseen migration to leaking faults, or unexpected permeable zones in an otherwise sealing lithology. However these risks are considered low and their effect is expected to spread over centuries, rather than be catastrophic.

Three elements of the risk assessment process are considered: data assembly, data elicitation, and data integration.

Data assembly refers to the gathering of as wide a range as possible of relevant or analogous data. Natural CO2 reservoirs are an obvious analogue. Relevant data include seismic records for specific storage sites. The petroleum industry has wide experience with the use of CO2 in enhanced oil recovery, and the types and rates of accidents associated with that activity can be analysed. Natural gas is stored underground at many sites world-wide and data from those sites are also available.

Data elicitation (the analysis of risk) in CCS relies primarily on attribution of event probabilities, which, as in other assessments of natural hazards, relies on expert opinion. The elicitation process thus has to be treated with great care, as there is a common tendency for 'groupthink' and convergence of opinion, even when objectively, the uncertainties remain high.

Finally we discuss the methods that are available for integrating data to arrive at a risk assessment. Many are based on probabilistic techniques, for example Bayesian networks or Monte Carlo modelling of so-called Features, Events and Processes. Logic trees are also used, as are methods based on three-valued logic. All of these methods however, insofar as they deal with long-term geological risk, are only as good as the underlying geological information and intuition that goes into their construction.

Constraining dryland salinity hazard in the Lithgow Valley, NSW

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Some landscapes immediately west of the Blue Mountains, NSW, have dryland salinity, soil sodicity and similar natural resource management (NRM) hazards manifesting in localised parts of the landscapes in patterns that do not initially appear straightforward to explain. Early work in the Capertee Valley (Moore *et al.* this meeting) using a whole-of-catchment, multidisciplinary landscape characterisation, successfully identified the stratigraphic, geomorphologic and hydrogeologic controls on the location of these problem areas. In the Capertee Valley land use is dominated by farming and the main infrastructure takes the form of small villages, roads, local utility supply networks and farm constructions. The nearby Lithgow Valley, western Blue Mountains, NSW, has similar geology and geomorphology, but by comparison has significantly greater infrastructure development. This includes: the large town of Lithgow and a number of other villages and rural properties; significant industrial buildings and plant, mostly associated with coal extraction and processing; and, major road networks and utility supply networks. In addition these areas are incredibly scenic and form part of the greater Blue Mountains tourist area. An analysis of the hydro-geological landscape (HGL) characteristics of the Lithgow Valley was undertaken to better understand the NRM risk in this area.

Early observations indicated that the mobility of natural salts in the Lithgow Valley was relatively low compared to other catchments in this area. However, an improved understanding of regolith distribution, hydrogeological pathways, land use, vegetation and natural salt stores in this landscape, has enabled division of the catchment into eight discrete hydro-geological landscape (HGL) units. A conceptual model has been constructed for each unit to indicate how and why salt is expressing in some parts of this landscape and in surface and subsurface waters, and not in others. Geologically this Valley straddles the contact between Permian sedimentary rocks of the Sydney Basin, and older, dominantly Devonian granitic rocks of the Lachlan Fold Belt. Consequently, the landscapes to the north and west of the catchment have different protolith,

regolith and relief configurations than the classic sandstone escarpment and broad valley floor configuration of the Blue Mountains.

The main patterns revealed in the data are that: in northern part of the catchment, in the Angus Park area there is moderate land salinisation; and at Pipers Flat moderate land salinisation and moderate salt export to streams. Surface and groundwater flows are strongly influenced by the relief contrasts associated with sandstone escarpment and granitic range landscapes. In general the greater catchment typically shows a low level of salt concentration in surface waters, and soil sodicity does not present as severe a hazard in the Lithgow Valley as that observed in adjacent catchments.

Understanding vegetation assemblages in these landscapes, particularly in areas of flat-lying Sydney Basin sediments, has helped delineate regolith and hydrological features in nearby catchments. This approach was also used in the Lithgow Valley. One of the most outstanding findings of the study was the remarkable correlation between the HGL units defined using biophysical measurement and evaluation and the typical vegetation assemblages found in these areas. This finding may provide a useful spatial analysis tool in future.

Biophysical characterisation of this landscape using the HGL approach helps stakeholders recognise where, how and why salt is naturally expressing in landscape. It also provides a base level against which future land and water salinity concentration can be assessed, particularly in an area with ongoing peri-urban development, increasing population density in agricultural landscapes, and continued growth of the coal mining and processing, and other, industries.

Using the 'Coupled Human-Environment Systems Framework' for exploring issues of hazard and risk: if it is worth doing—do it properly

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Natural hazards can cause enormous loss of human life and damage to homes, infrastructure, lifelines, businesses, agriculture and those other elements that we, as communities, value—tangible and intangible. In spite of the rhetoric, disaster risk research is generally fractured into two relatively disparate academic ideologies—one embedded within the physical and engineering sciences that explore issues of distribution, frequency, magnitude and design for mitigation—the other led by the social sciences and humanities that deal with the many human dimensions of risk management. As valuable as these two forms of inquiry are, efforts to integrate the discipline-specific tools and languages will fail to achieve effective disaster risk reduction until they are meaningfully combined in a holistic framework that addresses the hazard problem in context. We use a variety of examples from the work of our centre and laboratory to illustrate how the 'coupled human-environment systems' framework provides robust guidance to assess, develop and implement disaster risk research and management useful for emergency risk managers.

Of particular note was the International Tsunami Survey Team set up to study the South Pacific tsunami of 29 September 2009. This was led and managed by our centre and reported directly to the Government of Samoa (GoS). This was an unprecedented scientific effort, setting a benchmark for future coordinated international post-tsunami science surveys that will support national early recovery efforts, and through tsunami research, improve tsunami mitigation and preparedness and so build a stronger resilience of coastal communities. By working together, we achieved outcomes much stronger and more valuable than any one of us could produce alone. For the first time, strong principles of professional conduct, mutual respect, collaboration, partnership, and concern for the welfare of the affected communities, were explicitly embedded in the work plan.

The South Pacific tsunami of 29 September 2009 resulted in loss of life and damage to human infrastructure and environmental systems. Common to many tsunamis, international scientists expressed the intent to undertake science assessments. Traditionally, these surveys, sometimes under UNESCO-IOC auspices, have been single-discipline, and conducted individually with moderate government coordination, so that afterward, the country was left with a large integration task to produce a single coherent study. This changed in Samoa, where an integrated and coordinated approach emerged.

The ITST-Samoa was comprised of more than 80 scientists (seismologists, geologists, engineers, social scientists, modellers) from Australia, Fiji, French-Polynesia, Italy, Japan, New Zealand and USA who

volunteered to work in collaboration with the GoS, Samoa Red Cross Society, Samoa scientists, and non-government representatives. They worked as one survey team to collect data and assist the GoS to prioritise short- and long-term risk reduction strategies. Their novel work (1) partnered with a regional university to include South Pacific expertise and with the GoS to ensure that (a) international scientists worked in a culturally-sensitive and appropriate way and, (b) outputs achieved were relevant to both GoS and ITST scientists; (2) was interdisciplinary and multi-sectoral to capture a thorough understanding; and (3) used a 'coupled human-environment systems framework' to examine vulnerability and resilience before, during and after the tsunami.

The ITST- Samoa succeeded because of (1) the scientists' strong desire to share their knowledge; (2) GoS's belief that science will improve disaster risk reduction practices; (3) immediate engagement of UN and regional organisations to provide an umbrella framework for working together; (4) local support to provide the ITST's command centre and; (5) dedicated Science Coordinators to manage the scientific planning, logistics, information sharing, and Report preparation.

In 2010, UNESCO/IOC will revise its Post-Tsunami Field Survey Guide to document ITST-Samoa best practices and so provide guidance for future International Tsunami Survey Teams.

It is all too easy to pay lip-service to conducting 'coupled human-environment systems framework' research. Having said that, it is not a task to be approached lightly, and involves an enormous effort to organise, manage, and be a part of—BUT the outcomes are significantly more relevant to a World that demands complex answers to complex questions as soon as possible. It s worth doing, and it is worth doing properly.

SESSION 01DD (DYNAMIC EARTH: INTRAPLATE AND PASSIVE MARGIN PROCESSES)

What is driving intraplate deformation in the Mount Lofty and Flinders Ranges, South Australia?

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The Mount Lofty and Flinders ranges represent a continuous zone of intraplate deformation within the Australian continent that extends N-S some 750 km from the Fleurieu Peninsula in the south to the northern Flinders Ranges. The ranges rise from sea-level up to elevations of 1171 m while the width of the ranges varies from 60–150 km. The range fronts are marked by sudden changes in slope associated with neotectonic faults with a strong reverse component. However, direct exposure of these faults is limited due to the development of thick soil profiles and alluvial sediments over much of the fault strike length. In a few places where these surficial sediments have been removed the range-bounding faults are revealed as commonly reverse-thrust but also steeply dipping oblique faults. Intraplate deformation associated with the current stress field commenced in the late Miocene to early Pliocene as recorded by the deformation of Paleogene sediments and Neogene stratigraphic relations throughout SE Australia and probably occurred in discrete pulses. This research examines the nature, timing and kinematics of neotectonic faults in South Australia and reviews the possible driving mechanisms for this ongoing mountain building activity.

The question of what drives intraplate deformation far from the influence of plate boundaries has global significance as the earthquakes generated in these settings are probably the least understood and often occur sporadically in regions that are not well prepared for such events. The present-day Australian stress field is largely controlled by plate boundary collisions occurring in the Himalaya, Papua New Guinea and the southern highlands of New Zealand. The intersection of these stress regimes has created a complex stress field which is not aligned with the absolute NNE plate motion. In SE Australia the stress field is clearly defined with a NW-SE maximum horizontal compressional orientation. A key question is whether the neotectonic faults in the Mount Lofty/Flinders ranges have developed in response to the current stress field and independently of pre-existing structures or whether pre-existing zones of weakness have significantly influenced the current fault pattern arrangement. To understand intraplate deformation we must have accurate data relating to the current orientation of the Australian stress field and the way in which it interacts with major crustal discontinuities such as the range-bounding faults in the Mount Lofty/Flinders ranges and the large transform faults in the oceanic crust. Until recently there has been very little detailed mapping of neotectonic features in Australia so

little is known about their character or the amounts of vertical and horizontal offsets either side of major fault zones.

The intersection of a NW-SE orientated stress field with a major lithospheric discontinuity such as the Kangaroo and King George V fractures emanating off the South East Indian Ridge may result in differential motion between each oceanic crustal segment and potential reactivation of the transform faults in a way that then impinges on the continental landmass. The King George V Fracture is directly along strike of the structural trend of the Mount Lofty and Flinders ranges and we propose a new model to account for intraplate deformation in S.A. in which the large slabs of oceanic crust between major transform faults moves northward differentially, possibly due to the collision of Papua New Guinea to the north. As a result the eastern side of the King George V Fracture may be impinging into the Australian continent at a greater rate than the western side, creating a sinistral strike slip system that extends some 750 km north of the oceanic/continental boundary. This would help to explain the orientation of the Mount Lofty/Flinders ranges perpendicular to the South Australian continental margin and along strike of the Kangaroo (King George V) Fracture Zone. It also helps explain the sinistral, transpressional regime observed in various fault exposures along the Wilunga and Eden-Burnside faults.

Thermal weakening localises intraplate deformation along the southern Australian continental margin

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The southern Australian continental margin has been undergoing mild active deformation over the past ~10 Myr, manifested today by unusually high levels of seismicity for a relatively stable intraplate region. However, this deformation is markedly partitioned, with zones of abundant neotectonic structures, enhanced relief and high seismicity like the Flinders Ranges and Southeastern Highlands separated by areas of little neotectonic activity, subdued topography and low levels of seismicity like the Murray and Eucla basins. We have made a new compilation of heat flow data for the southern margin comprising 192 measurements. This new database shows that variations in heat flow correlate well with the distribution of neotectonic structures and historical record of seismicity, with regions of active deformation corresponding to elevated heat flows of up to ~90 mWm^{-2}. We propose that the southern Australian margin provides the best example to-date that active intraplate deformation may be localised by the thermal properties of the crust and upper mantle.

Basalt assault: dissecting long-term intraplate volcanism along Australia's Indo-Pacific mantle interface

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The continental-ocean passive margin of eastern Australia records rampant intraplate volcanism since 95 Ma. Basaltic magmas tapped both Indian and Pacific mantle reservoirs and migratory felsic centres evolved from depleted to enriched mantle plume sources. Recent studies provide improved age and geochemical restraints on this volcanism. This study presents further $^{40}Ar/^{39}Ar$, K-Ar and U-Pb zircon (LA-ICP-MS) dates on samples from Queensland to Tasmania and new Australian plate motion modelling, which bear on likely volcano-tectonic controls.

Palaeoplate motions determined for Australia differ, depending on whether Indo-Atlantic or Pacific hotspots are used, because of relative hot spot movements. Global reference framework comparisons suggest the Indo-Atlantic hotspots best match absolute motions, so are used here. Two main periods when the Australian motion appeared to cease, occurred from 105–95 Ma (when thermal rifting and mantle uprisings took place) and 50–40 Ma (before fast Southern Ocean spreading started). A short plate deflection and slowing from 26–23 Ma was proposed from SE Queensland and the offshore seamount migratory chains and related to an Ontong Java plateau collision, but this needs testing against plume deflection models. Palaeoplate motions calculated from the present plume positions across Bass Strait-Tasman Sea match the post-35 Ma felsic chain migrations and project onto the Coral Sea rift margin at 65 Ma, suggesting a potential causal link.

New U-Pb zircon ages from felsic volcanoes in inland Queensland decrease southwards from 34.0±1.4 Ma (Mount Blackwood, Hillsborough) to 27.9± 0.5 Ma (Gee Gee Gap, Buckland), at an average rate of 74 km/Ma. This migration continues southwards, marked by leucitites in NSW and Victoria and then by central Victorian trachytes with U-Pb zircon ages of 6.3±0.1 Ma at Newham. The overall 1850 km progression at 67 km/Ma is slower than in Queensland indicating some rate changes along its track. A late-felsic pulse at 2.3±0.1 Ma (Ar-Ar, zircon FT dating; Creswick, W Victoria) suggests compound plume events and zircon-bearing silicate melts that lingered to at least 0.27±0.07 Ma (a new U-Pb zircon age; Bullenmerri, W Victoria).

Dating now identifies significant Late Cretaceous magmatism (95–65 Ma) along rift margins (Cape Portland, Tasmania; central coast and Yarrowitch, NSW; Rockhampton, Qld).Transform faults in the Tasman Sea and Cato Trough spreading floors may have influenced locations of this activity, as in passive margins elsewhere. Late Cretaceous rifts related to Gippsland-Tasman-Dampier Ridge-Capricorn-Cato triple point sites also seem to contribute inputs into the earlier magmatism.

The genesis of such extended volcanism remains in contention. Bends associated with surges in the SE Qld and offshore seamount chains were linked to the effects of plate rotation and deceleration resulting from an Ontong Java impact. Such bends should be present in all plume traces in the area, but seem lacking across inland chains. More proximal events than the Ontong Java collision also may affect the Australian plume traces, such as slab detachment beneath New Caledonia. Do the basalt fields also track plumes? New England, NSW, studies show plume signatures differ at some migratory centres (Ebor) and that the variously aged basalt fields include some with plume-like characteristics. New concepts on 'splash plumes' need appraisal. The origins of young Queensland basalts remain enigmatic, but recent ideas for regional down tilting towards northern subduction zones need consideration.

Rapid emplacement of one of the world's greatest continental magmatic provinces—precise age constraints on the Bushveld Complex

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The Bushveld Complex (*sensu lato*) in southern Africa represents one of the largest examples of continental magmatism on Earth. If the precursor felsic volcanic rocks of the Rooiberg Group are included, the volume of magma generated is estimated to be up to a staggering 1,000,000 km^3. The timing and the origin of the various components of the complex are, however, poorly constrained with some work suggesting thermal activity could have continued for up to a billion years (McNaughton, et al., 1993). This research is aimed at determining a precise chronology of events covering the entire history of the Bushveld Complex, using combined TIMS and SHRIMP zircon U-Pb dating, with the aim at establishing some constraints on the possible origin of this massive and economically important event.

In the broadest sense, the Bushveld Complex is generally considered to include the intermediate to felsic volcanic rocks of the Rooiberg Group, the mafic layered rocks of the Rustenburg Layered Suite, the felsic intrusive rocks of the Lebowa Granite Suite, plus the enigmatic Rashoop Granophyres. Representatives of all these major components were sampled for dating. TIMS dating of felsites of the roofing Rooiberg Group show that these precursors to the main phase of the Bushveld Complex were emplaced 2059.9 ± 1 Ma ago. This is significantly prior to intrusion of the main phase of the complex—as shown by dates obtained on zircons from the famous PGE-bearing Merensky Reef, and from a late-stage basic pegmatoid. These gave statistically identical ages of 2055.3 ± 1.2 Ma and 2056.3 ± 0.7 Ma respectively. Dating of granites of the Lebowa Suite that demonstrably intrude and post-date the mafic rocks, shows they were intruded at 2054 ± 2 Ma (a mean of several dates obtained on a variety of granites from this suite). A date of 2054 ± 4 Ma recently published by Dorland et al., 2006 on a rhyolite within the overlying sedimentary sequence of the Waterberg Group shows that the Bushveld Complex had cooled and had undergone significant erosion short time after intrusion of the mafic phase.

This high-precision geochronological study established for the first time that the whole event occurred over a very short time interval of approximately 4 Ma. The emplacement of the mafic Rustenburg Layered Complex and the felsic Lebowa Granite Complex was within 1–2 Ma, a time interval similar to that measured for large igneous volcanic provinces such as the Karoo or Deccan. Extensive recent geochronological investigations of large parts of southern Africa have shown that Bushveld-aged igneous rocks occur over a vast region of the

subcontinent. These are currently the focus of a larger study aimed at discovering the full areal extent of rocks of this age and to establishing a possible causal link between the Bushveld Complex and a larger regional event. It certainly seems probable that the Bushveld Complex, unique as it is, was a part of some larger 'Bushveld event', rather than an isolated igneous event of unknown origin. Certainly some origins can now be discounted—it is unlikely that an extraterrestrial (impact) origin can be reconciled with the distinctly different ages now established for the Rooiberg and Bushveld events. The origin of this enormous and economically important complex is still uncertain, but the rapid emplacement and erosion does provide some clues.

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SESSION 01LD (LIFE AND SOLAR SYSTEM: ARCHEAN AND PROTEROZOIC LIFE)

Applications of Raman spectroscopy for early life studies

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In recent years Raman spectroscopy has become a valuable technique for studies of early Life, since it enables instantaneous and non-destructive chemical and mineralogical identification of a large variety of geobiological sample types. Fast high-resolution Raman mapping is an ideal initial technique for characterisation of small-scale features before other, more cumbersome, chemical and isotopic techniques are applied (such as TEM, SIMS, synchrotron-based microanalysis). Specific types of applications of Raman spectroscopy include mapping of microfossils, the study of crystal growth in biomineralisation processes, identification of mineral assemblages in stromatolites and microbial mats, and the detailed characterisation of fluid inclusions.

Here we describe the use of Raman spectroscopy to study graphitic microstructures in the oldest and most strongly altered part of the rock record. A highly metamorphosed quartz-rich rock on the south-western tip of Akilia Island, Southern West Greenland, has for long been the centre of attention regarding the oldest traces of life on Earth. This five meter wide outcrop was interpreted as a >3.8 Ga banded iron formation and was found to contain graphite inclusions within apatite crystals. The low $\delta^{13}C$ of these graphite inclusions suggested a biologic source material that had retained its original carbon isotope signature. Raman identification of graphite in CO_2-CH_4 fluid inclusions enabled the recognition of abiologic metamorphism-related processes. Thermodynamic constraints in the COH-system indicate that the graphite formed by dehydration reactions and temperature decrease during retrograde metamorphism, and does not represent altered organics. This observation greatly complicates any claims of early traces of life in these rocks.

Investigating modern and ancient biosignals using NanoSIMS

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Nano-scale secondary ion mass spectrometry (NanoSIMS) is being increasingly used in the investigation of both modern and ancient microbial communities due to its ability to map biologically relevant elements (carbon, nitrogen, etc) at the sub-micron-scale. It has the additional capability of being able to measure the biologically-induced isotopic fractionation of elements such as sulphur and carbon in phases such as pyrite or kerogen. We present here several examples of new and novel data obtained using the Cameca NanoSIMS 50 at The University of Western Australia. These examples include:

- the mapping of C, N, O, S and associated trace metals in ancient and modern stromatolites from Western Australia

- extracting putative biosignals from spherical Iron oxide concretions from Utah that are thought to be analogous with the 'blueberry' structures seen on the surface of Mars
- the mapping of elements and the measurement of C/N ratios in ancient laminated sedimentary structures and modern stromatolites to investigate how geochemical signals degrade over time
- measuring sulphur isotope fractionation and elemental associations in micron-sized pyrite grains found within a 3.4 Ga sandstone from the early Pilbara.

All these examples illustrate the advantages gained by investigating geochemical signals, *in situ*, at the micron to sub-micron scale.

Are Archaean microfossils really biomorphs?

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'Biomorphs' are nanostructured inorganic composite materials that bear a morphological resemblance to primitive life forms. They self-assemble in very simple laboratory systems, whose chemistry bears strong resemblances to that of hydrothermal vent systems in the 3.5 billion year old Dresser Formation of the Pilbara. It is therefore possible that some early 'microfossils' are in fact biomorph pseudofossils. Distinguishing the two is not straightforward. The nanoscale structure is different, but is unlikely to be preserved in either biomorphs or microfossils. Organic matter content is not diagnostic of fossils, since biomorphs have been shown to secondarily adsorb hydrocarbons.

The shapes of biomorphs arise from the interplay between carbonate crystallites (or aggregates) elongated in a specific crystallographic direction, a coating of amorphous silicate which inhibits crystal growth, and a tendency for crystallites to form parallel or subparallel aggregates. A wide range of morphologies has been observed, and there are systematic changes in nucleation rate and morphology with variation of such parameters as temperature, pH and reactant concentrations, as we demonstrate. Observation of corresponding variation in nature could be diagnostic for recognition of biomorphs as opposed to true microfossils.

SESSION 01TD (TOPICAL: PALEOMAGNETISM)

New paleomagnetic study of the 1450 Ma Lakhna Dyke Swarm in the Bastar Craton, India: implications for the Mesoproterozoic supercontinent

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The Mesoproterozoic paleogeography has been widely debated during last decades. Most of recently published articles suggest the existence of a Mesoproterozoic supercontinent, variably called Columbia, Nuna, or Hudsonland. However, its exact configuration and history is still provisional, owing mainly to the small number of Neoproterozoic high-quality, well-dated paleomagnetic data available. Recent paleomagnetic and geochronological studies in Baltica, Siberia and Laurentia suggest that these three continents could have drifted jointly between 1500 and 1200 Ma. Consequently, they could represent the core of the Mesoproterozoic supercontinent. Unfortunately gaps in the paleomagnetic record in other continents (Australia, Amazonia, India, Congo, Kalahari etc.) prevent unequivocal Mesoproterozoic reconstructions. In particular, there are no reliable 1600–1200 Ma paleomagnetic data from India. This makes it impossible to reconstruct Indian paleopositions and even to find if India formed part of the Mesoproterozoic supercontinent at all. To fill this gap we studied the Lakhna dyke swarm in the Bastar craton. These dykes have been dated using zircon U-Pb SHRIMP method at 1450 ± 22, 1453 ± 19 and 1442 ± 30 Ma. Most of them are intruded along N-S, NNE-SSW trends with some along E-W direction. Dolerites have a N-S and WNW-ESE trend and are medium grained with plagioclase, olivine, and augite. We collected 128 oriented cores from 11 dykes. Thermal and AF demagnetisations were carried out in four laboratories in Utrecht, Lulea, Bergen and Edinburgh. Most

dykes carry a stable coherent bipolar remanence. We used this new paleomagnetic pole and coeval poles from Baltica, Laurentia, Siberia together with paleomagnetic and geological data from Australia to find possible positions of India in the Mesoproterozoic supercontinent. Due to polarity ambiguity and longitudinal uncertainty the solution is not unique. However, the proximity of India to Australia is a possible scenario. Alternative reconstructions allow India to be close to Laurentia, but the possibility of an 'independent' drift of India cannot be excluded. This uncertainty could be reduced by more Mesoproterozoic paleomagnetic data from India. Here we present one version of an animated history of the Mesoproterozoic supercontinent with an emphasis on the possible role of India and Australia.

Palaeomagnetic evidence for cross-continental megashearing in Australia during late Neoproterozoic: no need for pre-750 Ma Rodinia breakup

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The breakup of the Neoproterozoic supercontinent Rodinia may have triggered dramatic changes in the Earth's climate and atmospheric conditions, leading to the explosion of complex life. However, there is a longstanding controversy regarding the timing of the breakup events, particularly that between Australia-East Antarctica and Laurentia. Early palaeomagnetic work demanded the breakup of the SWEAT-type reconstructions, if valid, to have occurred by ca. 750 Ma (Wingate and Giddings, 2000). However, stratigraphic record in south-east Australia indicates a rift-drift transition between the Sturtian glacial deposits (*ca.* 750–690 Ma) and the overlying sag-phase deposits (Powell et al., 1994; Preiss, 2000) that were recently dated at ca. 650 Ma (Kendall et al., 2006). This geologically based age estimation from Australia agrees with those from South China where the rifting finished at around the time of the Nantuo glaciation (Wang and Li, 2003), dated at between ca. 650 Ma and 635 Ma (Condon et al., 2005; Hoffman and Li, 2009; Zhang et al., 2008; Zhou et al., 2004), and for western Laurentia (Ross, 1991; Fanning and Link, 2004). There are even younger rifting ages suggested for eastern Australia (Crawford et al., 1997).

There appear to be systematic and significant differences between pre-650 Ma palaeomagnetic pole positions from the North Australian Craton and those from the South-West Australian Craton (South Australian Craton plus West Australian Craton), making tectonic interpretations and Rodinia reconstructions equivocal (Li et al., 2008; Schmidt et al., 2006; Wingate et al., 2002). However, both these differences and the discrepancy on the timing of Rodinia breakup can be reconciled by a possible trans-continental mega-shearing along the Paterson and Musgrave Orogens, manifested as a ca. 30° clockwise rotation of the South+West Australian Cratons relative to the North Australian Craton around a vertical axis near the eastern Musgrave Block. The timing of the mega-shearing (the shear zone termed here the Paterson-Musgrave mega shear zone) was likely active between ca. 650 Ma and ca. 550 Ma, as evidenced by the ca. 650–550 Ma Ar-Ar muscovite ages and granitic intrusions in the Rudall Complex of central Paterson Orogen (Durocher et al., 2003) and the 600–550 Ma foreland basin deposition and metamorphic/cooling ages in and around the Musgrave Block (Aitken et al., 2009; Camacho, 2002). The late Neoproterozoic dextral sense of shearing at both the Rudall and Musgrave complexes (Aitken et al., 2009; Bagas, 2004) is consistent with the hypothesised sense of rotation.

By comparing the Proterozoic palaeopole positions between Australia (after correcting for the 30° rotation) with those of Laurentia, it is suggested that Rodinia probably did not break apart until ca. 650 Ma, thus agreeing with the stratigraphically estimated rift-drift transition time. The proposed 30° rotation probably occurred during Rodinia breakup. The revised Rodinia fit still has a large enough gap between Australia-East Antarctica and Laurentia that could accommodate continental blocks like South China.

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Design of a database of remanent magnetisation dominated magnetic field anomalies

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Magnetic field interpretation is highly complementary to palaeomagnetic studies. Palaeomagnetism provides detailed information from small, localised samples whereas magnetic field interpretation provides estimates of the bulk magnetisation of substantial volumes (which may be completely buried and un-sampled by boreholes). Without palaeomagnetic and rock magnetic studies much of the geological information latent in magnetic field measurements (regarding lithology, structure, age, deformation or alteration) cannot be accessed, and without the coverage of magnetic field data the extents and relationships of subsurface magnetisation events revealed by palaeomagnetic studies cannot be fully mapped. The combination of palaeomagnetic studies and magnetic field interpretation is required for holistic and reliable geological interpretation

In Australia we are fortunate to have an unparalleled coverage of large parts of the country by medium and high resolution total magnetic field data, much of which is readily and freely available from the national geophysical database managed by Geoscience Australia. Expressions of remanent magnetisation in these data in part compensate for the fact that many of those areas are obscured by a cover of recent deposits and/or deep weathering which restricts access for palaeomagnetic sampling. This use of magnetic field interpretation to augment palaeomagnetic studies over a region of difficult direct access is somewhat equivalent to the application of the same combination of methods to the study of linear seafloor spreading magnetisations in marine areas. To facilitate linkages between magnetic field interpretation and palaeomagnetic studies, we have investigated the design of a database of magnetic field variations recognised to arise from magnetisations substantially rotated from the local geomagnetic field direction. We believe that such a database will be of considerable benefit both to those involved in magnetic field interpretation and to those undertaking palaeomagnetic studies, and expect that the database may act as a bridge between these sometimes diverse communities.

Magnetic field variations due in large part to remanent magnetisation are generally first recognised on visual inspection of magnetic field imagery. We propose that each entry in the database would include a local geo-coded clip of that magnetic field imagery. These images would be displayed in the database forms for each entry, and also be made available for display in widely used geo-located image displays such as Google Earth. A basic entry into the database could just be a selected magnetic field variation suspected of being due largely to remanent magnetisation. However entries would ideally be further investigated by forward modelling, inversion or magnetic moment analysis. The details and results of these studies would then be added to that database entry, including an optional link to any models in an associated model database. Links to other external databases would provide details of the survey data (a suitable database of regional surveys has already been compiled by Geoscience Australia), of any physical property measurements, and of any rock magnetic or palaeomagnetic studies. The database will be searchable by location, assigned geology, or inferred direction of the magnetisation. It will be a resource for magnetic field interpreters working in a new area, for palaeomagnetists looking to select sample sites, or for investigation of the geographic extent of a particular magnetisation event. The database could be supplemented with various utilities, for instance an ability to display images generated from a simple source model with user-assigned magnetisation direction in order to visually compare the observed magnetic field pattern against that produced by a proposed magnetisation direction, or to compare a derived magnetisation direction with possible matches predicted from apparent polar wander models. A problem both in generating the database and for users of it, are that it necessarily

encompasses data of quite different nature; direct knowledge (eg. measurements of rock properties), indirect knowledge (such as modelling results), and 'speculative' knowledge (eg. the judgement that a particular feature in the magnetic field is inconsistent with purely induced magnetisation). Assigning an entry to the database is necessarily interpretive, and even results of follow-up studies such as modelling will not be unique or conclusive. The database therefore requires metadata explaining the genesis and limitations of the provided information. It should be feasible to operate the developed and initially populated database as a 'Wiki', with interested contributors adding their own results either directly or through a panel of moderators.

Pre-Adelaidean palaeomagnetism for the Gawler Craton, South Australia: the Pandurra Formation and Blue Range Beds

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We report palaeomagnetic data for the Mesoproterozoic Pandurra Formation of the Cariewerloo Basin, north-eastern Gawler Craton, and the Blue Range Beds of the Itiledoo Basin, central Eyre Peninsula, South Australia. Both units are mainly arenaceous continental redbeds characterised by reddish brown and mauve colours with mottles and streaks of white and common Liesegang patterns. The Blue Range Beds may be in part coeval with the Wartakan Event at ~1500–1400 Ma and the Pandurra Formation yielded a Rb–Sr whole rock maximum age of 1424 ± 51 Ma. Hence the units may be broadly correlative.

The Pandurra Formation was sampled at Freyers railway cutting and elsewhere in the Whyalla area and the Blue Range Beds in the Talia area. Specimens were stepwise thermally demagnetised, revealing hematite as the dominant magnetic carrier with a Neél temperature of 680°C. The mean direction for the Pandurra Formation after unfolding (N = 90 specimens) is D = 248.2°, I = 46.7° (α_{95} = 4.4°), indicating a palaeolatitude λ = 27.9 +3.9/–3.4° and a pole position at latitude λ_p= 32.0°S, longitude ϕ_p = 62.2°E (dp = 3.6° and dm = 5.6°). The mean direction for the Blue Range Beds after unfolding (N = 61) is D = 233.9°, I = 50.2° (α_{95} = 4.0°), indicating a palaeolatitude λ = 31.0 +3.7/–3.5° and a pole position at latitude λ_p= 44.8°S, longitude ϕ_p = 56.9°E (dp = 3.5° and dm = 5.3°). Together the data for the two units constitute a positive fold test with 99 per cent confidence (ξ_{2h} = 52.9 and ξ_{2b} = 2.5, where h and b refer to horizontal and bedding respectively, cf. a value of 14.3 for p = 0.05 and 22.2 for p = 0.01). Their magnetisations pre-date tilting, which evidently occurred during the Wartakan Event.

Our results imply that the Pandurra Formation and Blue Range Beds are correlative. Combined results for both units after unfolding (N = 151) are D = 242.6°, I = 48.3° (α_{95} = 3.1°), indicating a palaeolatitude λ = 29.3 ± 2.8° and a pole position at latitude λ_p= 37.1°S, longitude ϕ_p = 60.4°E (dp = 2.6° and dm = 4.0°). This pole falls on the Proterozoic apparent polar wander path for Australia near the OP3 group of poles for the McArthur Basin, northern Australia, which are ascribed ages of 1.6–1.5 Ga. This is consistent with the stratigraphy and geochronology for the Pandurra Formation and Blue Range Beds.

Tuesday 6 July 2010

SESSION 02RA (RESOURCES)

The effect of dissolved sulphide in silicate melts on the solubility and crystal/melt partitioning of Ni and other potentially chalcophile elements

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The crystal/melt partitioning relations of potentially chalcophile elements like Ni or the Platinum Group Elements (PGEs) are often determined from experiments in sulphur-free systems, which raises the question of whether bonding or complexing between the chalcophile element and S^{2-} in the silicate melt would make such experimental results inappropriate for application to natural magmas containing sulphur. For example, most previous investigations into Ni partitioning between olivine and silicate melt have been on sulphur-free

systems, but of the two studies that have looked into the effect of S^{2-}, Li et al. [1] found a large effect but Gaetani & Grove [2] almost none.

In order to investigate this discrepancy, we have determined olivine-melt partition coefficients for Ni, Co, Fe, Mn, Cr, V, Ti and Sc in 6 model compositions in Fe-poor and Fe-containing systems (CMAS and FeCMAS) at 1 atmosphere and 1370 to 1400°C, over a wide range of sulphur fugacities (fS_2 = 0 to $10^{-1.3}$ bars, producing dissolved S from 0 to ~ 4000 μg g^{-1}), making a total of 61 experiments. The incompatible trace elements Y, Zr and Hf were also included in the study.

Olivine/melt Mg-Ni two-element distribution coefficients agree with the values reported previously in S-free systems and with those of Gaetani & Grove [2], and show that the influence of sulphur is very small, being much less than other compositional variables such as mg# of the olivine or SiO_2 content of the melt. Nor does S have an appreciable effect on any of the other trace elements studied. A companion study on the solubility of Ir in a komatiitic melt equilibrium with Ir metal shows no effect of S^{2-} either. A thermodynamic analysis of the problem confirms that indeed no effect is expected for physically plausible energies of metal-sulphide complexes in the silicate melt, simply because even at sulphide saturation the levels of S^{2-} dissolved in terrestrial basalts (which are typically ~ 1000 μg g^{-1}) are too small. Note that 1000 μg g^{-1} S^{2-} in a typical basaltic melt corresponds to molar S/(S+O) of 0.001 on the anion sublattice. Experimental results for chalcophile element partitioning relations or for PGE solubilities determined in sulphur-free systems may be applied to S-containing natural systems with confidence.

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Origin of nickel-rich sulphide assemblages in the Betheno deposit, Yakabindie, WA: evidence from synchrotron X-ray fluorescence mapping

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The low-grade disseminated nickel sulphide deposits of the Mt Keith – Yakabindie region are among the world's largest accumulations of magmatic nickel sulphides associated with komatiitic rocks, accounting for a total pre-mining resource of 790 million tonnes at an average grade of 0.56% Ni, for a total of 4.42 million tonnes contained Ni. These deposits consist of disseminations of a few per cent of magmatic Ni-Fe sulphides hosted by remarkably coarse-grained dunites, formed as olivine adcumulates within high-flux subvolcanic conduits from highly magnesian komatiite magma. Notwithstanding the low grades, the recoverable nickel is hosted in exceptionally Ni-rich sulphide assemblages. Sulphide Ni tenors in excess of 30% Ni give rise to nearly pure pentlandite assemblages at Mt Keith, this being the critical factor in making such low-grade ores economically viable.

The extreme high Ni contents of the sulphide assemblages, compared with those found in typical sulphide-rich komatiite-hosted ores, imply that there has been some upgrading of the original magmatic sulphide liquid component. Several mechanisms have been proposed, including release of nickel during serpentinisation of olivine and incorporation into sulphides; oxidation of pyrrhotite to magnetite, also during serpentinisation; and subsolidus, pre-alteration diffusional exchange of Fe and Ni between olivine and sulphide.

Pentlandite-rich sulphide assemblages have been observed in rare examples of disseminated ores in fresh unserpentinised dunites, at Perseverance and elsewhere. Recent observations of extremely Ni-rich pentlandite-millerite-pyrite assemblages in completely fresh dunites from the Betheno deposit at Yakabindie throw new light on this issue, and imply that the dominant mechanism may be diffusional olivine-sulphide exchange, completely unrelated to hydrous alteration of olivine. The critical control may be the changing equilibrium constant for the subsolidus exchange reaction for Fe and Ni between monosulphide solid solution (MSS) and olivine:

$$FeS_{(sulphide)} + NiO_{(olivine)} = FeO_{(olivine)} + NiS_{(sulphide)}$$

Experimental data by (Brenan and Caciagli, 2000) indicate that the K_d for this exchange reaction increases with falling temperature along specific oxygen buffer curves such as QFM, favouring higher Ni/Fe in sulphide relative to olivine at lower temperatures. This gives rise to very strongly Ni-enriched sulphides through reaction with olivine in situations where disseminated sulphides are present in extremely olivine-rich rocks. The reaction produces extremely Ni-rich MSS compositions, which decompose to assemblages of pentlandite plus pyrite or pyrrhotite, with or without millerite, at low temperature. This reaction is accompanied by loss of Ni from olivine, which can be seen in X-ray fluorescence maps of Ni distribution in olivine at thin section scale in Betheno dunites.

By inference, the pentlandite-rich assemblages at Mt Keith may be essentially primary, resulting from subsolidus Fe-Ni exchange between the olivine and sulphide components prior to hydrous alteration. This mechanism explains the otherwise puzzling observation that Mt Keith ores display very string positive correlations between Ni, PGE and S which extrapolate to compositions of the original sulphide component typical of komatiite-related sulphide liquid.

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SESSION 02EA (ENVIRONMENT)

Timescale of soil formation for weathering profiles developed over andesitic volcanics

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Soil is a critical resource, especially in the context of a rapidly growing world's population. Thus, it is crucial to be able to quantify how soil resources evolve with time and how fast they become depleted. Over the past few years, the application of cosmogenic isotopes has permitted to constrain rates of soil denudation. By assuming constant soil thickness, it is also possible to use these denudation rates to infer soil production rates (Heimsath et al., 1997). However, in this case, it is not possible to discuss any imbalance between erosion and production, which is the core questions when interested in soil resource sustainability. Recently, the measurement of uranium-series isotopes in soils has been used to quantify the residence time of soil material in the weathering profile and infer soil production rates. Thus, the combination of U-series and cosmogenic isotopes can be used to discuss how soil resources evolve with time, whether they are depleting, increasing or in steady-state.

In a previous study in south-eastern Australia, where a several tens of meter thick saprolite is developed over a granodiorite and underlains up to 1m of soil, saprolite residence times (i.e. the time elapsed since production from the bedrock) were found to range from 0.5 to 6 Myr whereas soil residence times (i.e. the time elapsed since production from the saprolite) would range from 6 to 38 kyr (Dosseto et al., 2008). Because of the contrasting thicknesses for soil and saprolite, production rates for both material were inferred to be similar: ~ 10–50 mm/kyr. Interestingly, soil production rates were similar to denudation rates inferred from cosmogenic isotopes and would suggest that, in an environment where human activity is minimal, soil is renewed as fast as it is destroyed via erosion.

Similar work has been undertaken in Puerto Rico for soils also developed over a granodiorite (Rio Icacos catchment). Results suggest comparable soil production rates (a few tens of mm/kyr; unpub. data), which would imply that modern climatic conditions have little effect on the rate of development of the weathering profile. In this study, we will present results obtained from a neighbouring catchment (Rio Mameyes) where soils are developed over andesitic volcanics. Climatic conditions are similar to that of Rio Icacos, and we will investigate different bedrock lithologies impact processes of soil formation and related timescales.

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Soil residence time in weathering profiles measured using uranium-series isotope disequilibria

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Soil production rates can be determined using ^{10}Be and ^{26}Al isotopes, with the assumption that soil production is balanced by denudation such that soil thickness is constant. This makes it difficult to use this technique for aggrading/degrading soils. Uranium-series isotopes can be used as an independent technique to measure soil production rates (Dosseto et al., 2008).

In silt-size soil material, a (^{234}U/^{238}U) activity <1 can be observed because when ^{238}U decays near the surface, its daughter nuclide ^{234}Th can be ejected from soil grains, and subsequently decays into ^{234}U. The measurement of this radioactive disequilibrium can be used to determine how much time has elapsed since the soil material was produced from the bedrock, i.e. a *soil residence time.* Residence times between 50 kyr and 1 Myr can be determined.

We have measured U-series isotope disequilibrium in soils from four different profiles at Frogs Hollow, a catchment area of the Murrumbidgee River in eastern New South Wales, which gave a top soil (^{234}U/^{238}U) activity ratio of 0.922 ± 0.002 and a saprolite (^{234}U/^{238}U) activity ratio of 0.930 ± 0.003. The results indicate that the soil residence time is over a million year.

Reference

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SESSION 02SA (SOCIETAL: IGC SYMPOSIUM)

Promoting the geosciences in our region: the 34th International Geological Congress

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The International Union of Geological Sciences (IUGS; www.iugs.org/) is the scientific sponsor of the International Geological Congress (IGC), which is generally held every four years and has a proud 140 year tradition. The main purpose of the IGC is to encourage the advancement of applied and fundamental research in the Earth Sciences worldwide. Recent IGCs have attracted 5,000–7,000 delegates from over a hundred countries.

Australia is hosting the 34th IGC on behalf of the Oceania region in Brisbane, 2–10 August 2012 (www.34igc.org). This large and prestigious event, which is also being referred to as AUSTRALIA 2012, offers the geoscience community of our region a wonderful opportunity for international networking and collaboration, and enhanced recognition of our geology and accomplishments. AUSTRALIA 2012 will be an important forum for interdisciplinary interactions in all fields of geoscientific endeavour.

The success of AUSTRALIA 2012 depends on attracting as many delegates as possible. The intention is to ensure the event is relevant to all people interested in the geosciences and related fields, including those who may not normally consider participating in IGCs.

The conference web site and articles in society newsletters have called for volunteers to convene symposia, participate in IGC subcommittee activities, suggest/lead field trips, etc. All IUGS' Commissions, Joint Programs, Task Groups, Initiatives and Affiliated Organisations have been invited to participate.

The Australian Geoscience Council (www.agc.org.au)—the peak representative body of eight geoscience-related societies in Australia—is the legal entity responsible for AUSTRALIA 2012. The AGC has agreed to the following goals for the event:

- international exposure to the geology of the Oceania region and to the high scientific standards and accomplishments of the region's geoscientists
- an important opportunity for interdisciplinary involvement in fields of geoscientific endeavour outside those usually canvassed at many specialised conferences
- delivery of a reasonable return to the member societies of the AGC and to the AGC itself.

The President of the 34th IGC, Dr Neil Williams, is leading high level representation and strategic promotion of the event. The primary responsibility for organisational activities rests with the Secretary General, Ian Lambert, and Deputy Secretary General, Paul Kay—both from Geoscience Australia—supported by other members of the core Organising Committee (OC). GA is providing considerable in kind and financial support for the IGC, including preparation of the ambitious book: Shaping a continent building a nation: a geology of Australia.

The OC as a whole sets the strategic directions. Individuals on the OC chair committees appointed to develop each of the major elements of the 34thIGC. An experienced Brisbane-based professional conference organiser—Carillon Conference Management—has been engaged.

The Congress theme is 'Unearthing our Past and Future', encompassing the crucial contributions of geoscience in meeting societal needs and sustaining planet Earth. Each of the 7 days of the congress will comprise a plenary 'theme-of-the-day' session on major contemporary issues, followed by up to 30 concurrent symposia. Australia's experience in developing a strong and sustainable mineral and energy resources sector will underpin a program emphasising future mineral and energy supplies. Other themes, which reflect major challenges for countries in the Oceania region and more broadly, will be climate change and its impacts on natural resource management and communities, understanding and mitigating geohazards, and geoscience information and standards.

Approximately 30 pre- and post-Congress field trips are planned, taking in each of the Australian states and the Northern Territory, New Zealand, Malaysia and New Caledonia/Vanuatu. There will also be a range of one-day tours available during the conference.

Expert workshops and short courses are also proposed. In large part, these will reflect Australian and New Zealand international assistance objectives, where feasible, so as to attract funding to support attendance by delegates from developing countries. These could include: sustainable mining (mineral exploration, mining regulation, resource reporting, environment impact assessment and resource assessment); carbon sequestration; groundwaters; geomedicine; and geohazards. The number and nature of these will depend on the availability of funding support.

A large GeoExpo (trade show) will comprise exhibitors from the resources industry, geological surveys, professional/learned societies, scientific publishers, consultants and technical services/products providers.

Shaping a continent—building a nation: a geology of Australia

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Geoscience Australia will publish a new book on Australia's geology for the 34th International Geological Congress (IGC) to be held in Brisbane in 2012. Shaping a continent–building a nation: a geology of Australia will tell the story of Australia's geological evolution through the lens of human impacts—illustrating both the challenges and the opportunities presented by the 'lucky country'. The book will not attempt to be a definitive authority on all aspects of Australia's diverse geology, nor will it follow the 'traditional' time-based treatment of the topic.

The main aim of the book is to showcase the excellence of Australian Geoscience and how the understanding of the unique geology has shaped the Australian continent and thus impacted the Australian people. The book will be novel in that it will integrate many disciplines of the geosciences in a systems framework to address 'big

questions' relevant to Australians. The book will be a high-quality desirable product written for the broader geoscientific community, with enduring and topical messages to society as a whole.

The first two chapters will define Australia and Australians, and will set the spatial-temporal and cultural framework for the rest of the book. The following eight chapters will be arranged into themes around geological influences on society, environment and wealth.

- *Living Australia* is about the emerging understanding of how Australia's biosphere evolved through time and shaped Australia. The geological influence on the unique Australian flora and fauna create an environmental management challenge.

- The *Out of Gondwana* chapter considers the break up and creation of unique Australia as an island continent, and the northward drift towards Asia. The location of the various break-up basins hosting hydrocarbon resources has profoundly influenced the energy source choices made by Australians. Some of these basins may potentially sequester CO_2—providing a geological solution to a global problem.

- *Old, flat and red* is a chapter that considers the formation of the unique Australian landscape and regolith, which has had a profound influence on the fertility of soils and water availability. This has impacted on where Australians live and how the country has developed.

- *Living on the edge—waterfront views* is a chapter about the geological processes that shaped the iconic Australian coastline, and ultimately determined the location of population centres and associated infrastructure. Past and future sea level changes and the effects of rivers, storm-waves and tides are emphasised in terms of likely impacts. Also living on the edge is Australia's unique marine ecology, which requires careful management and balance with ongoing development.

- *Water—the nation's life blood* considers why Australia is the driest inhabited continent and the role aridity has played in shaping the landscape, soils and demography. Water security is increasingly important as competing interests vie for access to this rare resource.

- The *Foundations of wealth* considers mineral systems and the great wealth of resources which shaped early cultural Australia, economically drove the country, and developed much of the dry interior. The world-class mineral deposits of Olympic Dam, Kalgoorlie, Mt Isa/Broken Hill and Victoria goldfields are highlighted in terms of a mineral systems understanding of how they formed.

- The bulk commodities *viz.* iron ore, hydrocarbons, coal and aluminium are *Sustaining* the *wealth* of Australia, through their enormous export earnings, job creation and regional development. Why Australia is so blessed in these resources, and the consequences of their development will be discussed.

- *Deep Heat: meeting future energy needs* considers geothermal and also nuclear options for energy in a carbon constrained world. With vast uranium and thorium resources, large regions of elevated crustal heat flow, Australia is energy rich. Why the heat-producing elements are so unevenly distributed in space and time, and why Australia is especially rich in these elements—will be discussed.

This 500 page full colour book will be hard backed covered at A4-plus size. Full use will be made of the beauty of the visual images of Australia's geology to illustrate our messages. The theme of the 34th IGC meeting is 'Unearthing our Past and Future'. This book will make a significant contribution to this theme in presenting Australia's unique geology in a new light.

Testing the behaviour of Hf isotopes in rutile in a high-temperature metamorphic environment

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The accessory mineral rutile has recently attracted attention for hafnium (Hf) isotope analysis [1, 2], which has traditionally been applied to zircon or whole rock samples. Rutile is an appealing target in metamorphic rocks, as it is more easily linked to metamorphic reactions, and therefore pressure-temperature-time space, than zircon. It also provides a target for Hf isotope analysis in samples where growth of metamorphic zircon was limited or absent. An important outstanding question is how the Hf isotope systematics of rutile compare to those of zircon—for example, is the more reactive rutile more easily reset under high temperature conditions and/or in the presence of fluids? We investigate this question in a Hf isotope study on rutile-bearing rocks from the Ivrea-Verbano Zone, northern Italy.

Hf isotope measurements can be made in-situ by laser ablation multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS). We have adapted analytical protocols for the analysis of rutile, which contains one to two orders of magnitude less Hf than zircon. In order to maximise accuracy and precision, well-determined baselines are critical, and can be achieved by a combination of long baseline measurement times and interpolation between bracketing baselines. Another adaptation is the regular analysis of a synthetic rutile doped with c.5000ppm Hf to monitor, and if necessary externally correct for, instrumental mass fractionation. It can be demonstrated that for low-Hf rutiles, the low precision with which mass bias coefficients can be measured may negate the advantages of internally correcting for instrumental mass fractionation. The accuracy of our method has been confirmed by results for two rutiles for which the $^{176}Hf/^{177}Hf$ is known by independent means.

The Ivrea-Verbano Zone (IVZ) is an ideal natural laboratory in which to investigate the behaviour of Hf isotopes in rutile under high-temperature conditions of metamorphism. The IVZ comprises an extensive lower crustal section, including crust-mantle transition, which has been tilted to be spectacularly exposed at the surface. Interlayered metapelitic and metabasitic lower crustal rocks document increasing pressure and temperature towards the base of the section, as well as extraction of significant volumes of partial melt. The same reaction that generated partial melting produced rutile in metapelitic lithologies. Stratigraphically below this formation is the Mafic Formation, which is made up of mantle-derived melts that intruded into or underplated the base of the lower crust. Near the base of the Mafic Formation, partially digested metapelitic slivers relating to the overlying crustal sequence are abundant.

Strategic sampling of metapelites from across the IVZ has provided a suite of rutile-bearing samples, including both restite and leucosome, which record a range of pressures and temperatures; interaction with fluids; and variable amounts of overprinting by a later, lower-temperature metamorphic event. Hf isotope analysis of these samples will provide valuable insight into the behaviour of the Hf isotope system in rutile under a range of conditions. The presence of metamorphic zircon rims in some samples allows comparison of the behaviour of Hf isotopes in the two minerals—but their absence in other samples emphasises the relevance of a thorough understanding of the significance of Hf isotopes in rutile.

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Dislocation recovery and damping in deformed synthetic and natural upper mantle materials

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Motivated by theoretical considerations of damped vibrations of dislocations, we have undertaken a laboratory study of the attenuation of seismic waves and associated shear reduction in pre-deformed specimens of upper mantle olivine. Polycrystalline olivine, $(Mg_{0.9},Fe_{0.1})_2SiO_4$, the most abundant upper mantle mineral, is hot-pressed from polycrystals of a solution-gelation precursor powder and deformed in the laboratory under high temperature and pressure conditions. Natural San Carlos olivine is similarly prepared from a powder of crushed hand-picked grains and deformed. Compressional deformation of the cylindrical specimens was carried out at ANU for differential stresses up to 280 MPa and 22% strain. Torsional deformation of the same material was done at the University of Minnesota to a shear stress of 200 MPa and shear strain of 0.5. Micro-structures of the deformed specimens mostly show a foam texture of relatively uniform grain size of 4 µm for the synthetic olivine and ~30 µm for the natural olivine. Dislocations tend to be of mixed edge-screw nature and are heterogeneously distributed. Synthetic samples, deformed in compression, do not show a Crystal Preferred Orientation, whereas preferred orientation is clearly observed in the specimen deformed to larger strain in torsion. In addition, all materials appear to be dry, as determined by infra-red absorption (< 20 ppm water). Therefore there is no contribution to attenuation by the presence of water.

Dislocation recovery experiments were done on samples cut from the end of a specimen, deformed in compression, and annealed under controlled redox conditions and at temperatures up to 1500°C for different durations. Using oxidation-decoration and Backscatter Electron Imaging techniques, we demonstrated a systematic reduction in dislocation density, ρ in olivine as a function of temperature and time. The data were fitted to a second order rate equation ($d\rho/dt = -k\rho^2$) with an Arrhenius temperature dependence of the rate constant, *k*. There is no discernible difference in the rate and activation energy of dislocation recovery between the synthetic and natural olivine of this study. However, previous research (e.g. Karato and Ogawa*,* 1982) showed a recovery rate 1–2 orders of magnitude higher. The difference can be explained by the use of a low resolution light microscope (LM, 1000x) as opposed to a Field Emission Scanning Electron Microscope (8000x). Simply put, 99 in 100 dislocations are not imaged using the LM. The difference of two orders of magnitude in the measured dislocation density is carried through when calculating *k*.

The newly measured recovery kinetics were used to determine the maximum allowed temperature (1100°C) for the maintenance of nearly constant dislocation density during prolonged mechanical testing (>50 hours). Torsional Forced Oscillation (TFO) experiments at different temperatures and oscillation periods (1–1000 s) show that dislocation damping increases with increasing dislocation density resulting from prior compressive deformation towards increasing stress and strain. It is anticipated that work in progress on the natural samples, with a higher average grain size, will show this even clearer due to a reduced effect of grain boundary sliding which also contributes to the damping. Any effect of the mode of prior deformation, compression versus torsion, will also be highlighted in the forthcoming results. Theoretical calculations of resolved shear stress for active slip systems as a function of crystallite orientation, indicate that torsional deformation prior to attenuation experiments may generate a population of dislocations more favourably oriented to dissipate shear strain energy in the TFO tests.

Reference

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Syn-tectonic platform evolution of Late Devonian reef complexes, northern Canning Basin, Australia: implications for platform architecture, paleogeography and mass extinction

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Late Devonian (Frasnian–Famennian) reef complexes of the Fitzroy Trough (northern Canning Basin), are well exposed in a series of predominantly NW-trending limestone ranges and are also distributed across the Lennard shelf in the subsurface. Two major phases of platform growth are represented corresponding to syn- and post-rift activity associated with opening and evolution of the Fitzroy Trough. The older (Frasnian) platforms of the Pillara phase developed on fault-block highs, however, the role of faulting during platform evolution has remained contentious despite previous recognition of syn-sedimentary faults and fault-controlled subsidence to generate the backstepping geometry of these platforms. The younger (latest Frasnian–Famennian) platforms of the Nullara phase with their contrasting prograding geometry developed during post-rift subsidence. We have used analysis of platform-to-basin facies architecture, stacking patterns and distribution of paleokarst to identify likely syntectonic control on platform evolution.

We have identified at least seven third-order phases of Pillara platform growth and demise through the Early to early Late Frasnian in outcrop on the south-eastern Lennard Shelf. All are bounded by flooding surfaces associated with backstepping platform margins and consistent with 2nd order retrogradation. Depositional ages of these flooding surfaces been variably constrained by conodont dating to Frasnian ~Zone 2–3, Zone 3, late Zone 4, Zone 6, late Zone 6, and Zone 9 and all are associated with backstepping platform margins. Only two flooding surfaces are clearly associated with or preceded by relative sea-level falls, one of which was mostly likely controlled by footwall uplift and is best represented in the Hull Range area. A major phase of ~mid Frasnian (Zone 6) progradation leading to platform margin collapse is recognised in two areas (Hull Range and northern Lawford Range). Stacking patterns in coeval fore-reef successions and major influx of coarse siliciclastic sediments suggests that this was probably a eustatic event. It is likely that the Zone 9 flooding event on the south-eastern Lennard Shelf coincided with flooding on the north-western part of the shelf leading to development of the basal platform fringing Precambrian basement. This platform represents the oldest of another seven third-order phases of platform growth which show intial backstepping leading to maximum flooding in the Latest Frasnian and then progradation until the last phase which is retrogradational. Relative sea-level falls are recognised in the latest Frasnian (base of Zone 13a), at/near the Frasnian–Famennian boundary (tectonically influenced) and in the Early Famennian (likely eustatic). In contrast to the Pillara platforms, Nullara platforms are most easily differentiated by these sequence boundaries consistent with overall 2nd order progradation. Backstepping and deepening of the last platform in the Late Famennian suggests a major change in platform style prior to ramp development of the overlying Fairfield Group.

Establishing a sequence–stratigraphic interpretation and the relative dominance of tectonic vs eustatic controls on relative sea-level changes provides an important framework for considering the Frasnian–Famennian mass extinction in the Canning Basin. Elsewhere major emphasis has been placed on relative sea-level rises during the latest Frasnian. These intervals, typically known as 'Kellwasser events' are associated with anoxic facies and positive $\delta^{13}C$ excursions. In the Horsespring Range (SE Lennard Shelf) there are no matching anoxic facies, however, we have evidence for positive excursions in this stratigraphic interval that match similar curves from elsewhere. The $\delta^{13}C$ excursions are associated with elevated TOC but coincide with relative sea-level falls in the region (notably base of Zone 13a) and suggest that they represent burial of organic carbon following sea-level lowering and influx of organics. These data highlight the importance of recognising tectonism during platform development and suggest that anoxia is likely to be a function of other environmental changes and, therefore, a contributor rather than a major driver of the Latest Devonian extinctions.

Depositional and post-depositional controls on reservoir quality, Latest Devonian–Early Carboniferous Fairfield Group, Lennard Shelf, Northern Canning Basin, Australia

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The Latest Devonian–Early Carboniferous mixed carbonate-siliciclastic Fairfield Group has been considered a potential petroleum reservoir on the Lennard Shelf for decades. Although the three formations that comprise the Fairfield Group are recognised reservoir, seal and source rocks in several producing and uneconomic oilfields, these rocks remain under-explored. Surface exposure is very poor but the group is intersected by about 40 wells on the outer northern Lennard Shelf, some of which have core. This study focuses on re-evaluation of the Fairfield Group within a sequence–stratigraphic framework to establish a geological model in which to examine the role of depositional facies and diagenetic modification on reservoir quality.

Mid-Devonian extension resulted in rifting, faulting and compartmentalisation of the Lennard Shelf and growth and demise of Late Devonian reef-rimmed platforms. The Fairfield Group was subsequently deposited on distally steepened ramps during the post-rift subsidence phase. Two major stratal packages separated by a flooding surface can be recognised in all the fault blocks. Available biostratigraphic data indicate a Late Devonian (Famennian) age for the lower package and an Early Carboniferous (Tournaisian) age for the upper package. Fining-upward stacking patterns in the upper package, interpreted from wireline log data, are consistent within fault blocks but facies associations vary between fault blocks indicating lateral facies changes along the Lennard Shelf. Variable stacking patterns in the lower packages within and between fault blocks suggests more complex internal facies arrangements.

Approximately 15 carbonate-dominated and siliciclastic-dominated facies associations are identified in core. Inner ramp facies associations are dominantly carbonate and feature fenestral, typically dolomitised, microbial mats and skeletal packstone to grainstone. The Middle-outer ramp setting is characterised by mixed carbonate-siliciclastic facies associations that feature sharp-based skeletal sandstone and carbonate mudstone. The dominant facies association of the outer ramp to slope is sediment gravity flow-deposited sandstones with distinctive Bouma sequences.

Subtidal to peritidal depositional settings are important for reservoir development. The most productive reservoirs in the Fairfield Group are dolostones with moldic and/or vuggy porosity developed on structurally controlled paleo-highs (e.g. Blina). Other uneconomic reservoirs are known from dolomitic/calcareous sandstones (e.g. Meda). Significant diagenetic processes for porosity enhancement were, therefore, dolomitisation and dissolution of primary carbonate grains. Faults and fractures were important for increasing permeability. Early pervasive dolomitisation of carbonate matrix/cement in wackestones/packstones before dissolution of skeletal grains was effective in secondary porosity development. Dolomitisation of peritidal microbial mats has created high porosity, low permeability units. The outer ramp turbiditic sandstones deposited on the hangingwall of major faults near the edge of the Lennard Shelf represent poorly studied reservoirs. These deeper water sandstones are potentially significant given that several small producing reservoirs on the Lennard Shelf are in sandstones of the overlying Anderson Formation and Grant Group.

SESSION 02RB (RESOURCES)

Geochemistry of the late Archean Windimurra layered mafic intrusion: insights into voluminous mantle melt evolution and the role of fO_2

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The ~2.8 Ga Windimurra Complex is situated in the northern Yilgarn craton in Western Australia, and constitutes one of the world's largest layered mafic intrusions (LMI) with a size similar to that of the Stillwater Complex in Montana. A major difference of the Windimurra Complex compared to other LMI is its apparent lack of voluminous and economically important platinum group element (PGE) deposits, and an apparent deficit in hydrous minerals. The latter can be attributed to a lack of crustal contamination during magma ascent and emplacement, as evident from Sr-Nd isotope systematics [1]. Hence, the Complex offers a unique

opportunity to investigate the role of crustal assimilation in the genesis of LMI, and to study the genesis of voluminous melts of solely mantle-derived origin. In addition, with the absence of crustal geochemical contamination, the Windimurra Complex constitutes an ideal setting for studying the isotopic nature of the depleted mantle underlying the Yilgarn Craton in the Late Archean.

Here, we report major and trace element mineral and whole rock data from a series of core samples from 450 m continuous drill holes into the upper section of the Complex. The rock series shows typical LMI banding of anorthosistic-noritic layers embedded in mafic gabbroic to magnetitite sequences. PGE were investigated in representative rock samples and were all below detection (i.e., < 1 ppb), except for one sample with elevated S contents with PGE concentrations in the lower ppb range. The sequence exhibits extreme Fe enrichment up to 65 wt.% FeO (as total Fe). On the basis of Fe enrichment, two distinct trends can be identified with either downhole enrichment or depletion. Total rock Nb/Ta decrease with Fe content indicating the absence of liquid immiscibility as the cause for the distinct trends in Fe enrichment in upper and lower sequences, respectively. V/Sc vs. P/Nd show two distinct trends that coincide with the opposing Fe enrichment, which argues for a variable oxygen fugacity (fO_2). Modal mineral abundances indicate that strong magnetite-ilmenite accumulation in the lower sequence was the major cause for Fe enrichment (up to 90 modal%), whereas the upper section is characterised by extremely Fe-rich olivine (>Fa90) with substantially less magnetite-ilmenite (< ~25 modal%). The lower sequence shows sparse ol-fsp-opx, whereas the upper sequence is characterised by ol-fsp and rare cpx with a lack of opx. Total V contents in the cumulus magnetite sequence (< 300 ppm) in combination with sub-solidus ilmenite exsolution from magnetite indicate a low initial $fO_2$with increasing subsolidus oxidation. In the upper section, the strong Fe enrichment in olivine suppressed orthopyroxene formation, as indicated by subsolidus orthopyroxene exsolution from olivine.

We interpret the distinct Fe enrichment features result from a combination of physical and chemo-genetic parameters. The apparent lack of crustal assimilation and subsequent water addition resulted in more dry magma conditions compared to other LMI such as Bushveld or Stillwater, and an extreme tholeiitic trend. Massive magnetite crystallisation caused strong decrease in the ferric-ferrous ratio of the remaining liquid, which enabled Fe-rich olivine crystallisation. Magnetite accumulation was followed by fayalite-rich olivine formation in a more reducing environment with physical separation of the ol-mt-pyx rich sequence from a feldspathic assemblage. The latter accumulated on the top of the sequence, possibly assisted by filter pressing. Further geochemical, petrological and isotope data collection is currently under way in order to confirm or disprove this hypothesis.

Evidence for plagioclase re-equilibration under magmatic conditions

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Plagioclase is considered to preserve cumulate geochemistry more effectively than mafic silicates, particularly in layered mafic intrusions (Grove et al. 1984, Morse 2008, Tegner and Cawthorn 2009). Plagioclase is also inferred to be resistant to re-equilibration because it has a low diffusion coefficient, buffered by the charge coupled substitution of $(NaSi)^{5+} \leftrightarrow (CaAl)^{5+}$. Lundgaard and Tegner (2004) have observed that plagioclase phenocrysts from layered mafic intrusions contain far less Fe and Mg than high temperature plagioclase observed elsewhere (i.e. plagioclase analysed from natural basalts and experimental studies) and predicted from thermodynamic calculations. However, Lundgaard and Tegner (2004) suggest the reason for this discrepancy is unclear. This problem could be explained by the re-equilibration of plagioclase. Plagioclase is more likely to re-equilibrate in layered mafic intrusions, as the thermal anomaly is greater and preserved longer. Here we show evidence that suggests plagioclase re-equilibrates, particularly in layered mafic intrusions.

The trace element geochemistry of *in situ* plagioclase phenocrysts was studied across the 3000m Bellevue Core, using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The Bellevue Core intersects Upper Zone and Main Zone lithologies from the Northern Limb of the Bushveld Complex, South Africa. In accordance with data from (Lundgaard and Tegner, 2004) the Fe and Mg in Bellevue plagioclase was found to be significantly lower than expected. LA-ICP-MS traverses across plagioclase confirmed a lack of compositional zoning of major elements, and showed significant heterogeneity with respect to the distribution of minor and trace elements. A diffusion profile was obtained between plagioclase and adjacent clinopyroxene. Scanning Electron Microscopy (SEM) and optical microscopy showed equilibrated textures throughout the length of the core. These observations suggest that the geochemistry of the Bellevue Core has

been significantly altered since primary crystallisation. Either the diffusion coefficient for plagioclase or crystallisation time for layered intrusions is incorrect; or diffusion in layered intrusions is fluxed by the presence of volatiles or brines.

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Platinum-group element geochemistry of mineralised and non-mineralised komatiites and basalts

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Platinum-group elements (PGE) are strongly chalcophile and are therefore potentially sensitive indicators of processes involving segregation and accumulation of sulphide melts from silicate magmas. A large body of new high-precision PGE data for komatiites and komatiite basalts, spanning a wide range of emplacement and crystallisation histories, has been combined with available literature data on PGE in magmatic systems from other barren and variably mineralised environments, to test the effectiveness of platinum-group element geochemistry as an indicator of processes forming magmatic sulphide ores.

Our results show that PGE depletion is not as common or as strong as expected: samples displaying strong (order of magnitude) degrees of PGE depletion represent less than ten per cent of any given data set from any location. The data confirm that most if not all komatiites were sulphide-undersaturated when they separated from their sources and remained undersaturated on eruption. Some ore-bearing komatiite sequences display no detectable depletion, and the degree of PGE depletion is commonly less than expected based on modeling using experimentally-determined D values. Platinum-group element enrichment is more common and spatially widespread than PGE depletion, commonly representing a better target in lithogeochemical exploration, even where samples containing anomalous Ni or S contents are absent. PGE enrichment/depletion associated with sulphide enrichment/segregation can be discriminated from secondary hydrothermal/metamorphic processes and analytical imprecision by co-variance of all PGE, with the exceptions in some cases of Ir, Ru and Os whose abundances may be complicated by the presence of accumulated Ir-Os alloy. Variations attributable to other magmatic processes, such as olivine accumulation and fractionation, can be distinguished by variations in PGE/Ti ratios and strong correlations between Pt/Ti, Pd/Ti, and Rh/Ti ratios in mineralised systems.

The *degree* of PGE depletion is consistent with the relatively low R factors estimated for many komatiite-hosted deposits, which range 20–200 for Thompson, 100–500 for Kambalda, and 300–1100 for Raglan, implying that the volume of magma that interacted with sulphide liquid was relatively small. This is also consistent with the relatively small proportion of komatiites displaying PGE depletion within ore-bearing flow sequences, as only magmas in ore-forming channels or conduits will interact with sulphides. False negatives, i.e. mineralised komatiite sequences with no detectable PGE depletion, are associated with relatively small systems characterised by high magma:sulphide ratios (high R factors).

Basalts and komatiitic basalts show more complex patterns of variation, which can broadly be divided into three categories: 1) systematic PGE depletion over a range of Mg#, as in MORB suites, consistent with retention of sulphide in the mantle during partial melting, 2) increasing PGE depletion with decreasing Mg# in LIP-associated basalts, interpreted to reflect attainment of sulphide saturation during fractionation with subsequent cotectic olivine-sulphide segregation, and 3) variable PGE depletion over a range of Mg# in

komatiitic basalts (e.g., Raglan) interpreted to reflect ore-forming sulphide assimilation and segregation processes. The results of this study confirm that the PGE geochemistry of komatiites and basalts is a powerful indicator to sulphide saturation and ore-forming processes, but that it must be interpreted with the context of physical volcanological and fluid dynamic processes.

SESSION 02EB (ENVIRONMENT)

Stable isotopes of seawater from the Australian North West Shelf

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The stable isotopes of oxygen and hydrogen in seawater, $\delta^{18}O$ and $\delta^{2}H$, can be used as tracers for ocean circulation and mixing of water masses. These isotopes are controlled by evaporation and precipitation at the sea surface, as well as from input of freshwater from land sources. Water masses can have distinct isotopic signatures based on where they form and the regional climatic conditions at the sea surface. As we have shown in our work in the Great Australian Bight, isotopes have more conservative behaviour than temperature and salinity, and can provide information on different mixing conditions of water masses and how they have been modified. This makes them a beneficial tool in regions of complex oceanography and water mass mixing.

This presentation will focus on oxygen and hydrogen stable isotope data from seawater collected from the Australian North West Shelf and Western Australian Shelf. The North West Shelf is an area of complex oceanography and the source region of the Leeuwin Current, which influences shelf waters along the western and southern margins of Australia. Conclusions drawn from this research will contribute to understanding of ocean circulation and water masses around Australia.

The impact of decadal climate variability on estuarine sedimentation: a case study on the Hopkins and Glenelg estuaries, south-east Australia

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The Hopkins and Glenelg estuaries occur along the western coastal plains of Victoria, except for a small section of the latter which extends into south-east South Australia. A study of sedimentation rates, sediment reworking events and palaeoenvironments evident within Pb210-dated sediment cores from these estuaries has revealed three phases of sedimentation between 1977 and 2006. These are:

- Phase 1 (1977–1986). High sedimentation rates with extensive evidence of subtidal sediment reworking and disruption except in protected backwaters.
- Phase 2 (1987–1996). High sedimentation rates with no evidence of bottom sediment reworking by water currents in subtidal settings.
- Phase 3 (1997–2006). Low sedimentation rates (some exceptions in upper gorge regions of Glenelg Estuary) with no evidence of bottom sediment reworking by water currents in subtidal settings.

These sedimentation phases correlate with river discharge trends and decadal-scale regional climate (rainfall) variability. Thus, from sediment core analyses of the Hopkins and Glenelg estuaries, a general *temporal estuarine sedimentation model* can be constructed for the microtidal salt-wedge estuaries of south-west Victoria for the period 1977–2006. This model has three components.

- Major flood events (early 1980s). Significant flushing of sediment from estuarine settings. Slugs of new and disrupted sediment deposited. Extensive reworking and widespread scouring of subtidal bottom sediments. Probable net loss of bottom sediment in subtidal settings.
- 'Normal' period of seasonal high and low flows (1987–1996). High sedimentation rates in subtidal settings. Minimal reworking or disruption of subtidal bottom sediments. Moderate net gain of bottom sediment in subtidal settings.

- Drought period seasonal 'high' and low flows (1997–2006). Low sedimentation rates in subtidal settings. No reworking of subtidal bottom sediments. Small net gain of bottom sediment in subtidal settings.

A consequence of the direct relationship between river discharge and estuarine sedimentation is that shifts in climate variability over decadal and multi-decadal time scales are likely to have pronounced impacts on sediment distribution and mobility within estuarine settings in SE Australia.

Rhodoliths: a new biogenic archive of environmental change?

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Rhodoliths are free-living forms of calcareous, coralline red algae that can be found all around the world, from low to high latitudes, in relatively shallow (0–250m) waters. They can live hundreds of years forming a high-Mg calcite skeleton that presents periodical growth bands.

Recent studies on rhodoliths-forming coralline red algae show that the variation of specific chemical elements along these periodical growth bands seems to reflect the variation through time, of key parameters (such as temperature) in the ambient seawater.

This project is aiming to assess this reliability of rhodoliths as recorders of past environmental changes for temperate to cold waters, as corals are for the tropics. By doing so, through the comparison of chemical analysis of rhodoliths from New Caledonia and Victoria with results from corals and/or instrumental measurements, we believe we will be able to provide with a new high-resolution climatic proxy for temperate and cold waters, where corals can not be used.

Monthly to sub-monthly resolution is obtained by using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA ICPMS) technique on rhodolith transects, in order to analyse trace elements incorporated in the algae skeleton. Sensitive High Resolution Ion MicroProbe (SHRIMP) analysis is used to extract the oxygen isotopes ($\delta^{18}O$) signal out of these slow growing (~0.5mm per year) organisms.

Both of these analytical techniques, combined with accurate datations (^{14}C and U/Th) will help assessing the potential of rhodoliths as reliable recorders of past environmental conditions.

Holocene climate reconstructions and modelling from Australian speleothems

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The use of multiple geochemical tracers to provide quantitative estimates of environment variables is well-known from other paleoclimate archives, for example, the tracers Mg, Sr, ^{13}C and ^{18}O in corals are used jointly to separate and provide quantitative estimates for variables such as SST, salinity and precipitation amount. Networks of coral records are also used to reconstruct tropical climate modes, such as ENSO. From speleothems, however, high-resolution quantitative climate reconstructions over the last millennia are still rare. There is no well-established theory on how to use multiple proxies to separate distinct environmental signals (precipitation, temperature, water balance), and it is not understood how the joint stochastic properties of climate variables—for a range of climate conditions—affect the fidelity of climate reconstructions from speleothems. In this presentation, a preliminary model of an environment+speleothem system is introduced, and investigated using modern statistical techniques. A soil+hydrology model is forced using gridded observed climate data (with a high spatial and temporal resolution) for Australia for the last century. Climate proxies are introduced into this model using four main parameterisations:

- precipitation isotopes are reconstructed for the pre-1960 period using climate-isotope transfer functions, and these water isotopes then transit through the soil hydrology model
- soil carbon isotope variation is reconstructed using a recent hydrobiotic parameterisation
- a speleothem is simulated using a carbonate growth rate model
- trace elements (Ba, Mg) are simulated based on epikarst effects plus the carbonate precipitation model.

All these parameterisations are linked together to form a speleothem multi-proxy model, that is forced by real climate data. Using the statistical method of canonical correlations with a split validation scheme, we show how speleothems from four different sites in southern Australia can be combined to reconstruct various ocean/atmosphere modes including the Southern Annular Mode, the Australian Winter Anticyclone, and the Southern Oscillation and Indian Ocean Dipole modes. These speleothem-based reconstructions are then compared with the same modes reconstructed from historic SLP datasets which span the last century. The model developed here provides a tool for understanding the science of regional climate reconstructions in Australia from speleothems over the last few millennia.

SESSION 02SB (SOCIETAL: IGC SYMPOSIUM)

Living Australia

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Life has had a profound effect on our planet. It has changed the composition of the atmosphere, it has changed the composition of the oceans and it has changed the composition of the sediments laid down on the deep ocean floor, on continental shelves and slopes, in lakes and on floodplains. In so doing, it has had an equally profound effect on this continent, an effect which has shaped the way the continent has developed and the way we live on it. Conversely, the geological development of the continent has had a profound effect on the life which has inhabited it.

Apart from the origin of life, which possibly occurred over 4 billion years ago, the most far-reaching event in the early history of life was the development of oxygenic photosynthesis by cyanobacteria or their precursors during the Neoarchean or earlier. By the Paleoproterozoic, oxygen reached concentrations in the oceans which oxidised the iron in solution and caused it to precipitate as banded iron formation, a resource with which Australia is particularly well endowed.

The next great leap forward was the evolution of the Eukaryotes by symbiogenesis of Archaea, Proteobacteria and Cyanobacteria during the Neoarchean. This allowed the development of sexual reproduction, probably during the Mesoproterozoic, which greatly increased the variation upon which natural selection could operate. Multicellularity evolved several times during the latter part of the Proterozoic among various groups of organisms, allowing the specialisation of cells, and a concomitant increase in their complexity. This altered the planet dramatically such that the world of today is vastly different from the world of aquatic, unicellular organisms which characterised its first 3 billion years.

The first widespread flowering of multicellular life is characterised by the Ediacara biota, shown especially well in its Precambrian context in South Australia. Understanding the relationship of these organisms to modern phyla is proving to be an intractable problem. Postdating the Ediacaran Revolution by a few tens of millions of years, the Cambrian Explosion produced a diverse marine biota in which many modern phyla are recognisable. A snapshot of this explosion can be seen in the early Cambrian fauna of the Emu Bay Shale on Kangaroo Island, where many soft-bodied organisms are preserved.

The invasion of the land probably began in the Proterozoic with algal and cyanobacterial crusts, but it was only during the Cambrian that multicellular non-vascular plants began to colonise the land. These were followed in the late Ordovician by the vascular plants, their evolution allowing the greening of the land away from bodies of water. One of the earliest well preserved vascular plants is the late Silurian *Baragwanathia longifolia* from Victoria. Land plants remained fairly small until the Devonian Transformation which gave rise to the first forests and subsequently, in the Carboniferous, the first forest wildfires.

The coalescing of the continents to form Pangaea in the Carboniferous and the planetary cooling with the onset of the Karoo Ice Age led to large tracts of Gondwana being covered by ice caps and the remainder with an impoverished flora and fauna. It was only with the post-Karoo warming that the flora and fauna diversified and the circumpolar *Glossopteris* flora took over the landscape in the Gondwanan part of Pangaea, leading to the deposition in the latter part of the Permian of the huge black coal deposits characteristic of the southern continents.

The isolation of Gondwana, which had begun to separate from Laurasia during the late Jurassic, inhibited the spread of Eutherians (placentals and their closest relatives) into Australia. The continent's separation from Antarctica and movement northwards subsequently allowed the better adapted marsupials to diversify into many niches.

While *Homo erectus* had reached the Indonesian Archipelago by 750,000 years ago, it did not reach Australia. The arrival of *Homo sapiens* around 50,000–60,000 years ago probably played a major role in the extinction of much of Australia's megafauna by hunting or alteration of the vegetation, while the introduced dingo largely replaced the top marsupial and reptilian predators.

Homo sapiens lived a largely nomadic existence in Australia, at least in part because there were no large-seeded grasses native to Australia and because weather patterns were unreliable. This is perhaps ironic, as the grasses (Poaceae) may have evolved in eastern Gondwana. While there were settlements along the Murray Valley which relied largely on fishing, it was not until the arrival of Europeans and their northern hemisphere crops and livestock that large scale agriculture began in Australia.

Out of Gondwana

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'Out of Gondwana' is a chapter of the new book on Australia's geology being published by Geoscience Australia for the 34th International Geological Congress (IGC) to be held in Brisbane in 2012. As part of this book, Shaping a continent–building a nation: a geology of Australia, this chapter will tell the story of the break up and creation of Australia as the island continent, and how this unique geology has impacted the Australian people. Geoffrey Blainey recognises climate and distance as the two major influences on the historical development of Australia and Australians; and the 'tyranny of distance' was established with the separation from Gondwana. But the Gondwanan history has also bestowed resource riches—coal, gas and oil—which power the Australian economy today.

The Out of Gondwana chapter encompasses the Paleozoic through to the Cenozoic, with a focus on Permian and Mesozoic events as recorded in Australia's sedimentary basins both onshore and offshore. A strong narrative spine is given to the chapter by the progression from a region locked within Gondwana during the Pangaean interval through break up to now an island continent 'girt by sea'. It is a journey from the tropics to polar latitudes and back again, with major events including Late Paleozoic glaciation, Permian coal deposition, and the progradation of giant deltas in the Triassic which now host Australia's major gas fields on the North West Shelf. During the break up new oceans formed in the north and west, to the south and east, as Australia was unzipped from Gondwana during the Jurassic and Cretaceous. Most of Australia's known oil resources are found in failed rifts, on the north-west margin or in the south-east corner, a legacy of the break-up. Today Australia is heading north, colliding with Asia and ensuring a long term future back within a super continent—*Pangaea Ultima*.

Some of the key concepts in our science are well illustrated by this progression out of Gondwana. Australian examples of plate tectonic processes and icehouse to greenhouse super continent cycles that have provided insights of global importance will highlighted in the chapter. For example the rift-drift framework for analysing the sedimentary fill in marginal basins owes much to the work of Australian geoscientists.

Old, flat and red: the origins of the Australian landscape

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The iconic Australian landscape is old and flat and red. The 'red centre' is part of the myth of Australia. So how did it form and when? Why is it red? Moreover, Australian landforms and regolith have had a profound and unique influence on the way people live and how the country developed. The evolution of the Australian continent is the story of development from the great southern continent to the great southern land. The Australian continent has landscapes that have probably been exposed to weathering and erosion for longer than anywhere on Earth. Parts of Western Australia have been subaerial since the Cambrian. The legacy of Gondwana is present over large parts of the continent. There are remnants of landforms and regolith that

began their evolution while Australia was still part of Gondwana. Conditions would have been rather different on a super-continent. Rivers would have been longer, and perhaps the landscape was even flatter!

The separation of the Australian continent from the other southern lands set in train a new set of events. Australia has been moving northwards, and at present is the fastest moving continent on Earth. The continent is also surrounded by passive margins, and as a consequence is very broadly saucer-shaped. On all sides there is an important geomorphic boundary line or zone marking a transition from active processes and younger landforms related to the continental edges, and older landforms and less active processes in the centre. In eastern Australia this is the Great Escarpment, while in the west this is the Meckering Line. These lines do not coincide with continental divides but are rather the inland limit of geomorphic activity that has taken place since continental subdivision. There is some disagreement about how much denudation has occurred, especially around the edges, but is is clear that, although the Australian landscape has been active, there are also relicts of Mesozoic and even earlier landscapes.

The broad saucer shape of Australia contains explanations of its flatness. The Lake Eyre Basin is one of the largest internally draining basins in the world. Other parts of Australia are also internally draining, and have been for long periods. Within such basins sediment may be eroded and transported, but it can only move within the confines of the internal drainage. This means that higher parts of the landscape are eroded, and lower parts are filled up leading to ever greater flatness. The same is also true, if to a lesser extent, to areas inland of the geomorphic boundary mentioned above, even if drainage reaches the continental edges. For example, the middle reaches of the Shoalhaven River upstream from the Great Escarpment now flow at a higher level than they did in the Miocene. Many of the inland rivers such as the Darling River, Cooper's Creek, and the Finke River have very low angle beds. During floods water spreads out over large areas outside the channels. Water also flows slowly through these river systems—it can take months for floods that rise in the upper reaches of the Lake Eyre Basins in Queensland to reach Lake Eyre. Many of these rivers, even during floods, often carry only fine suspended load, so much of the floodplain environment tends to be dominated by clays and other fine sediments.The increase in flatness and the overall very low relief of Australia, especially the central part, has meant that even with Late Cenozoic aridity there has been a tendency for weathering to dominate over erosion. In addition there appear to have been distinct periods of intense weathering. All this has led to weathering profiles that are several 10s and in places 100s of metres deep. Such intense weathering usually leads to the concentration of iron in the upper part of the weathering profile, which in turn helps explain the colour of the 'red centre'. However, not all weathered material is red; much of it is white or light grey. Another important feature is the development of indurated horizons within the upper part of deep weathering profiles. These are resistant to erosion and frequently lead to the development of the flat-topped mountains and tablelands so common in the Australian interior.

In the Late Cenozoic increasing aridity led to the expansion of deserts and the widespread development of dunes. Many of these dunes are also red, reflecting the origin of the sand in iron-rich regolith materials. The dunes, and especially the linear dunes that occur in much of the interior, are also an iconic part of the Australian landscape.

Australia has also been glaciated. The results of Quaternary glaciation are obvious in the Snowy Mountains, and in Tasmania. Not so obvious in the landscape are the consequences of earlier glaciations; Australia is one of the few places in the world where Permian glacial forms and deposits are still exposed at the surface.

Finally, human occupation has had a considerable influence on the Australian landscape. Accelerated erosion has led to much soil loss with both surface stripping and gully erosion occurring within years of European settlement. However, it is also clear that settlement much earlier also impacted the landscape, often as a consequence of 'firestick farming'.

Living on the edge—waterfront views

Brendan Brooke[1], Peter Harris[1], Scott Nichol[1], Ralf Haese[1], Andrew Heap[1], Lynda Radke[1], Paul Taylor[1], Jane Sexton[1], Craig Arthur[1], Martyn Hazelwood[1]
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Australia has developed as a maritime nation, from the reliance on coastal seas for transport and trade to the present day where most of the nation's population, industry, tourism and recreation are located along its coasts. In 'A Geology of Australia', we discuss how coastal geological features and processes have strongly

influenced the pattern of post-colonial settlement and development of Australia, and how our experience of the coast varies radically depending on our location on the continental margin. Examples are provided of the influence of coastal geology on society as well as the impacts people have had on coastal systems.

Australia's coasts have been shaped by geological processes that extend back millennia. The break up of Gondwana and northwards migration of the continent set the position and configuration of Australia's continental shelves. As a consequence, the eastern and western margins today have southwards flowing warm currents and distinctive spatial patterns of biodiversity. The onset of aridity and the repeated fluctuations of sea level during the Quaternary have also left imprints on the coasts and shelves.

The seabed of the continental shelf and coast is both dynamic, with currents that mobilise sediments, and relict, with structures formed under periods of lower sea level. Sea level has been at its present high position for only around 13% of the time over the last 120,000 years. For most (~60%) of the Pleistocene it was 20–60m below its present position. During these low sea level periods, exposed land bridges between the Australian mainland, Papua New Guinea and Tasmania provided important migration routes for the first humans, whilst coastal currents incised the seafloor, creating deep channels and canyons. Today, these channels and canyons represent major challenges for infrastructure, such as gas pipelines.

Multibeam sonar mapping of coastal waters and the shelf has revealed the true geomorphic complexity of the seafloor over large areas. These high-resolution acoustic data in combination with biological surveys are revealing that the distribution of marine biological communities is closely related to seafloor geomorphology. For example, drowned Pleistocene shorelines in the outer part of Ningaloo Reef World Heritage Area (WA) provide habitat for pristine coral and sponge assemblages, whilst the shelf surrounding Lord Howe Island is a drowned coral reef far larger than the modern reef. This information is better informing the monitoring and management of these ecologically and economically important marine environments.

At least half the Australian coast is composed of sand and mud, and is inherently dynamic. Paradoxically, most people and infrastructure are located on these soft 'unstable' coasts, especially around estuaries. Most estuaries trap sediments delivered from the catchment or brought in from offshore by tide and wave-generated currents. As a consequence, estuaries in Australia are often characterised by extensive sandy beaches alongside their entrances and calm inshore waterways, and have been subject to intensive urbanisation.

Estuaries are prone to nutrient enrichment from urbanisation and intensive catchment land use, leading to a decline in water quality and ecological integrity. However, the geomorphology of the estuary also exerts a significant influence on biogeochemical processes affecting nutrient dynamics. For example, the relatively narrow channels of the upper Swan River Estuary (Perth, WA) are turbid, high in phytoplankton concentration with anoxic bottom water and occasional toxic algae blooms. In contrast, relatively broad estuaries such as Wellstead Estuary (Bremer Bay, WA) typically have light penetration to the bottom of the estuary giving rise to abundant seagrass meadows, high benthic primary production, permanently oxic bottom water and low phytoplankton concentrations despite intensive grazing in their catchments. These differences have significant economic and social implications, with the Swan River Estuary requiring multi-million dollar cleanup programs whilst Bremer Bay is regarded as a prime 'sea change' destination.

Finally, the coast is exposed to a range of natural hazards such as cyclones, storms and tsunami. Cyclones and storms regularly give rise to storm surge and shoreline erosion that can have significant economic, social and environmental impacts, particularly where there is extensive infrastructure. Although Australia has never experienced a catastrophic tsunami, it is surrounded to the north and east by 8,000 kilometres of active tectonic plate boundaries capable of generating tsunamis that would reach the coast within two to four hours. Historically, the tsunamis that have created the largest impacts in Australia have come from earthquakes off the south coast of Indonesia. In conclusion, the coastline not only defines the Australian landmass, but has shaped the social, environmental and economic wealth of the nation.

Long-lived, autochthonous development of the Murchison Domain, Yilgarn Craton

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Map, geochronological and geochemical data are used to develop a new stratigraphic scheme and tectonic evolution for the Murchison Domain of the Yilgarn Craton. Greenstones are divided into four groups: 1) c. 2960–2930 Ma Golden Grove Group in the southern part of the domain; 2) 2820–2805 Ma Norie Group of mafic volcanic rocks, felsic volcaniclastic sandstones and banded iron-formation; 3) 2800–2735 Ma Polelle Group of mafic-ultramafic volcanic rocks, intermediate to felsic volcanic and volcaniclastic sedimentary rocks, and banded iron-formation; 4) 2735–2710 Ma Glen Group of coarse clastic sedimentary rocks, komatiitic basalt, and minor rhyolite. Younger greenstone groups display unconformable relationships with older greenstones, whereas the basal Golden Grove Group is intruded by granites. Granitic magmatism accompanied volcanism (2785–2710 Ma) and outlasted it by 110 Ma, becoming progressively more fractionated through time. Deformation included two early periods of greenstone tilting (D_1=2930–2825 Ma; D_2 = 2735 Ma) and two later (D_3 and D_4) events. D_3 structures include tight to isoclinal, steeply-plunging folds of greenstones and granite domes, resulting from inferred partial convective overturn at c. 2676 Ma. D_4 developed in response to strong east-west compression at 2660–2630 Ma, resulting in broad, NNE-striking dextral shear zones, gold mineralisation, and large, upright folds. Post-tectonic granites are 2630–2600 Ma.

The major, late crust-forming events in the Murchison Domain commenced 60 Ma after widespread, yet-to-be-documented, c. 2950 Ma magmatism, with eruption of komatiites sourced at >250 km (Barley et al., 2000) and emplacement of very large layered mafic–ultramafic complexes (e.g. Windimurra Igneous Complex) and further basaltic lavas at 2820–2790 Ma. Nd isotopic data and geochemical modelling show that mantle melts were sourced from juvenile mantle at progressively shallower depths during lithosphere thinning and/or extension.

At 2760–2740 Ma, widespread calc-alkaline andesitic through rhyolitic volcanic rocks were erupted together with felsic to intermediate melts derived from a variety of crustal sources, and basaltic melts that mixed and mingled with felsic melts. This was followed by a brief hiatus and deposition of clastic sedimentary rocks above an angular unconformity. Subsequent komatiitic basalts were derived from shallow mantle melting (<30 km) during renewed lithosphere thinning/crustal extension at c. 2735–2710 Ma.

Collectively, the data indicate autochthonous development of Murchison Domain over 350 Ma. Comparisons with adjacent terranes reveal a common history at 2950 and 2810 Ma, but separate events at 2790–2665 Ma, and common events again from 2665–2630 Ma. Contrasting tectonic models for craton development are discussed in light of this new data, but firm conclusions require additional data, particularly from the Southern Cross Domain.

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New constraints on Palaeoproterozoic tectonism in the Harts Range, Arunta Region, Central Australia

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The Harts Range area of the Arunta Region in central Australia comprises high-grade metamorphic and igneous rocks belonging to the Palaeoproterozoic Aileron Province and the structurally overlying Neoproterozoic to Cambrian Irindina Province. Over the past two decades, investigations in the Harts Range area have mostly focused on characterising late Neoproterozoic to Palaeozoic sedimentation in the Irindina Province, and the deformation and metamorphism associated with the Palaeozoic Larapinta Event and Alice Springs Orogeny (e.g. Mawby et al 1999). In comparison, Palaeoproterozoic tectonism in the area has remained relatively

poorly understood, partly due to locally intense Palaeozoic reworking. However recent mapping by the Northern Territory Geological Survey in the Harts Range (Quartz 1:100k mapsheet) has provided new constraints on the nature and timing of Palaeoproterozoic deformation and metamorphism in the area.

To the north of the north-dipping, Palaeozoic Illogwa Shear Zone, granulite facies metasedimentary rocks are preserved in areas of low Palaeozoic strain. These metasedimentary rocks, which have a likely deposition age of around 1770 Ma, outcrop in the Entia Dome and in the newly identified Alooarjara Metamorphics to the south-east. In the Alooarjara Metamorphics, early migmatitic layering is overprinted by a strong co-axial strain fabric with a north-east to east plunging stretching lineation. In the Entia Dome, Palaeoproterozoic structures and mineral assemblages are only preserved in localised megaboudins surrounded by intense Palaeozoic strain. South of the Illogwa Shear Zone, in the Albarta Metamorphics, metamorphism occurred at mid amphibolite facies and was associated with the development of north-south fabrics.

SHRIMP U-Pb dating of metamorphic monazite and metamorphic zircon overgrowths from Palaeoproterozoic units in the Entia Dome, Alooarjara Metamorphics and Albarta Metamorphics all yield ages ranging from 1735 to 1713 Ma (e.g. Maidment et al 2005; Whelan et al 2008; Worden et al 2008; Carson et al 2009). This suggests that the Palaeoproterzoic tectonism in the Harts Range occurred during the 1730–1690 Ma Strangways Event, and confirms that this event was the dominant Palaeoproterozoic tectonothermal event in the eastern Arunta Region.

Calculations of metamorphic conditions from a number of localities in granulite facies Palaeoproterozoic rocks in the Harts Range area north of the Illogwa Shear Zone suggest peak temperatures in the range 750 to 925ºC and pressures of 8.1 to 10.6 kbars. PT analysis of a metapelite in an area of low Palaeozoic strain in the north-western Entia Dome yielded estimates of 845–925°C and 8.1–9.0 kbars. In the northernmost outcrops of Alooarjara Metamorphics, immediately south-east of the Entia Dome, metamorphism occurred at 750–900°C and 8.9–10.6 kbars, associated with poorly constrained zircon rim growth at 1730±17 Ma. An isolated klippe of Alooarjara Metamorphics in the Bruna Gneiss, 10 km south of the Entia Dome, was metamorphosed at 830°C and 9.3 kbars. These estimates are similar to, although slightly cooler than, the P-T conditions calculated for the Strangways Range, 50–100km west of the Harts Range, (8–9 kbar and 850–950ºC; Goscombe et al 1992, Diener et al 2008), but the similarities in structural style and timing of metamorphism suggest that the areas experienced a similar tectonic evolution during the Palaeoproterozoic.

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An Australian tectonic reconstruction at ~1650 Ma: a Baltica link

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Aspects of the tectonic history of Paleo- to Mesoproterozoic Australia are recorded by metasedimentary basins in the Mt Isa, Etheridge Provinces, and Coen Inlier in northern Australia and in the Curnamona Province of southern Australia. These deformed and metamorphosed basins are interpreted to have been deposited in a tectonically linked system based on similarities in depositional ages and stratigraphy (Giles at al 2002). Neodymium isotope compositions of sediments and felsic volcanics, when combined with U-Pb geochronology, are independent data that are important tools for inferring tectonic setting, palaeogeography and sediment provenance in deformed and metamorphosed terrains.

Basin fill from the Mt Isa, Etheridge and Curnamona Provinces which accumulated in the interval 1780-1650 Ma, is characterised by age components of ~1840 Ma, 2500-2750 Ma and 2900-3100 Ma, and has $\varepsilon_{Nd(1650\ Ma)}$ values of -8 to -6. Subsequent successions that accumulated at ~1650-1640 Ma have few Archean detrital zircons, are characterised by ~1650 Ma detrital grains, contain volcaniclastic intervals around 1650 Ma in age, and have $\varepsilon_{Nd\ (1650\ Ma)}$ values of -2 to -1. The Nd isotopic difference and change in age profile of zircon defines a continental-scale isotopic signal which has been documented in the Etheridge Province, and in the Eastern Fold Belt of Mt Isa, with a decreasing influence into the Western Fold Belt of Mt Isa. A similar transition at ~1650 Ma has also been documented in the Broken Hill and Olary Domains of the Curnamona Province (Barovich and Hand 2008) and in the Coen Inlier (Blewett et al. 1998).

No significant juvenile magmatism is known to occur in Paleoproterozoic eastern Australia at ~1650 Ma. Thin tuffs are known within 1660-1640 Ma sedimentary units in the Western Fold Belt of the Mt Isa Province (Page et al. 2000; Page, 1981), the Eastern Fold Belt contains one known thin rhyolite band (Page & Sun 1998) and only minor felsic peperites are known in <1650 Ma successions in the Etheridge Province. However, Nd and zircon U-Pb isotopic data suggest proximity of an as yet unidentified, relatively juvenile source that contributed detritus on a continental scale at ~1650 Ma. Although significant felsic magmatism is known in the Western Fold Belt at ~1670 Ma, these granites and rhyolites have more evolved $\varepsilon_{Nd\ (1650\ Ma)}$ values of -5, and are incompatible with the Nd data from the <1650 Ma successions. Hence, no local source is compatible with the influx of juvenile detritus at ~1650 Ma. Page et al. (2005) and Barovich and Hand (2008) attributed the felsic source in the Curnamona Province sediments to be tuffaceous air fall deposits, which can be transported long distances from the source volcanism.

The unidentified source to the north-east of Australia requires juvenile magmatism occurring simultaneously with basin development at 1650-1600 Ma, which is then halted by basin closure and tectonism at 1600-1550 Ma. Provinces with ~1650 Ma felsic juvenile magmatic events coupled with basin development at ~1650 Ma and later 1600-1550 Ma tectonism are sparse. Globally, juvenile ~1650 Ma felsic magmatism occurs in Laurentia (Bennett and Depaolo 1987; Karlstrom et al. 2001) and in Baltica (Brewer et al. 1998; Ahall et al. 2000). South China (Li et al. 1995) and Siberia (Sears and Price 2003) are not known to record these ~1650 Ma magmatic events and we do not consider models linking Australia with these provinces as geologically viable, preferring linkages with either Laurentia or Baltica.

The AUSWUS reconstruction (Karlstrom et al. 2001) uses palaeomagnetic data from 1550 to 750 Ma. However, the palaeomagnetic data at ~1650 Ma (Chandler and Morey 1992) are not consistent with the AUSWUS configuration. Similarly, the AUSMEX-like configuration (Wingate et al. 2002) does not satisfy the 1650 Ma palaeomagnetic data. The SWEAT configuration of Dalziel (1991); Moores (1991) and the modified SWEAT model of Betts et al. (2008) are not supported by the lack of proximity to a juvenile felsic source. A tectonic reconstruction is provided here based on the Pesonen et al. (2003) reconstruction model at 1650 Ma. In this model, palaeomagnetic data allow Australia and Baltica to be located west of Laurentia with the Baltica Idefjord terrane providing a major source of juvenile detritus present in late Paleoproterozoic eastern Australia.

North Queensland geodynamics—a new subsurface perspective

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As part of initiatives by the Australian Government, Queensland Government and AuScope, four new seismic reflection lines and three corresponding magnetotelluric lines were acquired in 2007 over the Mt Isa, Georgetown and Charters Towers regions. These data, combined with existing multidisciplinary data, have provided new insights into the 3D architecture, geodynamics and economic potential of the North Queensland region.

The eastern extremity of the Mt Isa Province marks the site of a major crustal feature, which is imaged in the 07GA-IG01 seismic line as a major change in crustal reflectivity and a series of mid to upper crustal west-dipping reflections, with abrupt crustal thickening to the Moho in the west. This boundary is also a prominent feature in the gravity, aeromagnetic and magnetotelluric datasets. This geometry places the economically significant IOCG deposits of the Mt Isa Eastern Fold Belt in the hangingwall of this structure. To the west of this structure, reflectivity is relatively homogenous through the crust. In contrast, to the east there is a highly reflective lower crust termed the Numil Seismic Province, overlain by a less reflective upper crust, the Kowanyama Seismic Province, which is probably a subsurface equivalent of the Etheridge Province to the east. In the upper crust, the seismic and MT datasets also image a relatively flat-lying, mildly inverted stratigraphic succession of undetermined age, termed the Millungera Basin.

The north-eastern end of the 07GA-IG01 seismic line, in the Croydon area, images a major crustal structure that continues from the mid-crust into the mantle and offsets the Moho by ~6 km. We interpret this to be a possible relict subduction zone similar to examples described in seismic sections from Canada and north of Scotland. The magnetotelluric 2D conductivity section also images a conductivity change at this locality, with the region to the east showing significantly lower conductivity. The crust to the east of this structure images a highly reflective lower crust (Abingdon Seismic Province) and a less reflective upper crust (Etheridge Province), which continues to the intersection with the 07GA-IG02 line. The east-west trending 07GA-IG02 line images two distinctive crustal layers, with the upper less reflective crust interpreted to be the Etheridge Province and the underlying highly reflective zone interpreted as possible Archean or Paleoproterozoic age, termed the Abingdon Seismic Province.

Both 07GA-GC01 and 07GA-A1 seismic lines image the eastward-tapering termination of the Abingdon Seismic Province. This interpretation is consistent with Sm-Nd isotopic data and inherited zircon ages from granites, which show old model crustal ages in the west, intermediate ages above the tapering Abingdon Seismic Province and younger ages further east. To the south-east of the mapped location of the Tasman Line, the mid to lower crustal reflectivity is defined as the Agwamin Seismic Province. The Sm-Nd data suggests a more juvenile crust in this region. Overlying this province, the Greenvale and Charters Towers Provinces have been mapped as two discrete provinces. The seismic interpretation raises the possibility that these two provinces are continuous in the subsurface, and also extend northwards to beneath the Hodgkinson Province, originally forming part of an extensive Neoproterozoic-Cambrian passive margin. Continuation of the Neoproterozoic-Cambrian passive margin at depth beneath the Hodgkinson and Broken River Provinces suggests that these provinces (which formed in an oceanic environment, possibly as an accretionary wedge at a convergent margin) have been thrust westward onto older passive continental margin.

The Tasman Line, originally defined to represent the eastern limit of Precambrian rocks in Australia, is an east-dipping fault beneath the Hodgkinson Province, but is a west-dipping fault beneath the Etheridge Province. This variation in structural character indicates that there is not a simple structure in this region and so the concept of the Tasman Line needs to be redefined.

International timescale calibration of the Late Permian – Early Triassic of Australia

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The Late Permian – Early Triassic interval of Australia contains a predominantly endemic biota. A paucity of international marine index fossils, in particular conodonts and ammonoids, has previously precluded precise correlation with standard northern hemisphere marine sequences and internationally established System and Stage Global Stratotype Sections and Points (GSSPs). The Permian-Triassic boundary and other Late Permian and Early Triassic stage boundary levels, and the major end-Guadalupian and latest Changhsingian (end-Permian) mass extinction levels in Australia remain poorly constrained. Attempts to calibrate the Late Permian – Early Triassic of Australia using U-Pb analyses on of zircons from volcanic products using micro-beam Sensitive High Resolution Ion Microprobe (SHRIMP) techniques have resulted in controversial radio-isotopic ages with per cent-level uncertainty and accuracy that may be compromised due to the use of a standard which is now deemed unsuitable. We will present new high-precision biostratigraphic, isoptopic geochronologic (U-Pb IDTIMS ages on chemically abraded individual zircons with permil-level resolution) and chemostratigraphic data that provide important international timescale calibration points in the Late Permian – Early Triassic of Australia. We expect that through integration of U-Pb and 40Ar/39Ar geochronology with chemo- and biostratigraphy, that the time scale of the Late Permian – Early Triassic of Australia will be greatly improved and will lead to more realistic evaluation of high-latitude end-Guadalupian and end-Permian biotic crises and their aftermaths and greater understanding of climate change in Australia and globally during this economically important time period.

The mountains that triggered the Late Neoproterozoic increase in oxygen and the radiation of animals

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The concessus view is that the O_2 concentration of the Archean atmosphere was very low and that it rose to its present level of 21% in a series of steps, two of which dwarf the others in importance. The first, known as the Great Oxidation Event, occurred at ~2.4 Ga. It involved an increase in the relative abundance of O_2, which has been estimated at four orders of magnitude, and it is important because it led to the first surface weathering. The second, although less important in relative terms, involved the addition of $9x10^{17}$ kg of O_2 to the atmosphere, about ten times as much as that required to produce the Great Oxidation Event. Its importance lies in the fact that it correlates with the rise of animals in the Ediacaran and Early Cambrian periods. Although it is widely accepted that an increase in atmospheric O_2 facilitated the appearance of animals at ~575 Ma, followed by the Cambrian Explosion ~50 Myr later, the cause of this increase remains controversial. We show that the surge in the O_2 level near the Precambrian-Cambrian boundary correlates with major episodes of continent–continent collision associated with Gondwana's amalgamation, including convergence between East and West Gondwana, which produced the 8,000-km-long Transgondwanan Supermountains. The eroded roots of these mountains include the oldest lawsonite-bearing blueschists and eclogites, and ultra high-pressure metamorphic rocks. The sudden appearance of these low-thermal gradient, high-pressure metamorphic rocks implies that the Gondwanan orogenic zones were cooler and stronger than those associated with the assembly of earlier supercontinents and therefore capable of supporting higher mountains.

There is a long-linear relationship between relief and erosion rate, and a linear relationship between sedimentation rate and organic C burial. Taken together these two relationships imply a log-linear relationship between relief and C sequestration. We suggest that the Gondwanan supermountains were appreciably higher than those produced during the assembly of earlier supercontinents and that rapid erosion of these mountains released a large flux of essential nutrients, including Fe and P, into the rivers and oceans, which triggered an explosion of algae and cyanobacteria. This, in turn, produced a marked increase in the production rate of photosynthetic O_2. Rapid sedimentation during this period promoted high rates of burial of biogenic pyrite and

organic matter generated during photosynthesis so that they could not back react with O_2, leading to a sustained increase in atmospheric O_2.

Modern humans extant at least 195 ka ago

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The provenance and age of two *Homo sapiens* fossils (Omo I and Omo II) from the Kibish Formation in southern Ethiopia, have been much debated. We confirm that Omo I and the somewhat more primitive-looking Omo II skulls (calvariae) are from similar stratigraphic levels in Member I of the Kibish Formation. Based on $^{40}Ar/^{39}Ar$ age measurements on alkali feldspar crystals from pumice clasts in the Nakaa'kire Tuff, a tuffaceous bed in Member I just below the hominin levels, we place an older limit of 198 $\pm$ 14 ka (weighted mean age = 196 $\pm$ 2 ka) for the hominins. A younger limit of 104 $\pm$ 7 ka (weighted mean age = 104 $\pm$ 1 ka) is provided by feldspars separated from pumice clasts in the Aliyo Tuff in Member III. Geological evidence indicates rapid deposition of each member of the Kibish Formation in deltaic environments associated with the Omo River, about 100 km north of Lake Turkana, when the level of Lake Turkana was up to 85 m higher than at present, and close to the Omo-Nile divide. This is a consequence of much greater precipitation in the Ethiopian highlands, the source of the Omo River and much of the water in Lake Turkana, which is within a closed basin. The members of the Kibish Formation were deposited at the same time as sapropels formed in the Mediterranean Sea, with the overall control determined by the Milankovich cycles. The sapropels are also formed during intervals of much higher runoff of freshwater from the Ethiopian highlands, in this case via the Nile river system. Between the dated layers in Member I and Member III are two disconformity-bounded sequences in Member II (IIa and IIb), which we interpret as being deposited at the same time as sapropels in the Mediterranean astronomically dated at 124 and 172 ka. The $^{40}Ar/^{39}Ar$ age measurements, together with correlations with sapropels, indicate that the hominin fossils are close in age to the older limit. Our preferred estimate of the age of the hominins is 195 $\pm$ 5 ka, making them the earliest well-dated anatomically modern humans yet described.

SESSION 02TB (TOPICAL: BRIAN LOGAN SYMPOSIUM)

Carbonate platform signature of greenhouse worlds

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Carbonate platforms that have developed under fully greenhouse conditions characterised by little or no ice at the poles, high carbon dioxide levels, and relatively high average global temperatures have distinctive stratigraphic signatures that can be used to define times of global greenhouse climates. The signatures reflect the dominance of precessional and millennial-scale forcing, that drives small sea-level changes. Stratigraphic successions on shallow platforms in greenhouse worlds are dominated by meter-scale, typically upward shallowing parasequences. In peritidal settings, the parasequences commonly are dominated by shallow water carbonates, that shallow up into well developed and extensive, microbially laminated caps and if sufficiently arid and restricted, evaporites. In humid settings, capping microbial laminates may be absent and upper parts of parasequences are disrupted by fenestral units and root structures and may be capped by paleosols or microkarst; transgressive laminites may occur at bases of these cycles perhaps reflecting more arid conditions during initial transgression. Subtidal parasequences toward ramp/shelf margins commonly coarsen upward, and if the shelf is sufficiently wave-swept, will be capped by hardgrounds marking the limit of shallowing. In intrashelf basins downdip of peritidal platforms, meter scale cycles may be upward-shallowing units from subwave base muds up into storm deposited coarse grained facies and hardgrounds; alternatively, upward-deepening cycles may be developed in which the sea level fall removes the regressive portion of symmetrical, transgressive-regressive cycles, leaving only the upward-deepening portion capped by a hardground, overlain by coarse grained resedimented facies as sea level starts to rise again.

On the peritidal platforms, emergence breccias and paleosols generally are not common, except toward sequence boundary zones, which develop when the platforms become emergent for substantial amounts of

time. The sequence boundary zones typically have two or more breccia/paleosol horizons rather than a single sequence bounding unconformity. Significant sea level falls of some tens of meters can occur at the sequence boundaries, indicated by oxygen isotopes in conodont apatites. These interupt long periods (1–3 m.y.) of relatively small precessionally forced sea level changes and probably are due to relatively short lived global cooling events within an overall greenhouse climate.

If deposited in shallow water, buildups during greenhouse times tend to contain cyclic platform interior facies, with capping peritidal units. If deeper, then the buildups tend to be dominated by relatively non-cyclic subtidal facies, with rare deeper water incursions perhaps marking periods of increased accommodation (rapid sea level rises or pulses of subsidence).

Any stable isotope excursions at the parasequence scale likely relate to early diagenetic effects. However, primary stable isotope excursions are evident at the parasequence-set scale (perhaps defining 100 k.y. fluctuations) in which C and O signatures become heavier toward parasequence set boundaries). This could reflect evaporation effects in nearshore restricted water masses (oxygen) and high productivity in near-shore shallow waters. Preservation of precessionally dominated successions requires that there is little 100 or 400 k.y. signal in the sea level curve (in contrast to icehouse conditions). If there is sufficient accommodation, this allows most precessional beats to be preserved on the platform (along with autocycles related to local shallowing and allocycles associated with jerky subsidence events). Preservation of millennial scale cycles on the shallow platforms typically reflect higher accommodation rates that are capable of recording the small millennial sea level beats on the platform. With lower accommodation, many such beats are missed and the precessional signal becomes the dominant signal recorded. True greenhouse conditions with their characteristic platform stacking patterns typify the late Early Cambrian to Early Ordovician, Late Silurian to Middle Devonian, the Late Permian, Triassic, Late Jurassic-Early Cretaceous, parts of the Late Cretaceous, and the late Paleocene- mid-Eocene. Most of these times coincide with times of postulated high temperatures on the globe based on climate proxies and geochemical modelling.

Stromatolite morphogenesis: the legacy of Brian Logan's work on stromatolite classification

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Brian Logan (1961) published the first description of modern stromatolites from Hamelin Pool, Shark Bay, Western Australia, that were comparable to the stromatolites described by Kalkowsky (1908) from the *locus typicus* in the Buntsandstein of North Germany. Logan used the name 'Cryptozoon' to describe the lithified modern forms, though they differed markedly in form from type specimens of this form (Hall, 1883), and he contrasted them with domed algal mats that he referred to 'Collenia'. Dissatisfied with the existing use of quasi-Linnean binomial nomenclature to describe Stromatolites, Logan then collaborated with Robert Rezak and Robert Ginsburg (1964) to create a system of stromatolite classification. This was based on arrangements of simple geometric forms such as hemispheroids and spheroidal laminae. Structural formulae were used to describe the associations of these forms within typical stromatolite structures. The underlying logic for this scheme was that diversity of stromatolite form is produced by diversity of environment interacting with the microbial mat and sediment so that correct interpretation of the structure, based on modern occurrences, is potentially useful in reconstructing events and environments in stromatolite-bearing strata throughout the geological column. It was recognised that other geometric forms would need to be added, but only when modern examples were discovered. This scheme was fundamentally limited by the two false assumptions that (a) the Hamelin Pool stromatolites were restricted to the intertidal or near intertidal zones, and (b) that the forms were influenced simply by location, exposure and tidal amplitude. We now know that much of the Stromatolite growth in Hamelin Pool occurs subtidally, and that relative fall in Holocene sea level has strongly influenced the evolution of the stromatolite associations (Burne 1992). In subsequent years the study of stromatolites became polarised between those dealing with Precambrian and Archean biostratigraphy, who continued to employ a quasi-Linnean binomial system of classification (Grey 1989), and sedimentologists and palaeoecologists who have sought a more appropriate descriptive system based on stromatolite morphogenesis. A promising approach that has evolved in recent years has been the application of the mathematics of evolving surfaces to the modeling of typical stromatolite growth patterns, and the explanation of the variables in these models in terms of specific environmental influences (Batchelor et al. 2004, 2005).

However Brian Logan's work remains the first attempt to provide a system for the ecologically meaningful classification of stromatolites.

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SESSION 02RC (RESOURCES)

Improvements to the Australian crustal temperature image

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Unlike conventional geothermal resources in volcanically active areas, Australian geothermal resources generally have no surface expression. Exploration for these resources has relied heavily on compilations of bottom hole temperature data obtained mainly from the petroleum industry. These data were first used to produce images of the crustal temperature at 5 km depth by Somerville et al (1994). Chopra and Holgate (2005) updated the image with improved data QA and different interpolation techniques. The extrapolation of temperature to 5 km depth is based on a simple two layer model defined by depth to basement models and surface temperature information.

The crustal temperature images have provided the emerging Australian geothermal industry with continental scale information on the heterogenous nature of the shallow temperature field within the Australian crust. The images have also provided a simple illustration of Australia's geothermal potential and have played a significant part in raising the awareness of the industry amongst the wider population. Due to limitations in the source data there are a number of restrictions to the interpretation which limit the application of the images as an exploration tool at anything but the broadest scale.

There has been a need to update the interpretation of crustal temperature as more temperature data have become available. The database has been expanded and updated with data sourced from State Geological Surveys, legacy heat flow studies and the geothermal industry. Major improvements include: updates to data in the states of Victoria and New South Wales; the identification and removal of around 500 duplicate or inaccurate data points; and the updating and standardisation of data fields including well name, spatial references and datum, borehole depths and elevations. Although relatively small in number, data made available by the geothermal industry is of particular significance as it is generally located in areas of previously sparse coverage. A new image has been constructed from a database which now contains 17 136 temperature and/or temperature gradient records from 5 409 individual boreholes located in both the on- and off-shore regions of Australia.

Additional data used in the extrapolation (to depth) and interpolation (spatially) of the temperature data has also been improved. The use of the SEEBASE™ depth to basement model is a significant improvement on the model used in previous versions of the temperature image. New surface temperature data for on-shore and off-shore areas have been sourced from CSIRO and the Bureau of Meteorology respectively to improve the

estimation of the geothermal gradient used in the extrapolation of the temperature to 5 km depth. A surface temperature correction has been applied to the on-shore data. The basis for this correction is a uniform value suggested by Beardsmore and Cull (2001); however the correction has been refined using soil temperature data also sourced from the Bureau of Meteorology. Legacy heat-flow data has been used to help constrain the temperature extrapolation through defining heat-flow provinces and applying varying basement geothermal gradient values.

Despite significant improvements to temperature data QA and to the ancillary data used, the appearance of the final image has not changed dramatically. The greatest limitations to the interpretation of the crustal temperature remains the distribution of the temperature data and the simplistic model used in the temperature extrapolation to depth. Realistically, the large areas of the continent without deep bottom hole temperature readings are not likely to be in-filled in the near future and surface heat flow measurements are a more effective method to acquire data for these areas. Heat flow modelling is also a more robust method for estimating temperature at depth. Geoscience Australia is working to improve the coverage of publicly available heat flow data as there are currently less than 150 onshore points for the continent. Another source of error is the depth to thermally conductive basement (as opposed to petroleum focused basement models largely centred on preserved porosity/permeability) and there remains a need for better mapping of this.

The National Geochemical Survey of Australia: why, how and when?

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In August 2006, the Australian Government announced its Energy Security Initiative, allowing Geoscience Australia to initiate a major program of onshore and offshore activities. The ambitious National Geochemical Survey of Australia (NGSA) project was launched in January 2007 as part of this program because until then Australia lacked a complete geochemical data coverage. Such a dataset informs on the concentrations and distributions of chemical elements in the near-surface environment. This pre-competitive knowledge, used in combination with other datasets, can contribute to making exploration for energy and mineral resources more cost-effective and less risky by helping target more detailed activities. As a spin-off, the multi-element dataset can also have applications in the fields of natural resources management, land-use decision-making and geohealth, for instance.

During precursor pilot projects carried out between 2003 and 2006 in the Riverina, Gawler and Thomson regions, various sampling media, grain-size fractions and analytical methods were tested. In particular, it emerged that catchment outlet sediments from either overbank or floodplain settings or from similar low-lying settings were an ideal sampling medium that could be found across Australia. These sediments are, by their very nature, well-mixed composites of contributions from the dominant rock and soil types found within a catchment. Further, being deposited during times of receding floods, they are typically fine-grained, a beneficial property that enhances the geochemical signal-to-noise ratio. The data from the pilot projects indicated that even surface catchment outlet sediments could reflect geochemical signatures from basement and mineralisation, even when covered by thick transported overburden.

Building on these methods, the NGSA project targeted catchment outlet sediments as a uniform sampling medium. A shallow (0–10 cm) and a deeper (~50–90 cm) sediment sample were collected at the outlet of 1187 catchments covering ~80% of the country between mid 2007 and late 2009. Access difficulties prevented the remaining area from being sampled. Sampling was carried out by State and Northern Territory geoscience agencies following protocols described in a detailed Field Manual and practiced during in-field training with Geoscience Australia project staff. All sampling equipment (augers, shovels, etc.) and consumables (bags, labels, etc.) were provided centrally in an effort to streamline the sampling process and minimise contamination risk. Dry and moist Munsell colours, soil pH, digital photographs, geomorphological information and GPS coordinates were recorded in the field.

In the laboratory, these transported, fine-grained regolith materials were dried and a split was archived for future use. Electrical conductivity and pH of 1:5 (soil:water) slurries and laser particle size distribution are recorded on part of the remaining bulk split. This split is further dry-sieved into two grain-size fractions (<2 mm and <75 μm) for analysis by x-ray fluorescence (XRF) and inductively-coupled mass spectrometry (ICP-MS) after total digestion, and by ICP-MS after aqua regia digestion (including low level gold), as well as by specialised methods for platinum group elements, fluorine and selenium. All procedures are documented in a detailed

Sample Preparation Manual. Additional analysis methodologies are being considered, and in some cases applied, through collaborative agreements with research and commercial organisations.

Quality control consists of minimising contamination in the field and laboratory, sampling every 10th catchment in duplicate and inserting blind laboratory sample splits, project and international standards and certified reference materials (CRMs) in the suite of samples sent to the various laboratories. In addition, each laboratory has its own quality control measures of repeating analyses and inserting CRMs in the analysis stream.

As at December 2009, both the sample collection and the sample preparation phases were completed. The sample analysis phase is well under way, with expectations to reach completion by the end of June 2010. Data analysis and interpretation will take place during financial year 2010–2011, with the public release of data, geochemical maps and reports planned for June 2011.

Australia's new marine research vessel: geoscience implications

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A new research vessel will replace the *Southern Surveyor* as Australia's marine national facility in 2013. CSIRO is leading the commissioning of the new vessel. An increased level of Federal Government funding means that a very high quality vessel, with excellent equipment and adequate support staff, will be at sea for about 300 days per year from 2013. The new vessel will be about 85 m long, ice strengthened, with a large open rear deck, have a range of 12,000 nautical miles, an endurance of 60 days, and be able to carry a scientific contingent of up to 50, which is a significant improvement over the current situation. It will be a very thoroughly equipped vessel (see www.
marine.csiro.au/nationalfacillity/management/RCAP_PII_Report_Exposure_Draft.pdf).

As far as marine geoscience requirements are concerned, the vessel will be fitted with full-ocean depth (5–8,000 m) multibeam sonars and a sub-bottom profiler so that for the first time it can map our entire marine jurisdiction. Other essential geoscience equipment includes: deep-sea winches and heavy wire for dredging, long (up to 30 m) piston-corer, deep-water grabs with camera, and 2D capable seismic system.

Detailed specifications, including equipment type and capabilities, were drawn up in 2009 and formed the basis of the Statement of Requirements based on consultation with the marine geoscience community (see http://www.iodp.org.au/index.php?p=news). Much equipment will be modularised, with specialised equipment and laboratories fitted into removable containers. The vessel will also be able to handle large items such as remotely operated vehicles and deep towed geophysical equipment and cameras. Dedicated space for a gravity meter is being incorporated into the ship design, although procurement of the gravity meter is unlikely to be part of the initial round of funding.

By January 2010, it was still unclear how much the construction of the vessel would cost, and thus how much would be available for equipment. At this stage the high-level technical advisory group, of which Exon and Heap are members, is concentrating on including essential built-in equipment, such as winches, corers, multibeam sonar, and seismic compressors, and spaces for handling, analysing and storing samples.

There is no doubt that the new vessel will be a huge step forward for Australian marine science. There will be a focus on multi-disciplinary voyages and an active program for student participation. This vessel is a once-in-a-generation opportunity to develop the capability required for Australia to better understand and manage our huge marine jurisdiction. This will underpin and enhance Australia's international reputation as a leading marine science nation.

Australian energy resource assessment 2009

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Australia's economic wealth is built on an abundance of energy resources. Geoscience Australia and ABARE have undertaken an assessment of Australia's energy resources as a contribution to government policy to ensure Australia's long-term energy security. Both non-renewable and renewable energy resources were assessed including oil (crude oil, condensate, LPG and oil shale), gas (conventional gas, coal seam gas, tight gas, shale gas and gas hydrates), coal, uranium and thorium, geothermal, hydro, wind, solar, wave and tidal, and bioenergy. The assessment includes an analysis of the current resource base and market for each of these commodities, and the outlook to 2030 taking into account technology advances and global and domestic drivers.

The assessment documents Australia's abundant, high quality and diverse energy resources. Australia is the world's ninth largest energy producer, accounting for about 2.4% of the world's energy production. Coal, uranium and natural gas currently account for 54, 27 and 11% respectively of production by energy content. Australia's primary energy consumption is strongly dominated by fossil fuels with oil and gas accounting for 55% and coal 40% with renewables making up the remaining 5%.

Australia's very large coal resources underpin domestic electricity generation and major exports of thermal and metallurgical coal. New low emissions technologies are being developed to enable coal to continue to be a major fuel in a carbon-constrained future. Australia has the world's largest resources of uranium and thorium (a potential future nuclear fuel). Coal, uranium and liquefied natural gas (LNG) exports are projected to continue to grow strongly to 2030 driven by global energy demand.

Australia's gas resources are becoming increasingly important. Coal seam gas (CSG) resources in eastern Australia are growing rapidly to complement the conventional, largely offshore, gas resources. Australia's combined gas resources are substantial and provide a firm base for domestic use, including a greater role in electricity generation, and for export, as LNG. Future trends include the development of giant offshore gas fields for export LNG and condensate production, and the increasing role of unconventional gas including CSG LNG projects. Condensate represents more than half (53%) of Australia's liquid hydrocarbon resources with the remainder being made up of crude oil (27%) and naturally occurring LPG (20%). The potential for the discovery of future oil resources in Australia's frontier basins is yet to be adequately assessed.

Australia has very substantial undeveloped renewable energy resources especially solar, wind, bioenergy, wave, and geothermal. In contrast, Australia's hydro energy resources — the most mature of the renewable energy technologies — are largely developed. Australia's wind resources are among the best in the world, primarily located in western, south-western, southern and south-eastern coastal regions but extending hundreds of kilometres inland. This potential is being rapidly exploited through the development of large (100–200 MW) wind farms based on mature turbine technology. Australia also has a world-class wave energy potential along its south-western and southern coast, and tidal resources located mostly along its northern margin. Australia has a large and diverse range of potential bioenergy resources that can be used to produce electricity and transport (bio)fuels. New technologies (including new generation crops) are expected to significantly increase the importance of bioenergy. Australia's high annual solar radiation provides a substantial potential energy source which is being increasingly utilised by off-grid distributed PV and solar thermal heating. Investment in RD&D aimed at developing and commercialising large-scale solar thermal power stations is increasing. Australia's geothermal resources are associated with buried radiogenic granites and are a potential source of base load electricity generation. Lower temperature resources in hot sedimentary aquifers have potential for electricity generation and direct use.

Development of Australia's renewable energy resources is being accelerated by government policy and R&D support. However, large-scale development and utilisation of many of these resources will require establishment of commercially-viable technologies at a significant scale, and greater access to the transmission grid. Fossil fuels will continue to dominate Australia's energy mix in the period to 2030.

Exploration targeting criteria for hydrothermal Ni systems

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Hydrothermal systems that result in Ni transportation and precipitation are relatively rare. They are economically less important than lateritic or magmatic Ni sulfide deposits because of their smaller tonnages and lower grades of 0.1 to 2 wt.% Ni. However, the recent discovery of hydrothermal Ni occurrences in Papua New Guinea, which contain up to 43.5 wt% Ni, indicates that very high grades are possible.

A conceptual model of hydrothermal Ni systems based on a comprehensive review of deposits/occurrences from different parts of the world was applied to identify the following as the key targeting criteria for hydrothermal Ni deposits:

- Availability of a Ni source: (1.1) presence of basaltic-ultramafic suites, preferably ultramafic suites (>20–25% MgO; the higher MgO content of these suites reflects their higher olivine and thus Ni content); (1.2) occurrence of a Ni sulphide deposit (remobilisation is a common phenomenon observed in large Ni sulphide deposits); and (1.3) presence of permeable Ni-rich sedimentary units such us metasomatised sandstones (since this increases rock-fluid interaction rates facilitating metal leaching).

- Presence of favorable parameters for Ni mobility involving release and movement of the Ni away from the source such as availability of a heat source, presence of a fluid phase and a permeable system that allows the fluid to circulate: (2.1) a heat source to raise temperature higher than 200°C and preferable to ~350°C or higher (granitic intrusion reflected as gravity lows; sills, dyke swarms interpreted from outcrops and aeromagnetic surveys; metamorphism at greenschist-amphibolite facies; active rifting zones or volcanic areas; migration of mantle plumes interpreted from the geological features); (2.2) the presence of carbonate-rich rocks to provide CO_2 and Ca by the brine-carbonate interaction facilitated by high temperature, thus promoting the formation of complexes such as bicarbonate that can facilitate leaching and transportation of Ni; (2.3) alkaline igneous suites to release alkali elements (K, Na, and Mg) for promoting oxidising fluid conditions for facilitating transportation; (2.4) evaporitic units rich in Cl− and/or alkalis (e.g., halite, anhydrite) to ensure availability of free radicals for Ni complexing;(2.5) organic-rich units (e.g., organic shale) to facilitate availability of organic ligands in an oxidising fluid that can transport by complexing Ni; (2.6) <1,000 m distance from the Ni source (twice the maximum reported distance of hydrothermal Ni deposits from the known sources); (2.7) shear zones and crosscutting fault systems through which large volumes of fluid can circulate; and (2.8) presence of anomalous values of Bi, Se, Te and/or Co, Cu, Au, Pb, Zn, Pb, Sb and Cd that may highlight pathways.

- An appropriate physical and/or chemical environment where fluids can accumulate their solutes and form deposits, i.e. 'traps': (3.1) organic and/or sulphur–rich sedimentary units (e.g., shale) that promote reducing conditions changing the redox condition of the oxidising Ni bearing fluids and complexing Ni by absorption; (3.2) irregularities at contacts between units with high rheological contrasts (e.g., contact between the Ni source and the country rock such as faults and/or bedding planes); (3.3) presence of positive magnetic anomalies that may reflect the formation of magnetite during serpentinisation; and (3.4) mineralogical changes associated with changes in redox conditions (e.g., oxidation: magnetite-pyrite; reduction: pyrrhotite-pyrite; depending on the resolution of the datasets), since redox gradients promote complexation or/and release of chemical solutes.

Furthermore, the above critical ingredients of a hydrothermal Ni system can be combined using probabilistic techniques in the framework of the mineral systems approach to estimate the probability of occurrence of hydrothermal Ni deposits in any area.

Innovative use of geoscience systems approaches to characterise and manage Australia's water resources

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Throughout pre-history, groundwater-fed springs in the Australian interior sustained life in a harsh climate, but it was the advent of new drilling technology in 1887, with the first flowing bore in the in the Great Artesian Basin, that unlocked Australia's groundwater resources. By 1910, artesian bores had been sunk in most of Australia's sedimentary basins.

Today, over 50% of Australia's groundwater use comes from large shallow (<200m) alluvial aquifers in the Murray-Darling Basin and on the Queensland coast, while 20% comes from the Perth and Great Artesian Basins. Inland, many towns like Alice Springs are totally dependent on groundwater, and mining in the nations's interior would not be possible without access to local groundwater resources.

However, after just over a century of development, it is estimated that over 70% of fresh groundwater resources in Australia are now substantially over-allocated and current extraction is not sustainable in the longer term. Moreover, as surface water resources have also become fully developed, and the impacts of prolonged drought (and predicted climate change) begin to take effect in the southern half of Australia, innovative strategies are required to secure water supplies for irrigation and regional communities, and to deliver environmental benefits to threatened lakes and river systems.

These challenges have provided an impetus for new hydrogeological research directions to sustain growth, promote wealth and protect landscape, infrastructure and biodiversity assets. Predictions are required not only to inform longer-term policy development, but also to guide shorter-term resource assessments and management interventions. These challenges, and the increasing focus on the need for evidence-based decision-making, have provided an impetus for new hydrogeological research directions beyond conventional discipline boundaries, with a marked increase in multi-disciplinary geoscience systems approaches.

Multi-disciplinary, multi-scale systems approaches take advantage of new or improved geospatial mapping technologies that enable key elements of the hydrogeological system to be mapped and characterised with greater certainty. This contributes to improved parameterisation of groundwater and surface-groundwater interaction models, and enables more reliable quantitative assessments to be made of the uncertainties and confidence levels in model predictions. These approaches underpin the development of more effective groundwater and environmental management strategies, and facilitate more targeted management actions.

In Australia, geoscientists have been at the forefront of an international effort to develop multi-disciplinary, multi-scale 4D system approaches to the integration, analysis of interpretation of complex hydrogeological, hydrogeophysical and hydrogeochemical datasets. These approaches incorporate an understanding of landscape evolution and scale, utilise modern investigative approaches to the conceptualisation and mapping of aquifer systems and aquitards, and combine state of the art hydrogeochemical and hydrogeophysical techniques to assess hydrogeological processes.

These approaches and the technologies used, vary depending on the nature of the geology, landscape, depth of investigation and nature of the management questions and challenges. Importantly, the approaches focus on using the most appropriate technology to map key components of the hydrogeological system critical to the storage and movement of water, salts and other solutes and nutrients in the landscape. In the case of the shallow alluvial aquifers, the approach integrates geophysical datasets such as ground and airborne electromagnetics (AEM), gravity, seismic and other remotely sensed datasets to create 3-D and 4-D constructs. These datasets provide a framework within which detailed hydrogeochemical investigations and process studies can be considered, resources quantified, numerical models parameterised, and management strategies and actions developed.

In Australia, application of systems approaches has not been restricted to the characterisation of fresh water resources. The increasing cost of water and improvements in desalination technologies has spurred interest in defining the brackish and saline resource. Similarly, the need for improved water efficiencies in many urban

and rural centres has seen growing interest in actively using aquifers as water storages through the development of Managed Aquifer Recharge (MAR) schemes This is driven by the desire to minimise evaporative losses from surface storages and to find cost-effective storage solutions for urban water re-use. In data-poor areas such as the Darling Floodplain, new geoscience-based risk assessment frameworks have been developed to identify potential MAR sites at a regional scale, while a 4D systems approach has been employed to characterise potential sites.

While many challenges remain if Australia is to manage our water resources more sustainably, geoscience systems-based approaches provide a science framework for accomplishing this goal. Studies to date have already demonstrated an ability to improve the understanding of hydrogeological frameworks and processes, and improved characterisation of aquifers and groundwater resources. These provide a more robust evidence base for the numerical modelling that underpins investment and management decisions.

Foundations of wealth—Australia's major metallic mineral provinces

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Along with the agricultural sector the minerals industry, with 49% of total export income, is the foundation of Australia's present wealth. Although most of this income is derived from the bulk commodities iron ore, alumina and coal, the earliest significant mining in Australia, apart from coal, was of precious and base metals. The first non-indigenous, metallic mine in Australia, the Glen Osmond mine in South Australia, began extracting lead and silver in 1841, but lasted less than a decade. The first major mining boom in Australia was the Victorian gold rush, which began in 1851 with discovery of gold near Clunes. This boom, and later rushes to silver-lead deposits at Broken Hill in New South Wales and gold deposits at Kalgoorlie in Western Australia, laid the foundations of Australia's future wealth in the latter half of the 1800s. These mining booms had major consequences for the establishment of provincial cities such as Bendigo, Ballarat and Kalgoolie. They also funded the early growth of Melbourne and Perth, provided the basis for major mining companies including BHP-Billiton and Rio Tinto, and resulted in diverse immigration from around the world. These and subsequent mineral discoveries, along with agriculture, were major drivers in opening up regional and inland Australia.

With the exception of bauxite, most of Australia's metallic mineral wealth can be linked to the amalgamation and breakup of global supercontinents (or supercratons), beginning with Kenorland in the latest Archean and ending with Pangea in the Paleozoic. Lode gold deposits in the Eastern Goldfields Province, one of Earth's major gold provinces, and in the North Australian Craton are associated with subduction and terrane accretion coeval with the assembly of Kenorland and Nuna, respectively. Moreover, banded iron-formation in the Hamersley Basin was upgraded to form iron ore during the earliest part of Nuna assembly. In contrast, the major Paleoproterozoic sediment-hosted Zn-Pb deposits of the Australian zinc belt and iron-oxide copper-gold(uranium) deposits of the Olympic and Cloncurry metallogenic provinces formed during extension associated with the break-up of Nuna. World-class deposits in these provinces appear to be localised by pre-existing sutures that may have formed during the amalgamation of Nuna. The Victorian goldfields, along with Paleozoic volcanic-hosted massive sulphide, porphyry copper and granite-related deposits in the Tasman Geosyncline also formed as the result of subduction and terrane accretion, but in this case, were associated with the growth of Pangea. Bauxite differs to most other metallic commodities in that it is produced by long periods of weathering and requires stable tectonic environments.

Analysis of major Australian metallic mineral provinces (Eastern Goldfields gold province, Pilbara iron province, Australian zinc belt, Olympic and Cloncurry copper-gold provinces, and the Victorian goldfields) indicate that despite differences in metallogeny and geological setting, most of these provinces share many features, including:

- a spatial association with the margins of crustal blocks
- an association with (inverted) extensional faults, many of which penetrate the crust
- a common, though not universal, association with mantle-derived magmas or fluids
- a temporal association with major plate reconfigurations
- localisation of ores by chemical or physical gradients

- an association with major fluid flow caused by either thermal or tectonic events.

These observations suggest that the major mineral provinces underpinning Australia's wealth are the products of the supercontinent cycle and developed preferentially along the margins of crustal blocks during amalgamation or breakup. The localisation of deposits is controlled by the basinal, structural and chemical architecture developed during these processes. However, the formation of major mineral provinces may be the consequence of unique combinations of factors or events that overprint the supercontinent cycle, such as the amalgamation of the Earth's first supercontinent and the supercontinent growth and breakup during and immediately after the oxidation of Earth's atmosphere at ~2.2 Ga.

The bulk commodities underpinning economic growth in Australia and the region

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Extensive stable periods in Australia's geological history have contributed to the creation and preservation of in situ bulk extractives resources including coal, natural gas, bauxite and iron ore. A stable political system and transparent regulatory environment has enabled commercial developers to invest in large scale export projects. Australia has been able to explore, define, develop, and export bulk commodities while simultaneously minimising potential negative social and environmental outcomes.

Minerals have long been part of Australian culture; Aboriginal people used minerals to colour paints for rock art and ceremonies, sandstone was utilised for building following the arrival of the First Fleet in 1788 and coal exports commenced in 1799. From the foundation of early development, through to the bulk commodities critical to contemporary wealth, Australia has relied heavily on the minerals sector. Each of the bulk commodities; coal, natural gas, bauxite and iron ore, have a unique story and influence on Australian society. Bauxite deposits, for example, have formed through eons of regolith reworking as a consequence of a stable geological history. Collectively, the bulk commodities provide resources to support the development of modern economies of Asia, while delivering substantial economic and social benefits to Australia.

Mining can be romanticised as individuals pegging claims in order to work land by hand, as was the case in the nineteenth century gold rushes. In contrast, the mining of bulk commodities is underpinned by massive economies of scale, organised labour, complex technology and substantial investment. Commercial entities developing these projects take substantial commercial risks which society can help mitigate by providing a high degree of regulatory certainty.

Mineral and energy production contributes strongly to Australia's exports and of the world's developed countries, perhaps only in Canada and Norway does the production of minerals and energy play as significant a role. Work in the sector often has parallels with manufacturing; however, the mining sector does not directly employ large numbers. Production of Australia's bulk commodities are characterised by boom times followed by periods less intense activity. Australia has developed the capacity to produce far greater volumes of commodities than are required for domestic consumption. However, this forces reliance upon the circumstances of the global market rather than setting prices according to the cost of production. The peaks and troughs of demand in international markets reinforce Australia's role as a price taker with external forces driving the boom periods.

Notwithstanding the relatively small workforce involved in mining, the social impacts of economic peaks and subsequent quieter periods can be profound. During boom times workers are drawn to remote areas for high wages. Often the communities these workers are drawn from find the labour pool inadequate to fill necessary jobs, while at the same time the remote towns swell straining physical and social infrastructure. The reverse situation occurs after the booms, where government plays a significant role in successfully managing social implications.

The wealth generated by the bulk commodities industry has contributed substantially to the support of community services such as social equity payments, hospitals, police, infrastructure and other government services. Australia is a developed country with a highly educated workforce and generally an early adopter of new technology. In effect the bulk commodities, along with other mineral exports, allow Australia to fit the mould of a developed first world country, without a large manufacturing sector that normally characterises such economies.

Development constraints that applied to the bulk commodities were replaced in recent years by pragmatic public policy supporting resource development. Limited domestic demand has facilitated Australia's role as the world's largest exporter of coal and iron ore. A contrasting example is that of the United States which has the world's largest coal industry, but due to strong domestic demand has only limited export capacity. Australia's land area, geology, demographics and stable legal system have enabled the development of a commodities sector which helps meet growing demand in Asia.

Unearthing our past and future

Increasing community intolerance for fossil fuels and the desire to establish domestic carbon emission controls will lead to increasing interest in Australia's large non fossil energy resources. These forces in turn will interact with increasing Asian demand for the bulk commodities and the economic imperative of maintaining and improving Australia's standard of living.

Deep heat: meeting future energy needs

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Energy drives the modern world and underpins our current way of life. The industrial age was fuelled by access to reliable high grade energy sources, such as coal and oil, which drove global economic expansion and modernisation. There is a strong correlation between energy consumption levels and GDP. Australia is a large consumer of energy (5.87 tonnes of oil equivalent per person annually), ranking 20th on total consumption, and 16th on a per-capita basis. Australia is well endowed with traditional energy resources, e.g., coal, gas, uranium, and is a large energy producer (8th in the world). Australia also benefits from energy exports. Energy, therefore, strongly contributes to the nation's wealth and living standards, but increasingly it is recognised that these are dependent on access to cheap energy.

To secure Australia's future prosperity, we must have energy security, i.e, accessible, secure, affordable and reliable energy into the future. This future energy security will need to be achieved against 3 competing concerns:

- Increasing annual energy consumption, both in Australia and the rest of the world. Predictions suggest that world energy consumption may double by 2050.
- Decreasing resources. The discovery rate of new fossil fuel resources is decreasing and figures suggest that present oil consumption is four times the discovery rate.
- Environmental concerns, i.e., emissions from fossil fuel use. Of most concern are the greenhouse gases (GHG), such as CO_2, which are in all likelihood contributing to global warming and climate change.

Environmental concerns and the need for energy security will drive a switch to other more sustainable energy types, preferably from indigenous energy sources. Although the Australian continent is ideally situated to make use of many alternate energy sources, e.g., our hot and arid nature make solar a potential renewable energy source, commentators suggest that such sources may not provide all of our needs and will not meet peak energy loads.

Fortuitously, Australia is endowed with above average concentrations of the radioactive elements (K, U and Th). The energy generated by the naturally-occurring breakdown of radioactive elements is immense, e.g., a kg of U gives as much energy as ~10 tonnes of oil, and can be captured either by fission of U (and Th) in nuclear reactors, or by the use of geothermal energy, i.e., using the earth's in-situ heat to generate power.

In Australia, the greatest concentrations are in U and Th deposits and Australia has ~38% of the world's current U reserves. K, Th and U are also anomalously concentrated within the continental crust, in particular, in some felsic igneous rocks which are termed High Heat Producing (HHP). There is a strong spatial association of HHP igneous rocks with both U mineralisation and major heat flow anomalies.

The distribution of HHP magmatism both geographically and through time in Australia, is not uniform. Geographically, HHP granites are extensively distributed in the central third of the continent, whilst in the west and east, they are more localised. The heat flow anomalies and the HHP granites are much more widespread than currently targeted by geothermal exploration.

Time-wise, the first HHP felsic igneous rocks appear in the (mid- to) late Archean and continue to the Mesozoic, with the greatest concentration in the Proterozoic from ca. 1880 to 1500 Ma. The unifying characteristics of these HHP igneous rocks are that they are granitic to granodioritic in composition (>65 wt% SiO_2) and predominantly I-type. All are generated from crustal sources largely during periods of high crustal geothermal gradients. Although such melting conditions promote preferential partitioning of K, Th and U into the melt, it is likely that these lower crustal sources were themselves enriched in these elements.

This anomalous enrichment of the Australian crust in K, Th and U puts Australia in a unique position for energy security. Not only do we have the ability to use the earth's in-situ heat to generate power over wide areas, we also have significant resources of U and Th in conventional deposits. Combined, both sources have the ability to meet base and peak load power requirements, and the potential to underpin Australia's energy requirements well into the future.

SESSION 02DC (DYNAMIC EARTH: GEODYNAMIC EVOLUTION OF AUSTRALIA)

How continents grow, really! Some lessons from the Australian Plate

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The processes governing the differentiation of continental crust from the mantle are fundamental to our understanding of Earth evolution. On the modern Earth, youthful mantle-derived additions to the continental crust occur dominantly within magmatic arcs, and oceanic rocks (island arcs or plateaux) are accreted, by definition, at convergent plate margins. There is ample evidence in the geologic record that comparable processes of lateral accretion have occurred throughout much, if not all, Earth history, and there is little doubt that they have contributed to continental growth. However, convergent margins on the modern Earth are also the location of continental consumption, arguably at globally averaged rates comparable to those of accretion. If this relationship holds true through time, then a) vastly larger volumes of continent must have been formed, and recycled, at convergent margins than are currently preserved and b) we might expect that there are other mechanisms, occurring distal to, and shielded from, the destructive processes of convergent margins, that contribute substantially to continental growth. In this paper I will use evidence from the Australian Proterozoic rock record to argue that a substantial, perhaps the dominant, contributor to crustal growth was a process of continental inflation. In contrast to lateral accretion, inflation occurred by intrusion and under plating of mafic magmas within broad zones of continental extension inboard of convergent margins. Mafic material was intruded into the lower crust, mixed with pre-existing continental material, remelted and intruded by younger mantle derived melts during successive cycles of extension and shortening. Felsic melts derived from these processes ascended into the upper crust carrying with them the isotopic signature of continual crustal rejuvenation. The result was a seismically differentiated crustal profile (igneous and sedimentary rocks of broadly grandiorite composition in the upper crust, refractory mafic granulite in the lower crust). Whilst influenced by processes occurring at the plate margins, the regions of continental inflation were sufficiently distal to escape convergent margin recycling, thus contributing significantly to long-term crustal growth.

Felsic magmatism and the Mesoproterozoic evolution of the west Musgrave Province, central Australia

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The Musgrave Province, in central Australia, lies at the convergence of Australia's main Proterozoic structural trends which ultimately reflect the Mesoproterozoic amalgamation of the North, West and South Australian Cratons. The province is dominated by felsic rocks formed, and metamorphosed, during several events within the late Mesoproterozoic, including the 1345–1293 Ma Mount West Orogeny (Wankanki Supersuite), the 1220–1150 Ma Musgrave Orogeny (Pitjantjatjara Supersuite) and the >1078–1026 Ma Giles Event (Warakurna Supersuite).

Protoliths to rocks of the Wankanki Supersuite were metaluminous and calcic to calc-alkalic hornblende-clinopyroxene-biotite granites with close compositional similarities to Phanerozoic subduction-related

continental arc granites. These are abundant in the south-western part of the west Musgrave Province (the Mamutjarra Zone), but their abundance decreases to the north-east, into the Tjuni Purlka Tectonic Zone, and they are absent from the Walpa Pulka Zone, in the far north-east. The origins of the Wankanki Supersuite, and the tectonic setting of the Mount West Orogeny, are difficult to constrain. Rocks of similar age occur in the Albany-Fraser Orogen, along the southern coast of Western Australia, and have been attributed to subduction during c. 1300 Ma convergence of the Yilgarn Craton and a southern continental mass. Dehydration melting of lower crust and incorporation into hydrous mantle-derived mafic magmas is consistent with the arc-like geochemistry of the Wankanki Supersuite, but not necessarily evidence of an arc setting. No evidence exists for a c. 1300 Ma suture within the exposed west Musgrave Province.

Rocks of the Pitjantjatjara Supersuite are abundant in the Walpa Pulka Zone but their abundance decreases to the south-west, into the Tjuni Purlka Tectonic Zone, and only rare, small intrusions are found in the Mamutjarra Zone. Protoliths were relatively anhydrous, orthopyroxene-bearing rocks that included rapakivi granites. They were metaluminous, ferroan and range from alkali-calcic to calc-alkalic, with compositional affinities with A-type granites. Various lines of evidence indicate that ultrahigh temperature (UHT, >1000°C) regional metamorphic conditions persisted at the level of granite emplacement more or less continuously throughout the ~100 m.y. intrusive period of the Musgrave Orogeny, making this one of the largest and longest-lived UHT provinces known. The prevailing UHT conditions and the estimated geothermal gradient of >40°C km^{-1} greatly limit the amount of felsic crustal source material available beneath the level of intrusion, because geologically unreasonable crustal temperatures are exceeded within only a few kilometres. The composition of the granites and the thermal regime in which they evolved reflect a significant mantle contribution in terms of both heat and source material. A lower crustal MASH (melting, assimilation, storage, homogenisation) domain, in which crustal melts and mantle-derived magma mixed in a crystal mush zone, provided the source region for the Pitjantjatjara Supersuite. During the Musgrave Orogeny, the Musgrave Province was rigidly fixed at the junction of the three cratonic masses, each with a significantly greater lithospheric thickness. This ensured that any asthenospheric upwelling was focused beneath the province, forming a lower crustal hot-zone and the Pitjantjatjara Supersuite. Whereas some of the thermal responses of an intracontinental rift setting (e.g. very high temperature felsic magmas) are apparent, they are not accompanied by many of the structural manifestations, such as major extensional deformation and fissure-controlled flood basalt magmatism.

The Tjuni Purlka Tectonic Zone is a broad northwest-trending zone of extensive shearing that was a focus of deformation and magmatism from at least c. 1220 Ma to c. 1050 Ma. The boundaries on either side of the zone have been the main focus for mafic and felsic magmatism formed during the Giles Event (Warakurna Supersuite), including giant layered troctolite-gabbronorite-gabbro intrusions, and extensive bodies of co-mingled gabbro and granite. Most granites of the Warakurna Supersuite are similar in composition to those of the Pitjantjatjara Supersuite. The Giles Event is a complex series of events punctuated over a period of at least 50 m.y. There is no evidence for a mantle-plume and no suggestion that the prevailing intracontinental tectonic setting during the Giles Event fundamentally differed from that of the Musgrave Orogeny. The upper age constraint on the Giles Event (>1078 Ma) is a minimum, and so the duration separating the Musgrave Orogeny (UHT metamorphic ages down to 1120 Ma) and the Giles Event may be small. It is possible that the two events could justifiably be viewed as a continuum.

Geophysical constraints on the tectonic evolution and 3D crustal architecture of the Southern Nawa Domain, Gawler Craton

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The 3D architecture of unexposed basement of the Nawa Domain is poorly constrained yet this architecture will provide a regional context for results obtained from the analysis of samples from the few existing and recently drilled cores samples obtained from basement in the region and also for the structures imaged on 2D seismic profiles. Analysis of basement samples has revealed that this region was affected by several orogenic events during the late Palaeoproterozoic-to-Mesoproterozoic assembly of Australia, but the extent of these orogenies, the geometry of resulting structures and their effect on crustal architecture has not been analysed in detail. We present an analysis of the basement architecture to the North of the Karari Shear Zone, focusing on the Mabel Creek Ridge, Tallaringa Trough and Nawa Ridge. On the basis of the interpretation and modelling

(forward and inverse) of potential field data combined with geological constraints from drill-hole samples we present an interpretation of the structural evolution of this region from 1700–1450 Ma.

Cooling and exhumation history of the north-eastern Gawler Craton, South Australia

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The Mount Woods Inlier in the north-eastern Gawler Craton is a geologically poorly understood region, which is primarily due to it being overlain by extensive cover sequences. Nonetheless, this region is considered highly prospective for FeO-Cu-Au deposits and has been explored for Broken Hill-type Pb-Zn-Ag mineralisation. The region hosts the economically viable Prominent Hill FeO-Cu-Au orebody. The Mount Woods Inlier has an extensive Proterozoic geological history involving an early period of sedimentation up to ~1740 Ma (e.g. Fanning et al., 1988, Precambrian Research, v. 40/41, p. 363), deformation and metamorphism during the Kimban Orogeny (~1730–1710 Ma), and a potentially younger period of sedimentation to ~1640 Ma (Holm, OZCHRON). Metamorphic zircon rims yield an age of ~1590 Ma (Holm, OZCHRON; Chalmers 2007, PIRSA Report Book 2007/20), which has been interpreted as the timing of peak granulite facies metamorphism (Forbes et al. in review, Precambrian Research). Peak metamorphism in the Mount Woods Inlier was approximately contemporaneous with Prominent Hill mineralisation and intrusion/extrusion of the Hiltaba Granite Suite and Gawler Range Volcanics.

Electron microprobe chemical dating of monazite, $^{40}Ar/^{39}Ar$ biotite geochronology and Fe-Mg garnet-biotite exchange geothermometry in conjunction with previous geochronology has been used to study the cooling and exhumation history and model the retrograde pressure-temperature (P-T) of the Mount Woods Inlier. This has shown that the region cooled from peak metamorphic temperatures of ~750°C at ~1590 Ma (Forbes et al. in review, Precambrian Research) through to ~300°C at ca. 1535 Ma. The retrograde P-T path shows decompression with minimal cooling followed by near isobaric decompression. Geological relationships between the Southern Overthrust terrane boundary at the south-west of the Mount Woods Inlier and the on lapping Gawler Range Volcanics in conjunction with the well constrained age of the volcanics (~1592 Ma; e.g. Fanning et al. 1988) and the timing of Prominent Hill mineralisation within the active Southern Overthrust (~1582 Ma; Belperio et al. 2007; Economic Geology, v. 102, p. 1441) shows that exhumation of the Mount Woods Inlier initiated between ~1592 Ma and 1582 Ma. The timing of initial exhumation therefore immediately follows peak metamorphism.

The late Palaeoproterozoic to Mesoproterozoic (ca. 1600–1570 Ma) is recognised as a period of intense orogenesis, metamorphism, magmatism and major mineralisation throughout eastern Australia, within which the Mount Woods Inlier has not been placed in context. Understanding the retrograde evolution, cooling rates and timing of exhumation of the Mount Woods Inlier gives insight to the style of tectonic setting (e.g. intracontinental versus plate-margin, shortening versus extensional), and brings in the possibility of relating the architecture of this region to other similar aged terranes (e.g. Coober Pedy Ridge, Curnamona Province, Mount Isa Inlier). In turn, this will influence our understanding of mineralisation processes within the north-eastern Gawler Craton.

SESSION 02LC (LIFE AND SOLAR SYSTEM)

Terrestrialization of the biota and atmospheric fluctuations during the Middle Palaeozoic

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Computer modelling of atmospheric O_2 and CO_2 levels on a multimillion year timescale requires numerous assumptions about geochemical cycling of rock-forming minerals, biogenic factors, the influence of biological processes on weathering, etc. The major effect on CO_2 and O_2 over the past 550 million years was the Devonian radiation of vascular land plants, including trees (Berner 2003, 2004), considered 'nearly as important to the evolution of life and the atmosphere as the rise of microbial photosynthesis during the

Archaean' (Berner 2005). The first forests evidently contributed largely to a steep increase in atmospheric O_2 between about 400 and 300 million years ago (Berner 2006; Berner *et al.* 2007). The COPSE model (Bergman *et al.* 2004) has this as a steady increase, but the GEOCARBSULF model (Berner 2006) shows a large drop after a latest Silurian peak to a minimum level in the early Frasnian (early Late Devonian). Charred plants and charcoal occur in the fossil record from the latest Silurian through the Early Devonian. A Middle Devonian 'charcoal gap' suggests that O_2 concentrations dropped beneath 12%, too low for forest fires (Scott & Glasspool 2006).

In contrast, atmospheric CO_2 was consistently falling through the Middle Palaeozoic, from ~4000 ppmv in the Early Devonian to approach modern levels by the Late Devonian (Osborne *et al*. 2004). Non-biodegradable lignin synthesised by woody plants and trees meant more organic matter was buried, removing more atmospheric CO_2. A delay in the evolution of leaves until the Late Devonian spread of archaeopterid trees is attributed to high CO_2 levels in the Early-Middle Devonian, when early vascular plants had only shallow root penetration (Algeo & Scheckler 1998) and small leaves (Beerling *et al*. 2001).

Several recent papers relate these atmospheric fluctuations to major evolutionary changes associated with terrestrialization and air breathing amongst arthropods and vertebrates (Ward *et al.* 2006; Berner *et al*. 2007; Clack 2007). However the data on which all these models and interactions are based derive almost entirely from the Northern Hemisphere. Gondwana was the largest Palaeozoic landmass, and should be expected to contribute significantly to global data on terrestrialization of the biota. Southern Hemisphere evidence (Retallack 1997; Edgecombe 1998; Rickards 2000) will be discussed in a biogeographic context (Young *et al.* 2010) to critically evaluate Northern Hemisphere models.

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Atmosphere-ocean states and the mass extinction of species

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The discovery of the K-T boundary asteroid impact and its coincidence with the end-Cretaceous mass extinction ~65 Ma-ago (Alvarez et al., 1980; Alvarez, 1986) heralded a major shift in the long-running debate

regarding the respective role of uniformitarian principles vs catastrophic events in natural evolution (Stanley, 1987; Raup, 1992; Sepkoski, 1996; Watson, 2008). A large body of stratigraphic and isotopic age evidence points to close temporal overlaps, within age determination error, between extraterrestrial impacts, volcanic events and mass extinction of species in the Phanerozoic (Glikson, 2005, 2008; Keller, 2005). Whereas an age coincidence does not prove cause-and-effect relationship, the effects of large impacts and major volcanic eruptions on the atmosphere and oceans inevitably resulted in abrupt changes in the composition and physical state of biological habitats and thus contemporaneous mass extinction and radiation effects. That an overall directionality pertains regarding the complexity, brain development and intelligence of species across extinction boundaries (Watson, 2008), may be attributable to genetic transmission by the surviving species (Convey Morris, 2003). Central to the understanding of mass extinction of species are changes in the levels of greenhouse gases (CO2, CH4, N2O) and aerosols induced by external forcing and internal feedbacks, with related changes in climate, oxygen levels and pH state of the hydrosphere. The dominant greenhouse state of the atmosphere on the early Earth, interrupted by glacial periods at ~2.4–2.2 Ga and ~0.75–0.65 Ga (*Snowball Earth*, terminated by a build-up of CO2), Cambrian ~0.53 Ga, Ordovician ~0.44 Ga, late Devonian ~0.36 Ga, Permian ~0.33–0.27 Ga, minor Jurassic and Cretaceous glaciations, and the post-34 Ma glacial-interglacial state. The emergence of land vegetation in the late Silurian (~0.42 Ga), enhanced photosynthesis and weathering-related CO2-sequestration led to atmospheric oxygen enhancement through organic processing of CO2 and removal/burial of carbon. Mass extinctions of species at the end of the Devonian, Permian, Triassic and Cretaceous were to a large extent triggered by atmospheric CO2 and CH4 spikes and ocean acidification. Greenhouse events at 55 Ma, 15 Ma, and 2.8 Ma associated with peak atmospheric temperatures allow estimates of climate sensitivity under both greenhouse and glacial-interglacial Earth conditions. These include (1) Paleocene-Eocene thermal maximum (~55 Ma: escape of ~2000 GtC as methane, CO2 rise from 400 to 800 ppm, T rise ~ +5C; (2) Mid-Miocene (CO2 rise from ~280 to ~520 ppm; T rise ~ +2.4C), suggesting a climate sensitivity of about 2.8°C per-doubling of CO2 (CS); (3) mid-Pliocene (CO2 rise to ~400 ppm and T rise ~2C to 3C). Estimates based on the last glacial termination (180–280 ppm CO2; T ~ +4.5C) yield high CS value of ~6 to 8C associated with an ice melt feedback loop ahead of CO2 rise. Central to the resolution of relations between these events and the appearance and disappearance of species are the rates at which environmental parameters have changed, and to which species may or may not have been able to adapt, a question which in many instances remain to be defined by further isotopic dating and stratigraphic constraints.

Mass extinctions or mass hysteria—symbioses as the soothsayers of doom

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All complex ecosystems that ever existed have suffered heavily during mass extinctions. But how can we tell when a complex reefal ecosystem is destined to collapse? In this talk, we will explore the potential of foraminiferid tests as the soothsayers of doom.

Some forty cycles of evolutionary change in larger benthic Foraminifera can now be traced from the mid Devonian though to Recent tropical marine carbonates, using a suite of morphological traits. Each evolutionary cycle has involved trends towards an increase in relative surface area, very large body size (<150mm) and greater wall translucency, plus shorter lines of communication within the test, here measured in terms of MinLOC and Parsimony Index. This combination of features is typical for foraminifera that are obligate cultivators of internal photosymbionts living in oligotrophic reefal ecosystems. Iterative emergence of these features in the fossil record can therefore be explained by episodes in which tropical benthic foraminifera experienced prolonged periods of relative environmental stability under oligotrophic conditions, driving potential host foraminifera towards ever greater dependence upon their internal photosymbionts, such as rhodophytes, chlorophytes, dinoflagellates and diatoms. Each of these evolutionary cycles in foraminiferan test architecture typically lasted for more than tens of million of years, and each was invariably followed by the inferred collapse of obligate photosymbioses, plus other ecosystem connections, during mass extinction events.

We use these patterns, and JAVA modelling of Boolean networks, to suggest that ecosystems finely tuned to specialisms under relatively predictable trophic regimes are inherently liable to collapse and dissolution when conditions change. These findings run counter to much current thinking. They reveal that the *magnitude* of mass extinction events cannot be caused by external forcings of great magnitude, such as bolides or ice ages alone. At best, such events merely constrain the *timing* of mass extinctions. Instead, we argue that the magnitude of mass extinctions is contingent upon biological factors involving the nature of connections within

the ecosystem itself. It is the prolonged period of stability that leads to collapse, a feature here called the Albert Effect. These findings have dire implications for complex living reefal ecosystems like the Great Barrier Reef. Such modern ecosystems have evolved yet again, to near the brink of collapse.

Biomarker distributions and isotopic signals associated with the Permian/Triassic and Triassic/Jurassic mass extinction events: a global perspective

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Some of the most significant pulses of evolution throughout Earth's history have coincided with extinction boundary events. The largest five extinction events [end-Ordovician, Frasnian-Famennian (F/F), Permian-Triassic (P/Tr), Triassic/Jurassic (Tr/J) and Cretaceous-Tertiary (K/T) are usually referred to as 'mass extinctions'. There is a consistent association of large magmatic provinces (with all but the end-Ordovician) suggesting that volcanism was a major contributor. Fossil and geochemical evidence suggests that mass extinctions were prolonged periods of biotic stress triggered by a combination of tectonically-induced hydrothermal and volcanic processes, leading to eutrophic oceans, global warming, sea-level rise and global anoxia. The consequences of abrupt global warming, generally associated with most extinction events, are mainly harmful to palaeo-biospheres.

The Late Permian event was the most profound extinction of the Phanerozoic. Biomarker evidence for photic zone euxinic (PZE) conditions within P/Tr sections, where concentrations of sulfide are sufficient to support anoxygenic photosynthesis, derive from pigments of green sulphur bacteria (GSB). We present evidence for such conditions at 6 localities globally. It has been proposed that a chemocline upward excursion provided a trigger for the extinction, releasing toxic H_2S to the ocean's surface and the atmosphere. Perturbations in the marine sulphur cycle and thus the redox-state of the seas are also reflected in $\delta^{34}S$ of pyrite (e.g. from China, Italy, Iran, Western Australia, East Greenland, Western Canada and Spitsbergen) supporting widespread PZE in both Palaeotethys and Panthalassa Oceans. C_{33}-*n*-alkylcyclohexane (C_{33} ACH) reported in 4 P/Tr sections has been attributed to a specific community of phytoplankton that bloomed during the marine ecosystem collapse (Late Permian) and well into the Middle Triassic. Dibenzothiophene, dibenzofuran and biphenyl have been detected in high abundances in samples prior to the marine collapse in East Greenland, Spitsbergen, South China and Western Canada. We have proposed that lignin derived from land plants, present during the Late Permian is their source. We provide sedimentological data, biomarker abundances and compound specific $\delta^{13}C$ and δD along with $^{34}S_{pyrite}$, $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{org}$ for several Late Permian sections. At 2 localities sedimentological and geochemical data supports a marine transgression and collapse of the marine ecosystem in the Late Permian. Strong evidence for waxing and waning PZE throughout the Late Permian is provided by GSB-derived biomarkers and $\delta^{34}S_{pyrite}$, implying multiple phases of H_2S outgassing and potentially prolonged pulses of extinction. δD of biomarkers reflect a change in microbial community structure. Further, we report biomarker and isotopic evidence for a phytoplanktonic bloom triggered by eutrophication as a consequence of the marine collapse.

The Tr/J is the fourth most acute extinction event of the Phanerozoic in terms of ecological impact. A number of mechanisms have been proposed for this extinction, including the release of CO_2 associated with emplacement of the Central Atlantic Magmatic Province. A negative $\delta^{13}C$ excursion has been detected in many sections, also supporting a perturbation in the global carbon cycle. The onset of the negative anomaly coincides with palynological biozone boundaries in Australia, an ecological collapse of terrestrial flora and ecological upheaval and extinction in the marine benthos. It is clear that major and abrupt ecological change including 80% extinction among plant species coincides with increased [CO_{2atm}] based on stomatal analysis of fossil leaves and a negative excursion in $\delta^{13}C_{wood}$ from a Tr/J section at Astartekløft, East Greenland. $\delta^{13}C$ of nC_{29} from plant waxes shows a -5‰ shift that corresponds with similar shifts in fossil wood, increasing CO_{2atm} and peak plant extinction. During this interval δD of the *n*-C_{29} increases (~+35‰), which we partially attribute to increasing degrees of evaporative fractionation in leaf water due to elevated leaf temperatures. After peak plant extinctions, δD of *n*-C_{29} changes to –160‰. This is likely due to a decrease in evaporative fractionation due to lower leaf temperatures in surviving plants that probably had smaller leaves and were less prone to heat stress, a declining influence of biomass burning and finally, a return to lower temperatures as CO_{2atm} dropped. Resin-derived biomarkers abundant in the plant extinction horizon were attributed to the production of gymnosperm resins probably produced under extreme environmental stress. Presently a global biomarker

and isotopic study is under way for Tr/J extinction and the effects of temperature growth and combustion on δD of land plant compounds have been determined.

SESSION 02TC (TOPICAL: ERNIE NICKEL SYMPOSIUM)

A renaissance in Australian mineralogy

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The last few years have witnessed a resurgence in the description of new minerals accredited by the International Mineralogical Association's Commission on New Minerals, Nomenclature and Classification. In part, this can be seen as being due to advances in analytical techniques that permit the unambiguous characterisation of very small amounts of material. Synchrotron and electron scattering methods have played a significant role in this regard. At the same time, what might be described as a renaissance in mineralogy in Australia has become evident, with several groups being particularly active in the field in collaboration with workers in other institutions. Newly characterised Australian species range from primary silicates to secondary base metal minerals. Allied to this area of research has been an explosion of topographical mineralogical studies of Australian deposits.

While work in this area has sometimes been disparagingly referred to as 'stamp collecting', this is a frivolous point of view. Every mineral has its own geochemical story to tell if the conditions responsible for its formation can be ascertained. Such information has considerable importance in fields spanning exploration geochemistry, the origin of ore deposits, mineral processing and pollution studies. A review of recent developments in Australian mineralogy will be presented, focusing on new minerals and their geochemical settings. In addition, the contributions made to Australian mineralogy by the late Ernie Nickel will be highlighted.

New minerals from the phosphate deposits north-east of Adelaide, South Australia

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Low-grade phosphorite horizons are widespread in the Cambrian marine sediments of the Kanmantoo Trough, in South Australia. The phosphorites have been variably modified by metamorphism, followed by weathering and secondary enrichment during the Tertiary. As well as being a source of rock phosphate, recovered by intermittent mining since the early 1900s, the deposits contain a diverse range of phosphate minerals, including new species. A number of small quarries in the Angaston–Kapunda district, about 70 km north-east of Adelaide, are the type localities for peisleyite, aldermanite and two recently described minerals: kapundaite and angastonite. Both new minerals were collected initially by Mr Vince Peisley.

Kapundaite, ideally $(Na,Ca)_2Fe^{3+}_4(PO_4)_4(OH)_3{\cdot}5H_2O$, is a new mineral (IMA2009–047) from Toms phosphate quarry, at Kapunda. Kapundaite occurs as cavernous aggregates of fibres up to several centimetres across, associated with leucophosphite, natrodufrenite and meurigite-Na. It has a striking golden colour and a silky lustre. Individual kapundaite crystals are very thin flattened fibres up to a few mm in length, but typically no more than a few microns in thickness. The structure of kapundaite is based on a unique corrugated octahedral–tetrahedral sheet which is composed of two types of chains parallel to *a*. Kapundaite is structurally related to mélonjosephite, $CaFe^{2+}Fe^{3+}(PO_4)_2(OH)$.

Angastonite, ideally $CaMgAl_2(PO_4)_2(OH)_4{\cdot}7H_2O$, is a newly defined mineral from the Penrice marble quarry (IMA2008–008). The mineral occurs as snow-white crusts and coatings up to about 1 mm thick associated with minyulite, perhamite, crandallite and apatite-(CaF). Angastonite is likely to be related to montgomeryite-group members and have a similar crystal structure, based on slabs of phosphate tetrahedra and Al octahedra.

Hydroxylian pseudorutile—a new mineral from the Murray Basin?

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In the 1980s and 1990s, Ernie Nickel played an important role in encouraging research that underpinned the revalidation of the ferric titanate mineral pseudorutile from South Neptune Island (neotype). His characterisation of the new mineral tivanite, $VTiO_3(OH)$, from Kalgoorlie provided the key to understanding the structure of pseudorutile as being a microtwinned domain form of the tivanite structure. More recently, Ernie was the catalyst for the characterisation of an Al-rich form of hydroxylian pseudorutile (HPR) from Kalimantan, which he expected to qualify as a new mineral. HPR is a potentially important source of titania in Murray Basin mineral sands deposits. We describe recent research on HPR and Al-HPR, aimed at establishing if they meet the requirements for new mineral status.

'Silver chloro-antimoniate': over 80 years of characterisation

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The phase 'silver chloro-antimoniate', first described in 1926 by George Smith, was found around 1910 in the oxidised zone of the Australian Broken Hill Consols Mine, Broken Hill, NSW. It occurred as relatively large (several kilograms) masses of a malleable, sectile Ag-rich (up to 55% Ag near the surface and 66–70% at lower levels) ore that had physical properties much like those of chlorargyrite. Associated phases were minor bindheimite, cerussite, goethite and malachite. Lawrence *et al.* (1999) conducted further work on this material and found that it largely consisted of a fine-grained (~ 20 µm) mixture of chlorargyrite, stibiconite, bindheimite, an antimony oxide (senarmontite and/or valentinite), cerussite, luanheite, a silver amalgam of variable composition and a lead iron antimony oxyhydroxide.

Over the past few years we have further characterised this material using a combination of optical microscopy, scanning electron microscopy, X-ray diffraction, electron microprobe and Fourier transform IR techniques with our main purpose being to characterise the iron lead antimony oxyhydroxide phase, the Fe-analogue of bindheimite, a new mineral currently being described by the authors. For both X-ray diffraction and Fourier transform IR analysis, we successfully removed the intimately associated chlorargyrite by immersion in concentrated ammonia solution (as confirmed by subsequent X-ray diffraction).

The Fe-analogue of bindheimite occurs as alteration rims (to 600 µm across) around dyscrasite. In places, it is rimmed in turn by fine-grained mixtures of bindheimite and goethite. It occurs as very fine-grained, powdery, pale beige aggregates, and under back-scattered imaging (BSE) in the SEM and microprobe, appears as distinct, highly pitted, rough-textured patches distinguished from intimately associated chlorargyrite by virtue of its somewhat darker shade of grey in the images. Under reflected light, it seen as distinct concentric intergrowths with chlorargyrite and has a characteristic beige colour. It has the cubic pyrochlore structure, space group $Fd\bar{3}m$, with *a* ranging from 10.258 Å for the natural phase to 10.385–10.390 Å for the synthetic analogue. It has a formula of $(Fe^{2+}_{2-x},Pb_x)_2Sb_2O_6(O, OH)$ where x > 0. Lead is a necessary constituent as its presence forces the mineral into the cubic pyrochlore lattice due to the large size of the Pb^{2+} ion. If Pb were not there, tripuyhite, $FeSbO_4$, would probably result in the geochemical setting of the oxidised zone.

'Silver chloro-antimoniate' forms from the initial oxidation of primary galena-bearing dyscrasite-dominant ore, in the presence of a siderite-rich gangue. Upon further oxidation, the Fe-analogue of bindheimite forms a mixture of bindheimite and goethite.

SESSION 02WC (GEOHERITAGE, GEOTOURISM AND THE GEOSCIENCES PROFESSIONS WORKSHOP)

There are no abstracts for this workshop

U-Th-Pb-He double-dating of zircon from the diamondiferous Ellendale E9 lamproite pipe

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Kimberlites and lamproites are volatile-rich, alkalic, mafic to ultramafic magmas that form at depths in excess of 150 km. They ascend to the surface rapidly (time spans of hours to days), entraining mantle and crustal wall rock fragments along the way. If diamondiferous portions of the mantle are transgressed, diamonds will be transported to the Earth's surface. Similarly, crustal zircon entrained in the erupting magma will also be transported to the surface. Zircon, like diamond, is a highly refractory mineral and resistant to physical and chemical weathering—and therefore if diamond and zircon can both be geochemically linked to the process of kimberlite/lamproite eruption, then zircon could be used as a new kimberlite/lamproite indicator mineral (McInnes et al., 2009).

As part of the MERIWA 405 project involving the evaluation of zircon U-Th-Pb-He double-dating in diamond exploration, samples were collected from the West Pit of the Ellendale E9 mining operation (17°33'44.58"S, 124°51'9.48"E, 88m asl), located approximately 130 km ESE of Derby, Western Australia. The E9 pipe is a funnel-shaped maar-diatreme volcanic complex consisting of inward-dipping lapilli and crystal tuff sequences intruded by lamproite plugs and dykes. The crystal tuff units contain rare charred wood fragments indicating that the maar eruption broke a vegetated paleosurface. Diamonds are present in the lamproite dykes, plugs and tuffs although economic recovery is only possible from the tuff units. The host rocks for the E9 pipe are Permian sandstones of the Grant Group, which unconformably overlie Carboniferous siltstones of the Fairfield Group.

The E9 mining operation has exposed the contacts of multiple lithological units within the maar-diatreme volcano complex, providing a natural laboratory to study the effect of volcanic processes on U-Th-Pb-He systematics. Zircon separated from both a lamproite dyke and a lamproite tuff unit returned SHRIMP U/Pb ages ranging from 464–2725 Ma (n=52), whereas the (U-Th)/He technique yielded a unimodal age population of 18.9 ± 0.1 Ma (n=60). These data indicate that the lamproite magma entrained crustal zircon xenocrysts en route from the mantle to the surface. During transit the temperatures were high enough for the helium to completely diffuse out of the zircon crystal such that helium only began accumulating following diatreme emplacement and cooling around ~19 Myr ago. In contrast, detrital zircon from the sedimentary host rocks of the Fairfield Group sampled at 0.1, 1, 5 and 21 m from the lamproite dyke contact, along with zircon from the 'sandy tuff' facies of the crystal tuff unit, yielded Carboniferous-Devonian (U-Th)/He age distributions.

The implications of these data are that:

- the E9 lamproite tuff eruption and subsequent emplacement of the lamproite dykes and plugs were relatively short-lived phenomena that did not thermally perturb zircon (U-Th)/He systematics of the host country rocks
- zircon within the lamproite tuffs and dyke has a unique U-Th-Pb-He signature, such that erosion of these units should produce a distinctive suite of detrital zircons with Miocene (U-Th)/He ages.

Work is under way to test if zircon with Miocene (U-Th)/He ages can be detected in the drainages around the Ellendale site.

This work is funded by the CSIRO Minerals Down Under Flagship and the Minerals and Energy Research Institute of Western Australia (MERIWA) Project #405.

Reference

McInnes BIA, Evans NJ, McDonald BJ and Jakimowicz J. 2009. Application of zircon double-dating techniques in diamond exploration, Merlin kimberlite field, Northern Territory, Australia. Lithos 112S, 592–599.

Maturation statistics of nitrogen aggregation in alluvial diamond: New South Wales and Kalimantan

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The published range (of nitrogen abundance/aggregation (NAAG) values displayed by 59 diamonds in a single peridotitic xenolith-Cullinan Mine) provides a model for the variation expected for a single mantle storage history, and results in a standard deviation of 0.23 (SD1) on values of log10(storage time in years). Published NAAG ranges for alluvial diamonds from NSW (Copeton, Bingara, Wellington) and Kalimantan are assessed relative to this model. A working mantle storage temperature is used to convert NAAG values to a log10(storage time), and these are treated with histograms, statistics relative to SD1, and range plots (for zoned stones). The new treatment regenerates previously published conclusions, but also adds new results: 1) Copeton and Bingara diamonds are similar in their mode of formation but differ significantly and recognizably in their mantle storage conditions, 2) Wellington diamonds include stones from 13% Bingara-type and 7% Copeton-type sources, 3) 8% of zoned Wellington stones tested have NAAG ranges that are far larger than expected relative to SD1, identifying the NAAG regime whereby plastic deformation has accelerated nitrogen aggregation for individual stones, 4) falling within this plastic deformation regime are 30% of Wellington stones, 10% of Bingara stones, and 11% of Kalimantan stones, but none of the tested Copeton stones, 5) The non-deformed stones from each region define maximum log10 storage times at 1100˚C of 6.9 (W1) and 7.2(W2) Wellington, 6.9(B2) and 7.3(B1) Bingara, 8.1 (Copeton), 7.9 (K1) and 8.5 (K2) Kalimantan. These are less than the much longer storage times typically proposed for cratonic diamond, suggesting that Kalimantan and Wellington alluvial diamond is atypical in terms of mantle storage conditions proposed for cratonic diamond. This is despite publications stating that the majority of alluvial diamonds from these two occurrences are cratonic in origin.

Published research shows that the Copteton and Bingara diamonds formed during Phanerozoic ultrahigh pressure (UHP) metamorphism due to subduction. They are non-cratonic, and can be recognised by 1) their much higher remnant internal pressures (12–25 kbar) on Cpx/Olivine/Garnet inclusions than for cratonic diamonds (2–6 kbar), 2) a second order Raman peak that is prominent in cratonic diamond is weak in Copeton and Bingara diamond. Some alluvial diamonds from Kalimantan and Wellington (NSW) have these two features, suggesting an analogy between the alluvial diamonds of Wellington and Kalimantan.

Published studies of hard rock microdiamonds in many exhumed UHP terranes show only early stages of NAAG, requiring complete exhumation soon after formation. In contrast, Copeton and Bingara UHP macrodiamonds show much higher aggregation states, requiring significant periods of mantle storage. Post-tectonic magmatic delivery is indicated, consistent with surface features on the Copeton and Bingara diamonds.

Hyperspectral insights in the 3D mineralogy of a channel iron ore deposit: implications to exploration, mining and ore genesis

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This study demonstrates that hyperspectral measurements from drill core (Hylogging™), when processed into 3D mineral maps, can be used as a fast and relatively cheap tool to delineate major ore zones in Channel Iron Ore deposits (CID) of the Pilbara. This hyperspectral technology provides valuable information about CID, including the types and abundances of iron oxides (hematite and goethite), clays (well ordered and more poorly ordered kaolins and Al-smectites), carbonates (calcite and dolomite) and silica (chalcedony/crystabolite). This spectral-mineral information complements more traditional analyses, such as geochemistry, X-Ray Diffraction (XRD) and Loss of Ignition (LOI). The 3D spectral-mineralogical architecture helps provide new geological understanding of the genesis of this type of iron ore deposit, especially the relationships between underlying parent rock and superimposed groundwater interaction(s), which are potentially useful for ore block characterisation and CID exploration in different geological/regolith settings.

The Rocklea Dome CID is located 40 km west-south-west of Tom Price and 1000 km north-north-east of Perth in a Tertiary river channel infilled with ooidal ironstones, crosscutting a variety of underlying Archaean rock-

types of the Hamersley Province, including granites, metasediments and meta-volcanics. More recent Quaternary transported material covers the CID in places, especially in the eastern part of the study area.

Preconditions for an economically mineable deposit are: a high concentration of Fe, low contents of clay, low levels of silica and alumina, negligible phosphorus (P) and a position close to the surface. As part of the original exploration process by Murchison Metals, geochemical analyses of 400 Reverse Circulation (RC) drill holes from a 30 km strike length of the Rocklea CID helped delineate a potential ore zone at approximately 20 m depth over the metasediments in the east, with Indicated and Inferred Mineral Resources of approximately 89 Mt at 53.2% Fe (cut-off grade of 50% Fe). Further hand sample investigation by Murchison of the nature of the ore showed two types, namely: (1) a vitreous (silica-rich) ore; and (2) ochreous goethitic ore. Each requires different metallurgical processing. This preliminary analysis also suggested a variety of clay-rich and carbonate-rich zones.

Hyperspectral data from the 400–2500 nm wavelength region (visible, near infrared and short-wave infrared (VNIR-SWIR) were obtained for over 150 RC drill cores (1 m interval) and 14 twin diamond drill cores (1 cm interval), using an ASD (Terraspec) instrument as part of CSIRO's commercially available Hychipper™ System. Hyperspectral processing of these reflectance data was based primarily on measuring (multiple) diagnostic mineral-spectral parameters, such as the continuum-depths and wavelengths of absorptions like the kaolin related 2160 nm vibrational feature and the iron oxide related 900 nm electronic feature.

The processed spectral-mineralogical results show that coherent 3D zones are developed. The near-surface is typically characterised by a 'calcrete' zone, which typically changes from calcite at the top to dolomite/magnesite at 2 to 8 metres depth. These carbonates appear to be associated with a massive, brecciated calcrete exposed as a prominent hill immediately N of the ore body and sitting stratigraphically above the CID. The clays associated with these carbonates are typically Al-smectites, consistent with more alkaline conditions. The clays become more kaolinitic below this carbonate zone, indicating more acid conditions at depth. The 25 m thick, ellipsoid-shaped, iron ore zone spanning 4 by 1 kms contains little/no spectrally-measureable clay, except in isolated veins that typically contain 'hydrated' kaolin and more rarely a trioctahedral smectite (e.g. nontronite). A flat zone, 1km wide, of 'hydrated' silica (SiOH absorption at 2250 nm) spans most of the area intersected by the diamond drilling and is positioned in the centre of the iron ore zone. This hydrated silica zone is the same as the vitreous iron ore identified by Murchison using geological logging of the diamond drill core. At the base of the iron ore zone, the spectrally measured iron oxide abundances decrease rapidly whereas well-ordered kaolin abundances rapidly increase.

Comparison in 3D between the spectral-mineralogy and the geochemistry shows similar patterns for both the RC and DDH data. Carbonate and silica are interpreted as overprinting groundwater effects where as the well-ordered kaolin at the top and bottom of the drill holes is interpreted as a primary sedimentary clay, later modified (in part) by alkaline groundwaters. The iron oxides being formed during the development of the oodial ironstones in drainage channels. The drill core mineralogy is now being combined with surface mineral maps generated from airborne hyperspectral imagery.

Alteration mapping for IOCG exploration in the Gawler Craton using geologically constrained potential field inversions

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South Australia's Gawler Craton is known for its proven potential for iron oxide copper gold (IOCG) deposits. In addition to the giant Olympic Dam deposit, relatively recent discoveries at Prominent Hill and Carapateena and a large number of smaller prospects confirm the attractiveness of the Mesoproterozoic rocks near the eastern margin of the Craton. The challenge facing explorers is that thick and extensive sedimentary and volcanic cover overlying these prospective basement rocks prevent effective mapping by conventional techniques.

The only way to effectively predict and map the character of deeply buried rocks is by integrated analysis of remotely measured geophysical data with all available geological knowledge. Deep reflection seismic data provides critical information on unit depths, thickness and geometries. Interpreted profiles along the 03GA-OD1 and 03GA-OD2 reflection seismic lines, centred on the Olympic Dam deposit, provide the best available information on the crustal-scale 3D geometries in that area. Using potential field data and regional drilling is critical in providing lateral context and ground control for the observed seismic reflectors.

An integrated geological and geophysical model is being developed throughout a 600 km east-west by 510 km north-south area of the eastern Gawler Craton, to a depth of 25 km below surface, using geologically-constrained 3D inversion of public domain gravity and magnetic data. It is critical to include geological constraints to ensure that the 3D property models recovered using the inversions are consistent with all available geophysical and geological data. Geological constraints are developed from surface mapping, seismic profile interpretations on the Olympic Dam lines, as well as regionally-extensive seismic reflection lines 03GA-CU1, 08GA-C01, 08GA-G01, 08GA-A01, and 09GA-CG1 across the Gawler and Curnamona Cratons, and 2D potential field modelling. Where knowledge of the cover rocks exists, it is included as a constraint to enhance the resolution of features at depth.

The 3D density and susceptibility models recovered from the inversion procedure provide the best available prediction of the subsurface given the supplied knowledge. They can be interpreted directly in terms of major geometries, but additionally the large size and unique oxide- and sulphide-rich nature of some IOCG mineral systems makes it possible to predict the occurrence of key alteration assemblages in the subsurface directly from the physical property models. The density and magnetic susceptibility of the basement rocks are primarily controlled by their mineralogy, and the presence of extremely dense or magnetic oxide and sulphide minerals can cause significant deviations from the values expected for common rock units. The magnitudes of these deviations can be used to quantify the likely abundance of alteration minerals.

The predictive 3D alteration maps we have derived for the Curnamona and eastern Gawler Cratons clearly identify the Olympic Dam deposit and other existing prospects in the area, as well as many anomalies which cannot adequately be explained by the available data. These may represent new prospective targets for IOCG exploration.

SESSION 02ED (ENVIRONMENT)

Sr/Ca in planktonic foraminifera *G. ruber*: a proxy for surface ocean carbonate saturation state?

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Culturing studies suggest that foraminiferal Sr uptake is dominated by the [CO_3^{2}] of the waters in which they grow (Lea et al. 1999, Russell et al. 2004, Duenas-Bohorquez et al. 2009). In light of this, a record of the Sr/Ca of planktonic foraminifera *G. ruber* spanning the last ~135kyrs has been constructed from marine core MD98-2167 from the Timor Sea. Foraminerfal Sr/Ca is also significantly influenced by temperature. Thus, to de-convolve [CO_3^{2-}] the influence of varying temperature on foraminiferal Sr/Ca needs to be removed. To achieve this paired Mg/Ca measurements were utilised to remove the temperature component form the Sr/Ca signal. [CO_3^{2-}] was then calculated using the relationships established in the culturing studies.

The resulting reconstruction shows large variations in [CO_3^{2-}] over the glacial-interglacial cycle. It suggests that during deglacials there is an early rise and maximum in [CO_3^{2-}] (~5% increase in Sr/Ca_{foram} for T1) that occurs in unison with sea surface temperature increase and leads sea level rise. This is followed by a decrease in [CO_3^{2-}] towards glacial levels. The elevated [CO_3^{2-}] during glacial periods (low CO_2) could be accounted for by a build up of alkalinity in the surface oceans as a result of decreased coral reef carbonate production. The rapid decrease in [CO_3^{2-}] as sea-level rises could signal the proliferation of coral reefs and a concurrent decrease in surface ocean alkalinity. Ultimately, this method will allow us to document changes in oceanic carbonate saturation state back in time and spatially as well.

Utilising tandem paleotemperature tracers to open new dimensions in paleoclimate study

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Two different paleotemperature proxies were used on sediment samples from the core MD98-2167 taken at 13 8.86S, 121 34.46E on the Scott Plateau in the Eastern Indian Ocean. The Mg/Ca was measured on the planktonic foraminifera G. *ruber* (white) at 10cm intervals. Sediment subsamples from immediately below the

foraminifera were taken for organic SST biomarker analysis. The second paleotemperature proxy we employed is the TEX_{86} proxy based on glycerol dialkyl glycerol tetraethers (GDGTs). The age model was based on 14C dates which showed our samples covered the glacial-interglacial interval back to 26,000 ybp. The two proxies are remarkably well correlated, with a R^2 greater than 0.9. Both proxies indicate the tropical surface waters in this area of the Indo-Pacific Warm pool were 4–5 degrees cooler than today during the glacial maximum. If we look closely at the data though, it is clear that the two proxies are measuring different parts of the surface ocean water column. G. ruber is know n to live out its life cycle in the top 50m of the ocean. The Mg/Ca temperatures derived from G. ruber are 1 degree warmer in the Holocene and 2 degrees warmer during the glacial than corresponding TEX_{86} temperatures. This indicates that organisms that are the source of the TEX_{86} cycle to deeper depths than the G. ruber. The greater difference in temperature allows us to infer that the mixed layer and hence the thermocline were shallower during the glacial times. The fabulous correlation between the two methods serves to increase our confidence in both techniques as robust paleotemperature indicators and the combination of the two lets us pull apart subtle changes in the paleoceanography.

The boron geochemistry of siliceous sponges

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The boron content and isotopic composition ($\delta^{11}B$) of marine carbonate organisms can be linked to the pH of the seawater in which they have grown, making carbonates a useful tool for palaeo-seawater pH reconstruction. A study by Furst (1981) documented unusually high boron concentrations in siliceous sponge spicules, ranging from hundreds to a thousand ppm. This observation and the potential for preferential incorporation of the tetrahedral borate species into biogenic silica raises the question as to whether the boron chemistry of biogenic silica might also be influenced by seawater pH. We have measured the boron concentration and isotopic composition of siliceous sponges from the Southern Ocean region, with a view to (1) confirming the observations of Furst (1981), (2) assessing the factors that control boron incorporation and isotopic compositions of sponge silica, and (3) investigating the potentially significant role of siliceous sponges in the marine boron cycle. The measured boron concentrations in a diverse range of both demosponge and hexactinellid sponges confirm the high boron concentrations previously reported. The boron isotope compositions of these sponges vary from around +2‰ to +25‰ and greatly exceed the range in marine carbonates. This isotopic variation is inconsistent with seawater pH control but is correlated with ambient seawater silicon concentration, in a manner that suggests a link to silicon uptake kinetics and demand by sponges.

Clumped-isotope thermometry

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The interpretation of conventional $\delta^{18}O$ values of carbonate minerals including fossils, in the general case, is made difficult, and is occasionally confounded, because both the temperature and $\delta^{18}O$ value of the host water are unknown but are required, to complete a standard palaeotemperature equation. Accordingly, most applications concentrate on geological or environmental problems where one of these parameters varies little. A recent development, the application of 'clumped isotopes', largely solves this difficulty. 'Clumped isotope geochemistry is concerned with the state of order of rare isotopes within natural materials. That is, it examines the extent to which heavy isotopes (^{13}C, ^{18}O) bond with or near each other rather than with the sea of light isotopes in which they swim' (Eiler, 2006). The proportions of ^{13}C -^{18}O bonds in carbonate minerals (i.e. mass 47 in CO_2, extracted from $CaCO_3$ with phosphoric acid) are sensitive to their growth temperatures, independent of bulk isotopic composition. All previously published work on the development and application of the technique emanate from John Eiler's laboratory at Caltech.

The methodology requires the simultaneous measurement of all six masses of CO_2 (44, 45, 46, 47, 48, 49). Ultra high-sensitivity gas-source mass spectrometry is required, measuring the equivalent $\delta^{18}O$ (i.e. CO_2 of mass 46/mass 44) to +/- 0.01 per mil. Hydrocarbon and chlorine contaminants (e.g. $^{12}C^{35}Cl$), even at the ppb level, are fatal to the analysis. Accordingly, CO_2 masses 48 and 49 are also measured, and CO_2 'clean-up' by gas chromatography is mandatory. Long analysis times (1h) are required to gain the necessary precision to declare a carbonate growth temperature of +/- 1.5 to 2 deg Celsius. Standardisation by calibrated standard gases, and

constant repeat analyses with overlapping unknowns, means that that the Caltech lab produces only 15 new results per week per mass spectrometer. The analysis times and temperature stability are crucial. The UoW laboratory achieves air-temperature stability of about 0.1 deg Celsius and utilises an improved gas chromatographic purification step.

Clumped isotope measurements are typically expressed in per mil variation of the relative abundance of a specific isotopologue (chiefly $^{47}CO_2$) from the theoretically predicted relative abundance based on a random distribution (Wang et al., 2004; Schauble et al., 2006). The latter standard is provided by CO_2 that has been isotopically homogenised by heating to 1000 deg Celsius. The clumped isotope palaeothermometer has now been calibrated successfully for inorganic calcite, biogenic aragonite (Ghosh et al, 2006a,b) and fish otoliths (Ghosh et al., 2007) and should be applicable to any carbonate minerals that were formed in the 0–200°C temperature range. Moreover, simultaneous determinations of $^{47}CO_2$ and $\delta^{18}O$ for carbonates will constrain the $\delta^{18}O$ value (to +/- 0.5 per mail) of the water from which they precipitate. Furthermore, initial empirical measurements (Ghosh et al., 2006b) suggest that the $^{47}CO_2$ values of carbonates remain unchanged despite later heating to 200 deg C even over geological time scales.

The clumped-isotope technique will revolutionise Earth and environmental sciences, providing quantitative estimates of ocean temperatures and sea water $\delta^{18}O$ values for much of geological time; terrestrial ground temperatures for the Cenozoic and earlier; hydrologic budgets (temperature + water evaporation/balance) for inland water-bodies and semi-enclosed water-bodies (e.g. Black Sea, Gulf of Carpentaria); and details of fluid processes during diagenesis and low-temperature ore deposition. Where carbonate precipitation involves evaporation (a non-equilibrium process) such as in speleothem and pedogenic carbonates, it is noted that the generalised $\Delta^{47}CO_2$ versus temperature equation is offset. More straightforward isotope systematics are evident for environments where the carbonate precipitates or grows in liquid water.

SESSION 02SD (SOCIETAL: SALINITY)

Manifestations of dryland salinity in the Windellama area, NSW

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The Hydrogeological Landscapes (HGL) method is a biophysical approach to landscape assessment. It has been undertaken across the Braidwood 1:100,000 map sheet, which includes the Windellama area. The HGL methodology identified areas of salt outbreak within the landscape, the export or concentration of salts in-stream and the presence of highly sodic regolith materials. The Windellama area was significant for a high occurrence of land salinity, a high salt load in stream, a moderate salt concentration in stream and significant areas of highly sodic regolith materials.

Windellama is located approximately halfway between Braidwood and Goulburn. In a regional geological context, it falls within the Palaeozoic Lachlan Fold Belt, while the local lithology comprises folded, faulted and variably metamorphosed consolidated rocks of the Adaminaby Group from the Ordovician period. There are significant areas of siliceous and ferric duricrust of the Abercrombie Formation which overlie sub-silcrete clay (altered sepiolite) which in turn overlies interbedded cherts, siltstone, mudstone and fine-grained quartzose sandstone. The cherts include the Nattery Chert Member and the Mummel Chert Member.

The biophysical classification of the Windellama area indicated that the salt outbreaks are typically associated with one of the HGL units, known as Spa Road. Stream sampling and detailed regolith, mineralogical and geochemical analysis were undertaken to assist with the development of the Spa Road HGL model, understand where salt was manifesting in the landscape, further define the groundwater flow pathways within the landscape, and inform land management activities in the area.

The model developed for Spa Road HGL suggests that a number of mechanisms are driving land salinity in the Windellama area. Salt is manifesting itself in the landscape via both near surface and deeper subsurface pathways. Rainwater enters the landscape through the fractured duricrust or the near surface and near vertically dipping interbedded Ordovician metasediments. There are at least four distinct flow pathways which are attributed to the development of dryland salt outbreaks in the Spa Road HGL. Dryland salt outbreaks from the topographically highest to lowest occurrences are found: immediately below duricrust but above more

impermeable clay layers; above the clay layer at breaks in slopes; above the near vertically dipping and relatively impermeable chert layers which act as subsurface dams forcing water and associated salts to the surface; and in colluvial deposits above valley fills and floodplain elements.

Subsoils and other clay dominated regolith materials are often highly sodic. High levels of sodicity adversely affect soil stability, plant growth and land use. The separation and expansion of clay particles resulting from sodicity causes soil dispersion, soil swelling and reduced soil permeability. Sodic subsoils aid in the development and expansion of dryland salt outbreaks by forming a relatively impermeable basement to seepages allowing for evaporation and resulting salt accumulation. In the Windellama area sodic materials are found at or near the surface in association with dryland saline sites irrespective of the flow pathway.

The HGL conceptual model developed for this area has by necessity combined a number of disciplines including geology, soil science and hydrology. The understanding of near and sub surface water movement and solute transport mechanisms in this landscape has enabled the development of best management practices tailored to the Windellama area. The Spa Road HGL model targets specific management actions to each and every part of the landscape. Only by implementing appropriate management actions can the impact of salinity on soil health and water quality be mitigated in an area as complex as Windellama.

Localised saline fluxes in the Upper Murray Catchment landscape, NSW

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Publicly accessible overviews of the nature of dryland salinity in the Murray give the impression that this hazard is pervasive throughout the landscape, when in the upland parts of the greater Catchment this appears not to be the case. In the Upper Murray Catchment, headwaters of the Murray and other significant tributaries originate in the Snowy Mountains, and waters from these mountainous regions are typically fresh. Immediately west of the mountains there is a rolling hill and low hill landscape that has been variably incised throughout the Quaternary. This landscape preserves broad alluvial plains along the axes of the main river and stream systems with the crests of largely buried rocky ranges forming the adjacent hill country. Further to the west this landscape opens onto expansive plains that have been the focus of dryland and irrigation salinity research in recent years. Rainfall distribution across the upland and range margin landscapes is strongly influenced by this geomorphology with extremely high precipitation on the mountains, rapidly decreasing to the west. These landscape and rainfall patterns have been recognised for some time and management strategies to ensure that the contribution of relatively fresh water to the catchment from upland areas is preserved have been established with care. Despite these efforts there is still a notable contribution of salt to natural waters as they transition through the range margin landscapes, before they reach the plains country to the west.

Possibly the least well understood component of this catchment is the range margin rolling hill, low hill and rise landscapes with broad intervening alluvial plains. Here there is the potential for significant natural salt stores to be present in regolith associated with infill of incised palaeo-landscapes, but mobilisation of this salt is dependent on whether surface and groundwater interacts with this salt. Here the dryland salinity signature is not pervasive, but highly localised and partly structurally controlled. A few known salinity hotspots have been detected due to elevated saline fluxes entering main water courses either via tributary streams or baseflow, and significant targeted research is taking place to understand the hydrogeologic and palaeo-geomorphologic controls in these locations.

In addition to this targeted work, a broader hydro-geological (HGL) characterisation of the western Upper Murray Catchment (NSW) has been initiated. This will allow development of a series of conceptual models describing the distribution and type of regolith materials in the landscape, how water moves through these materials, what controls there are on the physical configuration of the systems, and mechanisms for salt transport in this landscape. Preliminary findings include the recognition that there has been significant structural control on the main drainage systems, imposed by the substantive palaeo-range systems that are now largely buried by infill sediments, and manifest as low hill and rise features in the current landscape. This implies, for example, that the modern Billabong River system sits over the paleo-Billabong fluviosedimentary

deposits, forming a stacked on-axis aquifer system. What is also emerging from this work is the recognition that elsewhere in this catchment, the regolith is not as thick as had previously been assumed, despite the relatively subdued topography. It follows that better understanding the physical configuration of the regolith materials in this landscape, and the surface and subsurface structural controls on fluid flow, will enhance understanding of the mobilisation of natural salts in this landscape.

Using geomorphology and stratigraphy to clarify a dryland salinity, soil sodicity and vegetation distribution puzzle at Capertee Valley, Western Blue Mountains, NSW

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In the Capertee Valley, Western Blue Mountains, NSW, localised areas of low hills and rises on the valley floor and low relief 'benches', at the break in slope, below sandstone escarpments draped by talus aprons, support only sparse vegetation and are intensely eroded. These isolated low hills, rises and benches exhibit widespread soil sodicity, localised dryland salinity and they contrast strikingly with the landforms around them. Some promising amelioration works have taken place on the eroded low hills in the Glen Alice area, enabling some reestablishment of vegetation, but this natural resource management work is ongoing.

In the same catchment, there are multiple small (0.5–2 ha) areas of dryland salinity manifesting on some upper and lower colluvial slopes and alluvial plains in the open valley area, but in a few areas, large saline scalds up to 20 ha are present. In these areas infrastructure such as roads, fences and water troughs show evidence of degradation due to the presence of salt. It has been unclear to stakeholders in the Capertee Valley why hazards such as these manifest in some parts of the landscape and not others.

Hydrogeologic Landscape (HGL) characterisation in this area has involved: characterising the geomorphology of the landscape, reviewing how the land surface intersects the stratigraphic sequence in this valley, constraining the inferred distribution of regolith materials, better understanding the hydrogeologic pathways and noting the detailed variation in extant vegetation in the catchment. They key to this puzzle has been the recognition that particular horizons in the Illawarra Formation, in particular the Nile Beds, weather to form highly erodible, sodic soil profiles. The localised nature of the distribution of the eroded landforms can be explained as outliers of these beds on the valley floor, and beds intersected by the modern land surface in footslope areas. For example, In the Horse Gap area there is localised manifestation of an eroded bench at the footslope on the western side of the valley, but a similar feature is not observed on the eastern side of the valley where Quaternary alluvial terraces abut the valley wall, obscuring potential outcrop.

This interval in the Illawarra Formation stratigraphy also contributes a component of the salt flux observed in this landscape, but it appears there is addition from concentration of a dilute flux through the thick sandstone stratigraphy as well. This observation is supported by the presence of small salt sites in areas where the Illawarra Formation is not unroofed by erosion of the modern land surface. Presence of this unit in the stratigraphy below parts of the valley floor has implications for groundwater salinity.

The Capertee Valley has proven difficult to map for the purpose of this work because the stratigraphy is flat-lying and common throughout the area, and the variation is not presented if geology alone is mapped. The HGL units defined relate principally to the interplay between geology and geomorphology, but many of the landscape features do not differ greatly from those in the adjacent unit. Detailed characterisation of the vegetation in the landscape provided the solution. Different assemblages were present on adjacent HGL units because of the interplay between regolith materials (i.e. vegetation substrate) and physical location of vegetation in the landscape (e.g. microclimate). A whole-of-catchment multidisciplinary approach has therefore been pivotal in resolving this natural resource management puzzle.

Enhancing strategic management of erosion and salinity hazard in the Goulburn Area, NSW, through characterisation of regolith materials, hydrogeology, vegetation distribution and land use

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In the Goulburn area a number of agricultural properties have been monitoring surface water quality and endeavouring to manage this natural resource. This is because entrainment of fine materials from sodic and sometimes saline regolith profiles, developed over a range of Lachlan Fold Belt lithologies, has caused erosion, stream turbidity and siltation of waterways. Localised targeted works, including the construction of concrete flumes and reconstruction of eroded landscapes using earthworks and application of a high quality compost, have been successful in rehabilitating sites and influencing the particle transport issues in the treated areas. A broader characterisation of the landscape features is now under way so that a series of whole-of-catchment models are available to enable ongoing management of the investments in these areas and to identify other sensitive areas. This research is identifying additional management strategies that address the sodicity and localised salinity hazards, and is allowing stakeholders to consider their practice in areas around existing works so that they continue to be effective well into the future.

A significant challenge in this landscape is that the expression of sodicity and salinity hazard is highly variable. There appears to be both a landscape influence, where different parts of the landscape on the same protolith, have different expression; and a contemporary rainfall influence, where lower rainfall zone areas, particularly those that have lower relief, have a higher manifestation of land and water salinity, and sodicity.

Areas of high relief typically have a more limited expression of dryland salinity because the regolith veneer is thinner, hence the potential for salt store is lower, and groundwater throughflow is more rapid. However, where these areas are cleared there is potential for land instability and localised mass movement. On mid- to lower slope facets of low hills and rises erosion manifests primarily around minor alluvial depressions and drainage systems along channels that are variably incised, many illustrating headward 'knicking' by small streams that flow episodically. This erosion is less pronounced in areas where riparian vegetation has been retained. In-paddock historical earthworks are still present with some contour banks allowing fall to adjacent streams, but a number enhancing infiltration to groundwater. Perennial vegetation distribution is also highly variable but is typically limited to the agriculturally less arable areas, such as areas of shallow rocky soils. Where in-paddock vegetation is retained the erosion and land salinisation impact is typically more limited.

Lower relief areas, particularly those in the lower rainfall areas in the west, show a greater manifestation of dryland salinity. The natural concentration of salt in the lower parts of this landscape is enhanced because of the thickness of regolith, and hence moderate to large potential salt store, and the reduced flushing by groundwater. Locally there is also seasonal concentration of salts because of evaporation. Soil sodicity is present in this part of the landscape, particularly in areas where the regolith materials have been degraded by intensive use.

Mapping of the inferred distribution of regolith materials in this landscape, hydrogeological pathway information, extant vegetation distribution and land use, constrains a series of conceptual models that will help contextualise existing and future works in this area.

SESSION 02DD (DYNAMIC EARTH: GEODYNAMIC EVOLUTION OF AUSTRALIA)

New geochronology from the Mount Painter Province, South Australia—linking the Gawler Craton and Curnamona Province

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The Proterozoic Mount Painter Province in the northern Flinders Ranges, South Australia consists of two inliers. These basement rocks are uncomfortably overlain by Neoproterozoic metasedimentary rocks of the Adelaide Rift System, which forms a regional ~north-south trending basin, and also covers the boundary

between the older Gawler Craton and Curnamona Province to the west and east. The Mount Painter Province, therefore, represents a basement window between these two cratonic blocks.

Previous studies of the Mount Painter Province have suggested that the basal metasedimentary package is Paleoproterozoic in age, although more recent work has suggested maximum depositional ages of ~1590 Ma for these rocks. Although the ~1590 Ma ages are similar to both the Olarian Orogeny of the Curnamona Province and the Hiltaba magmatic event of the Gawler Craton, the Mount Painter ages record sediment deposition rather than high-grade metamorphism and magmatism. These basal units have been intruded by large volumes of predominantly granitic magmatism between ~1580 Ma and ~1550 Ma, suggesting that magmatism in the Mount Painter region extends to younger ages than currently identified in the Curnamona Province and Gawler Craton. Therefore, new samples were collected from the Mount Painter Province for SHRIMP U-Pb zircon geochronology to test the current stratigraphy. Samples were collected from basal metasedimentary rocks to compare to maximum depositional ages previously reported from samples further north within the Mount Painter Province. Secondly, gneisses and granites from both inliers were analysed to determine whether magmatism in this area occurred semi-continuously over a ~30 Myr period or as distinct pulses.

Two quartzofeldspathic metasedimentary samples from the Radium Creek Metamorphics in the Paralana Hot Springs area yield maximum depositional ages of ~1600 Ma and ~1590 Ma. These results are consistent with the maximum depositional ages reported by Fanning *et al*. (2003), and suggest that metasedimentary units previously suggested to be Paleoproterozoic are Mesoproterozoic in age. These ages further reinforce the observation that there are currently no known Curnamona- or Broken Hill- equivalent rocks in the Mount Painter Province.

New U-Pb zircon data from the Mount Neill Granite, Box Bore Granite, and migmatites and gneisses in the Paralana Hot Springs area provide magmatic crystallisation ages of ~1585–1575 Ma. The three samples from the Paralana Hot Springs area also have low Th/U zircons which yield ages of ~1550 Ma, and may record metamorphism at this time. New U-Pb zircon data from the Terrapinna, Wattleowie and Yerila granites provide magmatic crystallisation ages of ~1565–1555 Ma. Two samples from the Paralana Granodiorite yield a group of zircons which record weighted mean ages of ~1550 Ma. In addition, both samples also contain low Th/U zircons which yield a range of ages between ~520 Ma and ~460 Ma. One interpretation for these results is that these granodiorites crystallised at ~1550 Ma and were metamorphosed during the Cambro-Ordovician.

These new results, in conjunction with existing geochronological data can be used to revise the temporal framework for the Mount Painter Province. The oldest stratigraphic units currently identified in the area were deposited at or after ~1600–1590 Ma, and include the Radium Creek Metamorphics, Mount Adams Quartzite and Freeling Heights Quartzite. These ages are coincident with metamorphism and magmatism in both the Gawler Craton and Curnamona Province, and may represent development of a foreland basin. Proterozoic magmatism in the area can be divided into two distinct pulses—the first stage occurred between ~1585–1575 Ma and includes the Mount Neill Granite, Pepegoona Porphyry, Box Bore Granite and gneisses from the Paralana Hot Springs area. This magmatism may be correlated with the later stages of magmatism in both the Gawler and Curnamona regions. The second stage of magmatism at ~1565–1555 Ma includes the Terrapinna, Wattleowie and Yerila granites as well as smaller granitic bodies in both inliers. This second pulse was followed by emplacement of the Paralana Granodiorite at ~1550 Ma, and high-grade metamorphism recorded by the Hot Springs gneisses. There is no known equivalent stratigraphy in the Curnamona Province at this time, but there are some ~1550 Ma ages for rocks from the northern Gawler Craton, suggesting that the Mount Painter Province may be more closely linked to the Gawler Craton at this time.

The Svecofennian of Fennoscandia and Eastern Europe—a Lachlan Fold Belt analogue

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It was noted by Rutland and others (2004) that there are some close similarities in tectonic evolution between the Palaeoproterozoic Svecofennian Orogen in Finland and Sweden and the Lachlan Fold Belt in eastern Australia. Both are belts dominated by turbiditic sediments deposited over a relatively short period of time in a very wide basin system at a continental margin. In both there is evidence for diachronous deformation culminating in a major deformation (in places associated with low-P/high-T metamorphism) that closed the basins. In both the deformation includes major low-angle thrusting. In both the basin closure was closely

followed by crustal extension and widespread felsic magmatism well inboard of the contemporaneous active margin, resulting in large volumes of granitic and volcanic rocks, mostly produced by crustal recycling. In both the high-velocity layer in the lower crust is unusually thick. In both the debate about the nature of the basement and the role of subduction processes remains active. An implication of these similarities is that the Svecofennian developed in a west-Pacific type, retreating margin setting.

The Lachlan Fold Belt is part of an enormous basin system that formed along the continental margin of Gondwana in the earliest Palaeozoic, remnants of which are preserved as far afield as South America, South Africa, East Antarctica and New Zealand. In contrast, the Svecofennian Orogen is exposed only in Finland and Sweden, but there is increasing evidence that Svecofennian rocks are preserved as far south as the Trans European Suture Zone (TESZ) in Poland.

We have recently found that metasediments with a very similar age and origin to those in the exposed Svecofennian extend at least as far south as central Poland. The basement of Poland, north of the TESZ, is covered by low grade Phanerozoic sediments that range in thickness from 0.5 to >5 km. The basement is known only through core recovered from a network of over 260 deep drill holes. Most holes have been drilled on geophysical anomalies and have intersected buried igneous complexes that range in age from late Palaeoproterozoic to Early Carboniferous. A few holes drilled in areas that are geophysically bland, however, have intersected amphibolite grade paragneisses.

Two paragneisses from NE Poland that we have studied in detail have chemical compositions consistent with immature to moderately mature continental margin sediments, very similar to the 'classical' Svecofennian metasediments exposed in Fennoscandia. Further, the detrital zircon age patterns measured by SHRIMP on the zircon cores from the metasediments in Fennoscandia and Poland are very similar (Williams et al., 2009). This is strong evidence that remnants of the Svecofennian Orogen extend to the south, through Lithuania and into central Poland. It is now highly likely that rocks of the Svecofennian Orogen also underlie much of the Baltic Sea.

As with the early Palaeozoic sediments of the Lachlan Fold Belt, the source of the Svecofennian sediments has not been directly identified. Some areas of rock of appropriate age are known, for example in eastern Laurentia and western Sarmatia, but these areas are small relative to the very large volumes of sediment required. The Lachlan Fold Belt sediments are known to have a remote source. First, the pattern of detrital zircon ages does not match the ages of zircon growth in rocks exposed in the eastern portion of the Australian craton, and secondly the age pattern is almost indistinguishable from the patterns found in sediments throughout the enormous Gondwana margin basin system. A massive source of sediment remote from Australia is required, involving long-distance transport along the palaeocontinental margin. The Svecofennian might also be a remnant of a much larger, Pacific-type, continental margin system.

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Inheritance and polymetamorphism in monazite: examples from Central Australia and the alps

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Monazite is one of the minerals of choice when dating metamorphism: on one hand, it readily forms and recrystallises during thermal events and, on the other hand, its U,Th-Pb system is sufficiently robust to be commonly unaffected by thermal overprinting, retrogression and alteration. Compared to zircon, monazite is less likely to preserve inheritance and it appears to participate more readily in metamorphic reaction. These are reasons why textural relationships between monazite and major silicate minerals are commonly used for the interpretation of monazite ages. We present here the cases of two amphibolite-facies rocks in which metamorphic inheritance is dominant and where textural relationships are misleading.

The Harts Range in central Australia is an orogenic terrane dominated by Ordovician high-grade metamorphism (~720°C and 6 Kbar). Monazite is found in a granulite sample containing 5 cm diameter garnets

within a gedrite, sillimanite, biotite and plagioclase foliation. Monazite was analysed in a thin section as inclusion in a large garnet as well as its matrix and as mineral separate from a large garnet. Two distinct monazite generations were found. Circa 555 Ma monazite grains and large monazite cores are present in the garnet and within the matrix. These domains have common inclusions of metamorphic biotite, staurolite and gedrite. Notably, staurolite is not found as mineral in the rock matrix. This inclusion assemblage suggests amphibolite-facies metamorphism and the monazite trace element composition indicates growth in a garnet poor environment. This metamorphic event has never been recognised previously in the Harts Range. A second generation of monazite with a distinct chemical composition is found in the matrix or included in the garnet, and forms separate grains or rims around the ~550 Ma monazite. This second monazite also contains metamorphic minerals and yielded an age of ~460 Ma. The abundance of this age component in the matrix monazite, together with the trace element signature indicating growth in the presence of garnet, suggest that 460 Ma is the age of the main metamorphic foliation, in agreement with previous geochronology in the area.

A Phanerozoic Barrovian metamorphic sequence outcrops in the Central Alps, Switzerland. The staurolite-garnet zone (~600°C) is spectacularly exposed in the area of Campolungo, where monazite can be found as an accessory mineral in micaschists. Monazite forms tabular crystals oriented along the main Alpine foliation and has an internal foliation marked by graphite. Despite its textural position, monazite consistently yielded pre-Alpine ages of ~280 Ma, corresponding to the known Variscan metamorphism. No trace of Alpine (~30 Ma) metamorphism was found in monazite in this sample. The inheritance present in monazite is also preserved in garnet, which shows a core with oscillatory zoning truncated by a homogeneous rim.

These two examples testify to the robustness of monazite and the fact that monazite U,Th-Pb ages and compositions can survive amphibolite facies metamorphism up to ~700°C. It also reinforces caution in using textural relationships in interpreting accessory mineral ages. The Harts Range monazite that pre-dates garnet formation is found as inclusion in garnet as well as in the matrix. The pre-Alpine monazite at Campolungo is aligned with a foliation generally considered to be Alpine in age.

The biogeochemical status of the Palaeo-Pacific Ocean: clues from the early Cambrian of South Australia

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The Ediacaran-Cambrian transition was a time of profound reorganisation of the biosphere, coinciding with the tectonic upheaval involved in the final breakup of Rodinia and assembly of Gondwana, and the increased oxygenation of the atmosphere and oceans. The early Cambrian successions of the Arrowie and Stansbury Basins, South Australia, are renowned for their thick fossiliferous limestones and shales, the latter commonly black, pyritic and phosphatic. These marine sediments (including archaeocyathid reefs) were deposited in a humid tropical climate at low northern palaeolatitudes on the western margin of the emerging Pacific Ocean. Here we report the initial results of a multi-pronged investigation of the redox and nutrient status of that ocean employing minor and trace element abundances and stable isotopic (C, S) signatures from four formations: the Andamooka Limestone and the Heatherdale, Emu Bay and Karinya Shales (sequences C1.2 to C2.2).

The $\delta^{13}C_{carb}$ profile of the Andamooka Limestone in the Arrowie Basin, when combined with those of the underlying Wilkawillina Limestone, Woodendinna Dolomite and Parachilna Formation (Tucker 1989, Terra Nova v.1: 573–582), exhibits a falling trend from -1 to -4.5‰ during the Tommotian; a further decline to -6‰ before climbing to +1‰ in the mid-Atdabanian; and a final oscillating climb to +3‰ during the Botomian. This local record of early Cambrian $\delta^{13}C_{carb}$ chemostratigraphy is similar to the composite profile reported by for time-equivalent sections in the Anti-Atlas Margin, Morocco, and the Siberian Platform (Maloof *et al.* 2005, Can. J. Earth Sci. v. 42: 2195–2216). Both profiles reveal that the isotopic composition of dissolved inorganic carbon varied at several frequencies during this time, implicating multiple mechanisms in the modulation of the early Cambrian marine carbon cycle. The lack of glacial deposits and the presence of coeval black shales (notably the phosphatic Heatherdale Shale) suggest that these secular C-isotopic fluctuations may be linked to changes in nutrient cycling and the rate of burial of organic matter (Halverson *et al.* 2009, Dev. in Precamb. Geol. 16: 351–365).

Total organic carbon contents range from ≤0.1% in the carbonate units, through ≤0.5% in the Emu Bay Shale, to as high as 1.9% in the Karinya Shale and 2.6% in the Heatherdale Shale, the degree of organic enrichment reflecting the redox state of the seafloor at the time of deposition, viz. oxic (carbonates), sub-oxic (Emu Bay) and anoxic (Karinya, Heatherdale). For the shales, normalised Mn and Mo concentrations, in combination with enrichment or depletion of U, V, Cu, Ni and Zn, further constrain the oxicity, sedimentation rate and nutrient residence times in their respective depositional settings. Uplift and erosion of the nearby Trans-Antarctic Mountains was accompanied by enhanced pedogenic production of clay minerals (Kennedy *et al.* 2006, Science v. 311: 1446–1449). The resulting elevated fluvial influx of both nutrients and clays (especially smectite) to the Stansbury depocentre, possibly in tandem with upwelling of cold, Fe- and P-rich waters, facilitated the production, sequestration and burial of organic matter, thereby contributing to the rise of atmospheric pO_2 to levels necessary for animal life.

A final clue to the evolving biogeochemistry of the local Cambrian ocean is the striking secular decline in ^{34}S content of pyrite recorded in a 96 m section of the Karinya Shale ($\delta^{34}S$ decreases from +10 to -11‰). This may reflect a stepped increase in the oxygenation of the ocean and, hence, in the availability of sulphate for bacterial sulphate reduction during the Botomian.

SESSION 02TD (TOPICAL: ERNIE NICKEL SYMPOSIUM)

What really controls coordination number in mineral crystal structures?

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Compatibility of trace element in minerals, as well as the extent of solid solution of major components and the activity models appropriate for describing thermodynamics of mixing, are all determined by the preferences of specific cations for specific coordination environments. The majority of textbooks still rationalise coordination behaviour in terms of radius ratios of 'billiard ball' ions, despite the fact that this model gives wrong predictions more than 50% of the time for even simple classes of compound such as the alkali halides. Much more success in understanding and predicting structures and their stability, including subtle aspects such as preferred degrees of hydration, has been achieved over the last 30 years through a combination of the bond valence model for bond length-bond strength relationships and a Lewis acid/base strength model generating preferred bond valences between specific species.

The usual argument for the Lewis acid/base strength paradigm makes it seem rather circular. This is not the case, if it is understood as a consequence of nonlinear bond valence-bond energy relationships. However, it is likely that this is a strong controlling factor on bond valence and coordination number in only a few cases. In general, Madelunfg energies show that it is energetically feasible to maximise coordination number in so far as this is not counteracted by crowding of ligands. Hence, the major determinant of coordination number is actually a ratio of distances, but these are not 'ionic radii'; they are the centre-ligand bonded distance and the ligand-ligand nonbonded distance. Large minimum nonbonded distances between ligands, in turn, force the central atom to adopt off-centre asymmetrical coordination. Consideration of nearest-neighbour bonded and next-nearest neighbour nonbonded distances rationalises observed structure types far better than other approaches, and even distinguishes between stability fields of some topologically different structures with the same coordination numbers.

In this model, higher coordination number is associated with longer bonded distances relative to the minimum acceptable nonbonded distance between ligands along the edges of the coordination polyhedron. Both cations and anions must be considered, as centres of their respective polyhedra. The effects of pressure and temperature on coordination number depend on the relative sensitivity of these lengths to the state variables. For instance, the usually assumed increase in coordination with pressure arises since the nonbonded polyhedra edges are more compressible than the bonded centre-ligand distances.

New minerals and type localities in Tasmania

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Tasmania is the home to several new minerals. These include:

- Dundasite: Twelvetrees, 1893
- Philipsbornite: Walenta, 1982
- Petterdite, Birch et al., 2000
- unnamed Pb-Cr-Mn oxide, in prep
- Stichtite: Twelvetrees, 1910)
- Heazlewoodite; Petterd, 1896
- Hellyerite: Williams, 1959
- Shandite: Ramdohr, 1949
- Mawsonite: Markham & Lawrence, 1965, co-type locality with Tingha, NSW
- unnamed new tourmaline
- unnamed 'Ca-ralstonite', in prep

The main type localities include:

- The Adelaide Mine, Dundas (Dundasite; Philipsbornite)
- Red Lead mine, Dundas (Petterdite, unnamed Pb-Cr-Mn oxide)
- Stichtite Hill, Dundas (Stichtite)
- Lord Brassey Mine, Heazlewood (Heazlewoodite; Hellyerite)
- Trial Harbour (Shandite)
- Mt Lyell Mine, Queenstown (Mawsonite),
- Cleveland mine, Luina (a new tourmaline and 'Ca-ralstonite')

There are also several potential new minerals under investigation, most from the Zeehan and Heazlewood areas. These include:

- Fe-ammonium phosphate analogue of leucophosphite. Pedra Branca
- Ni-Fe sulphate, Lord Brassey mine, Heazlewood
- Ca-Fe silicate, Forster Prospect
- Ca-Cr silicate, Trial Harbour
- Bi-Ni-Fe-Pt Alloy, Lord Brassey mine, Heazlewood
- Amphibole ('potassic kaersutite'), Smithton
- K-Pb-Al silicate, Whyte River mine, Heazlewood
- Ag-Pb phosphate, Whyte River mine, Heazlewood
- U-Al phosphate, Storeys Ck
- Zn-Al silicate, Zeehan

These minerals, their locations and their geological and mineralogical associations will be briefly described. In summary, most of these mineral occurrences are associated with Cr-Ni-PGE rich Cambrian ultrabasics (serpentinites), altered by Devonian granites and related hydrothermal fluids, rich in lead, tin, bismuth, CO_2, sulphur, and arsenic. Deep weathering of ultramafics and associated mineralisation is also important for the formation of some of these minerals.

Mafic-hosted secondary mineralisation from the Shangri La Pb-Ag-Au-Cu mine, Kimberley, Western Australia

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The abandoned Shangri La Pb-Ag-Au-Cu mine is a small, mafic-hosted, polymetallic, hydrothermal quartz vein-type deposit that is situated near Kununurra in the north-east Kimberley, Western Australia. Primary sulphide

mineralisation consists of galena, sphalerite, chalcopyrite, bornite and tetrahedrite associated with a complex assemblage of supergene Ag-Sb and Cu sulphides. The age of the primary sulphide mineralisation is uncertain, however, the lead isotopic model age of galena from the mine is 1503 Ma suggesting that the lead in the deposit probably was derived from the host Palaeoproterozoic Hart Dolerite. The oxidised zone of the deposit contains a diverse assemblage of secondary minerals, including malachite, azurite, rosasite, aurichalcite, cerussite, smithsonite, otavite, bindheimite, osarizawaite, beaverite, beudantite, plumbojarosite, linarite, vanadinite, mottramite and hemimorphite. Chemical controls on the formation of the secondary mineral assemblage are discussed. Native silver and secondary silver halides are absent from the Shangri La assemblage and secondary silver-bearing minerals appear to be restricted to supergene sulphides. In other oxidised base metal deposits, such as Broken Hill, the presence of silver halides is indicative of arid to semi-arid conditions of weathering, thus their absence from the Shangri La mine is consistent with the development of the secondary mineral assemblage during weathering in a tropical climate. The oxidation of magnetite in the Hart Dolerite host rock is the probable source of vanadium for the mottramite-vanadinite secondary mineralisation. Mottramite and vanadinite, along with an otavite-hemimorphite-rosasite-smithsonite assemblage, probably crystallised from mineralising groundwaters under basic, oxidising conditions.

Wednesday 7 July 2010

SESSION 03RA (RESOURCES: AIG SYMPOSIUM)

Why geological mapping is important

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Geological mapping is carried out by mineral exploration and mining companies, government institutions and university departments. A geological map provides the context for all other geological investigations and shows the distribution and character, at or near the earth's surface, of rocks of various types or of various ages. The essential ingredients relate to observations made at particular geographic locations. Observations that can be used for geological maps are available in natural exposures, river or creek beds, mines and quarries, drill-holes and road cuts. Geological maps also contain information on the locations of 'unit boundaries' (contacts), displaced units (faults), and structural measurements on the angles of unit boundaries, beds and layering which can be tilted, contorted and folded. In addition to hard copy and digital geological maps there are also a wide range of other products that are of inestimable value to the earth scientist. These include an array of geophysical maps and data sets, mineral occurrence maps, geochemical data sets and geochronological data sets.

Geological maps can be developed at varying scales, for example 1:250,000 for regional mapping work to 1:500 for detailed mapping around mines and specific projects. Mapping for mineral exploration must take into account features which have a direct bearing on the location of a specific commodity. For example, this may include mapping out quartz-garnet horizons in Palaeoproterozoic terrains which are often intimately associated with Broken Hill Type Zn-Pb-Ag mineralisation. The preparation of geological maps, in conjunction with other data sets, are critical for the location and potential availability of most commodities exploited around the globe (for example, coal, ferrous and non-ferrous metal deposits, industrial minerals oil and water). These maps are also invaluable in allowing for environmental management, structural engineering studies (for buildings, dams), location of new cities and towns and natural hazard risk assessment.

The use of geological and other data sets allow for a three dimensional view of the upper parts of the earth's crust. Cross-sectional 'slices' can be prepared utilising deep drill-hole information, structural data as well as such geophysical information as seismic data sets.

In areas devoid of outcropping strata which are perhaps covered by soils or other young cover, the development of other 'mapping' techniques will be required. In these areas, which are becoming more interesting to mineral exploration companies due to the probable absence of historical detailed exploration, modern 'mapping' techniques are evolving. These can be geochemical and geophysical with new geochemical techniques involving the sampling of vegetation, for example. In addition, in most regions there is historic drill-hole information and stored drill-core which are ideal in developing local geological 'maps'. For example the

Primary Industries and Resources Department of South Australia (PIRSA) houses a drill-core library which contains approximately 10,000 kilometres of core and cuttings. These cores can be used to identify the rock-types present in any given region. With geochronological and petrographic investigations the units present can be given an age and an 'identity'. Local geological maps can then be prepared and the use of, for example, aeromagnetic data sets can extend these new maps.

This abstract has outlined the importance of geological mapping. If a government institution or public mineral exploration or mining company arrives in an area which is poorly understood, the first requirement will be the preparation of geological maps. These large scale maps can then be modified, expanded and updated as other 'maps' are created (aeromagnetics, geochronological data, petrographic data). This information can then be used to outline what commodities should be explored for in any future programs.

Application of IP geophysics to practical geology for mineral exploration

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When electric current passes through the earth, the method of conduction is primarily through the interstitial fluid. The degree to which the current is able to flow is dependent on the porosity of the rock and salinity of the fluid. Measurement of the voltage at the surface of the ground in response to a known electric current gives a measure of the average electrical resistivity of the earth and assuming groundwater salinities are constant over a limited area, a measure of rock porosity. With some knowledge of local geology, this may be related to the type of rock or degree of alteration.

Where metallic grains are present, which are individually conducting, the electric current passes from the groundwater through the conducting mineral grain and back into the groundwater. Where this occurs electrochemical reactions at the boundary between the conducting grains and the groundwater forming billions of tiny 'rechargeable batteries', which alter the measured voltage at the ground surface when the initial current is varied. This is known as the 'Induced Polarsation' (IP) effect and its measurement at the ground surface gives an estimate of the average total surface are of metallic grains in the area of the measurements. This is most commonly related to the abundance of disseminated sulphide minerals that are of key importance in mineral exploration.

In the time since the IP effect was first documented about a century ago, many different techniques for measuring the IP effect have been developed. These have reduced to the three main survey styles used in Australia today, gradient array, dipole-dipole array and 3D arrays.

Until the 1990s, interpretation of IP data was done by hand using rules of thumb and interpreter experience. There are now sophisticated computer programs' 'inversion modellers', which divide the earth into blocks and estimate the intrinsic resistivity (relative porosity) and IP effect (sulphide content) of the blocks. This software generates subsurface maps of these parameters, which may be extremely useful in geological mapping for mineral exploration.

While the IP/resistivity technique provides extremely useful information about subsurface geology there are limitations to its effectiveness. The technique provides maps of metallic mineral concentrations in the subsurface but has low resolution, particularly at depth. As a rule of thumb, the technique is only able to resolve details of subsurface features greater in size than half the depth of burial. Results from the inversion modelling software are non unique and may be ambiguous in some situations. Fine details observed in the modelled IP data should not be interpreted literally unless there is strong geological support. Penetration into the ground may be strongly attenuated in situations where highly conducting layers exist adjacent to or above resistive host rock. This is particularly apparent in areas of thick or salty alluvium or weathering above a silicified basement.

Despite the limitations of the technique, IP may be very useful for mapping sulphide content and major rock units in areas where surface geology, alteration or geochemistry are obscured or where these vary rapidly laterally of with depth. The technique has been found to be particularly useful in mapping porphyry intrusion systems but also has wide application for other styles of ore deposit.

Like all mapping techniques in mineral exploration practice, the usefulness of the IP/resistivity technique will depend on its cost relative to the information it provides in a particular environment. In areas where geology is

obscured by surficial material or changes rapidly with depth, it can provide maps of bulk sulphide content to depths in excess of 500 metres. At about A$12,000 per square kilometre (2010 dollars), the cost of IP surveying is significantly greater than some other exploration techniques but may provide geological information or drill targets in areas where these have failed or are inappropriate. The users of the information provided in an IP survey should, however, be aware of the limitations of this information, particularly with respect to the resolution that the system can provide for targets at depth.

SESSION 03EA (ENVIRONMENT: IODP SYMPOSIUM)

IODP 318 Cenozoic East Antarctic ice sheet evolution from Wilkes Land Margin sediments: preliminary results

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We present the initial results from the recent IODP Expedition 318 which drilled the Wilkes Land margin of Antarctica along an inshore transect to provide long-term sedimentary archives of Antarctic glaciation to investigate the relationships between global climate and oceanographic change.

Understanding the evolution and dynamics of the Antarctic cryosphere, from its inception during the Eocene–Oligocene transition (~33 Ma) through the significant periods of climate change during the Cenozoic, is not only of major scientific interest but also is of great importance for society. The transition from Greenhouse to Icehouse Earth conceivably was the most significant step in large-scale planetary change, impacting global sea level, albedo, and oceanographic and biotic evolution, among other changes. State-of-the-art climate models combined with paleoclimatic proxy data suggest that the main triggering mechanism for initial inception and development of the Antarctic glaciation was the decreasing levels of CO2 concentration in the atmosphere. With current rising atmospheric greenhouse gases resulting in rapidly rising global temperatures, studies of polar climates, and the Antarctic cryosphere behaviour in particular, are prominent on the research agenda.

The East Antarctic Ice Sheet (EAIS) in the Wilkes subglacial basin is grounded below sea level and therefore may have been more sensitive to climate changes in the late Neogene. The sedimentary sections on the Wilkes Land margin therefore not only hold the record of the time when the EAIS first reached this margin, but also the record of ice sheet fluctuations during times when the EAIS is thought to be more stable (15 Ma–recent). This information is critical for developing reliable models of future Antarctic ice sheet behaviour. Drilling the Wilkes Land margin provides constrains to the age, nature, and paleoenvironment of deposition of the previously only seismically inferred glacial sequences.

SESSION 03SA (SOCIETAL: EDUCATION)

Rethinking curriculum design using core representations

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A teacher's development of pedagogical content knowledge (PCK) is a much debated idea but there is general agreement that involves the intersection of their content knowledge and their pedagogical ideas. In its simplest form, PCK is the skill exhibited when a teacher takes a scientific concept and explains it to another in a manner that they can comprehend. It requires an intimate knowledge of the content and the capacity to gauge the competency of the student and then frame a task, or response to a student, in a discipline-specific and student-specific manner. PCK is unique to teaching, and if you find yourself doing it, you are teaching, no matter the environment. When interpreting syllabus and curriculum documents teachers must apply a lot of knowledge about teaching strategies, but they must also know what concepts they wish to teach and how

each concept is structured and fits within the broad scientific context. Identifying which concepts to teach is usually the job of the syllabus or curriculum documents, but the nature of each concept, its structure and how it relates to the real world, are generally less well defined and are left up to the teacher to decipher. So if we acknowledge that PCK is a fundamental aspect of science teaching, then it makes sense for syllabus and curriculum documents to embed elements of PCK, providing guidance to teachers about the nature of the scientific concepts they are teaching.

Content representations were originally developed when Australian science education researchers worked with expert and experienced teachers of science, and developed a conceptualisation of PCK based on concrete examples from those teachers' practice. The Content Representation (CoRe) offers an overview of the particular content taught, with specific reference to basic concepts, or 'big ideas'. The CoRes developed demonstrated that experienced teachers still organised their thinking and their teaching around scientific ideas, regardless of what curriculum initiatives may have been happening around them. We modified this approach to explore the potential role of Content Representations as an organiser for a geoscience curriculum. In this case a CoRe is developed by identifying the 'big ideas' associated with teaching Earth and Environmental Science and then probing these ideas in different ways so that specific information that impacts on the manner in which the content might be taught can be made explicit. Through this process, the CoRe becomes a generalisable form of the teachers' pedagogical content knowledge as it links the how, why and what of the content to be taught with what is agreed to be important in shaping students' learning and teachers' teaching.

Development of a CoRe for Earth and Environmental Science allowed identification that, unlike other sciences there was a two-tiered framework for the big ideas relating to the geosciences. There are master concepts that most closely map the Earth Systems and include recognition that: the Earth System has changed over a long period of time (4.5 billion years); the Earth is a chemically and physically dynamic system, the Atmosphere is a chemically and physically dynamic system, the Hydrosphere is a chemically and physically dynamic system; and, the Earth System has supported life for a long period of time. So, for example, the master concept behind the first one is the concept of geological time. When structured in this manner the CoRe illustrates that the sciences chemistry, and biology and much of physics, were originally derived from the study of the Earth System. It is only when these master concepts are probed that we arrive at the level of 'big idea' (e.g. evolution, plate tectonics, weather patterns) that somewhat parallel those observed in other sciences. For each of these 'big ideas' a concept-specific CoRe can be constructed that explores potential pedagogical approaches to teaching this idea. This approach provides an overarching logical and defendable framework for curriculum design. Further, this work identifies the need to discuss what we mean by scientific concepts, and how these relate to hypotheses and theoretical scientific ideas, but also about the specifics of which key concepts should be included in a geoscience curriculum and how these should be structured for students at particular year levels, in other words—a PCK problem.

Sustaining a new high school EES course in Western Australia

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Western Australia is arguably one of the most straightforward places in which to establish an Earth and Environmental Science (EES) course in high school. The minerals and oil and gas sectors are major employers and constructors of infrastructure in the region; pathways to employment are relatively clear and there is demand; industry support is available for development of teaching resources, support of field work, and work integrated learning; there is considerable environmental enterprise particularly in the areas of natural resource management and industrial development; several Tertiary sector institutions provide stellar opportunities for further education; and access to world class earth and environmental field sites is outstanding. So, two years since the establishment of the new senior EES curriculum in Western Australia, and a few years out from the implementation of the new National Curriculum for EES, how are we travelling?

Of the more than 250 high schools that could potentially teach EES, in the order of 40 are currently doing so, and this number is growing. Anecdotal evidence suggests that most of the schools teaching the EES Course have either an Earth Science qualified or an Environmental Science qualified 'champion'. However, there are rarely more than two of these individuals in a School's science staffroom, and more typically there is a single individual, or the classes are taught by interested teachers with a qualification in Geography or another science area (usually Biology or Chemistry). Preliminary findings from research commissioned by Earth Science

Western Australia (ESWA) confirmed that 'the most frequently cited reason for offering EES at a school was that a teacher had an educational qualification, employment history or personal interest in geology or environmental science.' Other reasons included: the belief that EES offered students increased career and University options and the importance of environmental issues in society. For a small number of schools their geographical location in an area influenced by an EES related industry was an important deciding factor for provision of the course. Justification by Schools for not providing the EES course yet included '… [EES] competition with other science and non-science subjects, the perceived difficulty of EES, and the lack of a qualified teacher.'

In an environment where earth and environmental science qualified individuals are highly paid to work in industry, the pool of EES qualified high school teachers may only grow incrementally, so relying on these 'champions' to ensure ongoing delivery of EES across the high school system is probably not sustainable. What it does provide is a critical mass of expert teachers who will undoubtedly play a significant part in professionally developing their peers, with the support of State Education agencies, Tertiary sector institutions and independent educational support organisations. Tensions that need to be addressed are: support for preservice and experienced science teachers to receive recognised professional development in Earth and Environmental Science and EES specific Education; the dichotomy in current and potential teachers' science qualifications (typically Earth Science or Environmental Science and only rarely both); recognising the need for instilling the rigour of scientific process in order to teach EES contextualised by Social Environmental Education, not vice versa, to high school students; supporting teachers with the provision of high quality educational resources (texts, rocks and minerals, field and laboratory testing equipment, field guides, access to experts), practical and field opportunities and work integrated learning opportunities; and the large potential demand for more qualified EES teachers when the National Curriculum is implemented after 2012.

SESSION 03DA (DYNAMIC EARTH: RESTLESS EARTH)

Is the Earth's inner core a conglomerate of anisotropic domains?

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Travel times of the Earth's core-sensitive compressional PKP waves from the South Sandwich Islands (SSI) region observed in Alaska have been known to depart significantly from theoretical predictions. This has been attributed to the existence of a uniform cylindrical anisotropy in the inner core (IC), with a fast axis aligned with the Earth's rotation axis. New PcP-P differential travel-time residuals from the SSI region presented here are similar in range to that of the PKP(BC-DF) residuals (four seconds), yet entirely insensitive to IC structure. This observation strongly suggests that the mantle structure can affect PKP travel time residuals from the SSI earthquakes more than previously acknowledged, and plays a significant trade-off role in the interpretation of body wave travel times in conjunction with IC structure. This presents a challenge to the existing conceptual framework of a uniform IC cylindrical elastic anisotropy and its hemispherical signature. The Earth's IC might be a conglomerate of anisotropic domains of different strength, and the travel time observations at the surface are most likely influenced by the proportion and the direction of a particular geometry of sampling, as well as by the inhomogeneous structure of the mantle. This concept reconciles complexities in the observed PKP travel times with preserving a net elastic anisotropy in the IC that is required by the observations of Earth's free oscillations.

4.5 billion years of crust-mantle evolution from a modern isotopic perspective

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A foundation of late 20th century geochemistry is the linking of chemical depletion of the mantle with the growth of continental crust. This has led to, for example, the extensive use of ^{143}Nd isotopic variations to map mantle chemical evolution and link isotopic variations through time with continental growth curves. A series of recent developments now challenges these straightforward views of crust-mantle dynamics. These include

extensive integrated field and geochronologic investigations of well preserved, >3.7 Ga terranes in south-west Greenland and elsewhere, new observations from >4.0 Ga detrital zircons from Western Australia, new analytical capabilities (LA MC-ICPMS) permitting *in situ* determination of initial ^{176}Hf isotopic compositions within single U-Pb (SHRIMP) dated zircons, *in situ* measurements within single crystals of oxygen isotope compositions (ion-probe) and high precision (better than ±3 ppm external precision) measurement capability using TIMS yielding the ability to measure subtle isotopic variations in ^{142}Nd isotopic compositions of early terrestrial, lunar and Mars samples resulting from the decay of short half-life (103 million years) and now extinct ^{146}Sm.

Here, using both published and new determinations, we present integrated high-precision ^{142}Nd and ^{176}Hf datasets from four of the oldest (>3.7 Ga) terrestrial rock terranes (Itsaq Complex of south-west Greenland, Napier Complex of East Antarctica, Anshan Province of China and Narryer Complex of Western Australia). High-precision ^{142}Nd compositions were determined from whole rock powders using TIMS (Johnson Space Center Triton); Lu-Hf isotopic compositions were measured using LA-MC-ICPMS (Neptune) on U-Pb age dated (using SHRIMP) zircons extracted, for most samples, from the same whole rocks. Significant (0–20ppm) variations in ^{142}Nd compared with modern terrestrial compositions reflect early (>4.4 Ga) formation of high Sm/Nd domains, while ^{146}Sm ($T_{1/2}$=103 Myr) was actively decaying. In contrast ^{176}Hf compositions are all near-chondritic (using CHUR values of Bouvier et al., 2008, EPSL 273: 48–57; and l^{176}Lu=1.867 X 10^{-11} yr^{-1}) requiring chondritic Lu/Hf ratios; there is no correlation of ^{176}Hf with ^{142}Nd (or ^{143}Nd) signatures as for example, characterises Phanerozoic granites. The absence of Lu/Hf fractionation places quantitative limits on the volumes and mean age of Hadean continental crust that could have been formed and preserved into the early Archean and indicates only a minor role for early continental crust extraction in generating Hadean-Eoarchean mantle chemical fractionation. Furthermore, the observation that modern terrestrial rocks all have a 20 ppm offset of their ^{142}Nd compositions from primitive (chondritic) meteorites (Boyet and Carlson, Science 309, 2005) requires consideration of models calling for a non-chondritic Sm/Nd composition for the bulk silicate Earth. Acceptance of such models requires a revision of crust-mantle mass balances through time, which have been previously largely based on ^{143}Nd isotopic variations. Thus, a key question in mantle chemistry is the relative roles of early planetary processes, including accretion and intra-mantle differentiation, versus on-going processes such as continental crust extraction and crustal recycling in creating and modifying mantle chemical signatures.

The coupled Sm/Nd and Lu/Hf depletions that produce well-correlated, positive ε_{Hf} and $\varepsilon^{143}_{Nd,}$ arrays, such as characterise the source regions of modern MORB and Phanerozoic granites, are features of the upper mantle since at least 2.7 Ga but not earlier than 3.5 Ga and may only represent the dominance of continental crust formation on mantle chemistry in the last half of Earth history.

SESSION 03LA (LIFE AND SOLAR SYSTEM: PLANETS WET AND DRY)

Isotope tracing of water in the solar system

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Known life in our solar system requires water. As such, the search for water throughout the solar system defines the potential for finding out where and how life formed. Water exists in three phases at the surface of the Earth and is likely the only place in the solar system where this is now so. On the Moon, water has been found as ice in the bottom of craters that see little sunlight and hence remain below freezing point. Venus has a vanishingly small amount of water remaining in the atmosphere and this quickly reacts with sulphur oxides in the atmosphere. The geomorphology of Mars is quite consistent with past oceans of water and water ice has been found in the subsurface. Water ice is also a fundamental constituent of outer solar system bodies and in particular the satellites of the outer planets, the dwarf planets of the Kuiper Belt.

Tracing the origins of water and knowledge of timing is extremely important if we are to establish the origins of life. Isotope tracing of water through D/H and $^{18}O/^{16}O$ and $^{17}O/^{16}O$ is distinctive in different locales in the solar system. The three isotopes of oxygen allow a distinction to be made between mass dependent isotope fractionation, and ^{16}O-fractionation which appears to be pervasive in solar system sources. Solar wind has streamed out through time and interacts substantively with many inner solar system bodies. The Sun has no D

because of its destruction through nuclear burning in the core. The oxygen isotope composition of the Sun appears light, depleted in ^{17}O and ^{18}O relative to terrestrial oxygen. Earth and Moon have the same intrinsic oxygen isotope compositions. This similarity requires a paired origin for Earth and Moon because of the range of compositions measured from meteorites which were the building blocks for planetesimals, and through oligarchic growth, the planets. Earth's D/H ratio has been compared with that in meteorites and comets too and it is often stated that the D/H of comets is too high for much cometary water to be part of the oceans. On the other hand meteoritic water such as in carbonaceous chondrites would be a suitable source. The surface water on the moon has been ascribed to solar wind interaction. In this case the water should be isotopically light provided it has not reacted and equilibrated with the lunar soil. Water on Mars, as found in the Martian SNC meteorites, is quite distinctive in that it is substantially enriched in D/H, up to four times the terrestrial value, and the oxygen is slightly enriched in ^{17}O compared to Earth (for a given $^{18}O/^{16}O$).

Meteoritic oxygen isotope compositions show wide diversity. The lightest oxygen in the solar system is found in a single chondrule and is some 8% enriched in ^{16}O relative to terrestrial. Refractory inclusions, often referred to as solar consensates, are also enriched in ^{16}O and at a level similar to the Sun. The rocky bodies of meteorite parent bodies, Earth, Moon, Mars foer which we have samples are similar. Chondrites, in particular carbonaceous chondrites show more diversity in bulk, and show both enrichments in ^{16}O and enrichments in ^{17}O and ^{18}O. In the matrix of one carbonaceous chondrite that has seen little alteration, an Fe-rich phase has oxygen with ^{17}O and ^{18}O enrichment of up to +180 ‰. This has been ascribed to nebular water in the early solar system representing initial oxygen isotope heterogeneity in the solar system. Heavy oxygen on the Moon, in young soils, might have a similar origin and carried to the moon in comets. Lacking from our inventory are any measurements of outer solar system bodies. Will they show oxygen isotopes similar to the Sun, the inner solar system planetary bodies, or be dominated by nebula water?

Pressure-temperature phase diagrams of the Earth and Mars

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Terrestrial life is known to require liquid water. However, studies into the extreme habitats of microbial life have revealed apparent temperature and water activity limits on the environments which support life. These limits fall within the stability regime of liquid water, indicating that if these limits are real then there exists liquid water on Earth without life. This conclusion suggests we should refine our strategies in searching for extant life. Based on a pressure-temperature (P-T) phase diagram model of the Earth, Jones & Lineweaver (2010) quantified and reported the location of uninhabited terrestrial liquid water. Our model represents the atmosphere, surface, oceans and interior of the Earth—allowing the range of P-T conditions in terrestrial environments to be compared to the phase regime of liquid water. Here we present our Earth phase model and our results on the habitability of terrestrial water. The intersection of liquid water and terrestrial phase space indicates that the deepest liquid water environments in the crust occur at a depth of ~75 km. The volume of the crust above a depth of 75 km is 3.5% of the volume of the Earth. Considering the 3.5% of the volume of the Earth where liquid water exists, ~12% of it is inhabited by life while the remaining 88% is uninhabited liquid water. This is distinct from the fraction of liquid water occupied by life. We find that at least 1% of the volume of liquid water on Earth is uninhabited. Potentially uninhabited liquid water occurs in the atmosphere; permafrost and ice (shallower than 4.6 km in some areas), thermal vents (eg. Mothra field at 2200km depth and Lucky Strike field at 1600km depth) and deep intra-terrestrial environments (below 38 km). We also present our preliminary Mars phase model and our constraints on the potential Martian biosphere (Jones & Lineweaver, 2008) based on superimposing the phase space of Mars with the phase space of terrestrial life and liquid water.

SESSION 03TA (TOPICAL: AUSCOPE SYMPOSIUM)

AuScope+: opportunities, challenges and responsibilities

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This presentation will outline some ideas on the opportunities, challenges and responsibilities that the the Australian Earths Science community faces in articulating a coherent infrastructure program for the next decade. The motivation is to seed discussion for a compelling program for whatever follows the NCRIS program that currently underwrites AuScope—i.e. AuScope+. In addition, there will be the opportunity to review the objectives of the AuScope-AGOS EIF round three bid, submitted in late 2009.

AuScope Geospatial: measuring the contemporary deformation of the Australian crust

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Ongoing developments in geodetic positioning towards greater accuracies with lower latency are now allowing the measurement of the dynamics of the Earth's crust in near real time. However, in the Australian circumstance a sparsity of geodetic infrastructure has limited the application of modern, geodetic science to broader geoscience research programs. Recent enhancements to the Australian geodetic infrastructure, through the AuScope initiative, offer opportunities for research into refinement of geodetic accuracies, as well as their application to measuring crustal deformation.

SESSION 03RB (RESOURCES: AIG SYMPOSIUM)

Architectural controls on Paleozoic porphyry gold–copper mineralisation in the Cadia Valley, NSW

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The Cadia Valley contains Australia's largest and highest grade porphyry gold-copper deposits, with resources of 2,347 Mt @ 0.44 g/t Au, 0.28% Cu at Cadia East, and 152 Mt @ 0.77 g/t Au, 0.39% Cu at Ridgeway (Newcrest Mining Ltd 2009 Resources and Reserves Statement—17 August 2009). Alkalic porphyry-style mineralisation was associated with the emplacement of monzonitic intrusive complexes into shoshonitic volcano-sedimentary rocks during the late Ordovician – early Silurian. This magmatism marked the culmination of igneous activity in the Macquarie Arc, coinciding with the onset of the Benambran Orogeny. Intrusive geometries vary from pipes (Ridgeway) through dykes (Cadia East) to stocks (Cadia Hill, Cadia Quarry/Cadia Extended).

Detailed facies analysis of the Ordovician volcaniclastic rocks that host the Cadia porphyry deposits, coupled with geometric studies of the mineralised intrusive complexes, are providing new insights into the controls on magmatism and mineralisation in the Cadia Valley. Deep drilling has revealed that the oldest porphyry deposit, Ridgeway, is partly hosted by arc-derived submarine turbidites of the Weemalla Formation. These fine-grained distal clastic rocks are overlain by thick sequences of feldspathic sandstones that are intercalated with, and overlain by, volcano-sedimentary breccias with associated lavas, sills and dykes of the Forest Reef Volcanics. Both units are interpreted to have been deposited in an active submarine sedimentary basin, prograding from a distal to proximal volcanic setting. Volcanism evolved as a relatively low-relief, multiple-vent submarine volcanic complex. The vents comprised mafic to intermediate lava flows, cryptodomes and subvolcanic intrusions (dykes and sills). Stacked lava sequences, including hyaloclastites, massive lavas and their reworked

equivalents, are up to 1 km thick, forming significant intra-basinal topography. Erosion and irregular unconformities, including one that is extensive across the district, developed late in the basin history.

Explosive volcanism during the late stages of Forest Reefs Volcanic deposition resulted in the deposition of tuffaceous sediments rich in accretionary lapilli and juvenile clasts. The tuffaceous rocks are interpreted to have formed from sustained subaerial phreatomagmatic eruptions. Good textural preservation of these air-fall deposits, combined with coexisting shallow water faunal assemblages, imply that arc-related volcanism became locally emergent prior to the onset of porphyry-style mineralisation in the latest Ordovician to Early Silurian.

At Cadia East, contrasting permeability in the upper units of the Forest Reef Volcanics strongly controlled mineralisation and alteration styles. An unusual stratabound zone of disseminated Cu-Au mineralisation characterises the upper parts of this giant orebody, and a large stratabound domain of albite-sericite-tourmaline alteration caps the deposit, indicative of strong facies controls on outflow. Thickness changes of key marker units at Cadia East have highlighted that the mineralised dyke swarm was emplaced in an area of localised extension, and that sub-basin-bounding normal faults were reactivated at the time of mineralisation, controlling upflow of mineralising fluids.

The volcano-sedimentary strata of the Cadia district were tilted and deformed both synchronous with and after the intrusion of Cu-Au mineralised porphyry monzonite complexes. Ore deposit preservation occurred because of post-emplacement processes that exhumed, eroded and, then buried the partly eroded ore deposits beneath Silurian rift-sag conglomerates, sandstones and siltstones.

Our reconstruction of the Cadia district reveals that volcanism, porphyry intrusions and related mineralisation were focused along major structural zones in an active marine sub-basin within the Macquarie Arc. Porphyry emplacement occurred during periods of basin inversion and relaxation. Basin architecture, thermal and deformation history and hydrology all influenced the distribution of hydrothermal alteration and mineralisation assemblages. The nature and distribution of host rocks with contrasting permeability and reactivity profoundly affected the distribution of Cu and Au resources in the district. Orogenesis, including basin inversion, not only helped localise these world-class porphyry ore deposits, but also dictated the tectonic and surficial processes that ultimately lead to their preservation.

The importance of good geological control in resource estimation with several examples

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The estimation of mineral resources is an essential step on the continuum from exploration to production. Past reviews of estimation practices have highlighted the crucial importance of geology in the estimation process. For instance, the use of geology as the foundation for the domaining required for effective geostatistical estimation cannot be over emphasised.

The mining industry went through a stage in the 1980s and 1990s where purely mathematical and statistical treatments of assay data were regarded by many as an acceptable estimation process. This was despite a review by King, McMahon and Bujtor of CRA ore reserve estimation processes, published in 19821, emphasising the importance of the geological factor. One of these authors, Dennis McMahon, commonly used the phrase ‘we need to put the “geo” back into geostatistics’, to emphasise the apparent lack of attention to geology as an essential input to estimation prevailing in the industry at the time.

The understanding of the distribution of the mineral species which comprise the mineralisation being estimated often provides the essential input to establishing domains that demonstrate statistical stationarity. Domains based simply on structural divisions, rock types or grade ranges can fail to deliver statistical stationarity, because the variations in the mineralisation are associated with later alteration or weathering.

With the application of effective geological control, mineral resource estimates are commonly robust on a global scale whereas without effective geological control there is a real danger of producing order of

[1] King, HF, McMahon, DW and Bujtor, GJ, 1982, A Guide to the Understanding of Ore Reserve Estimation, The AusIMM, Distributed as a Supplement to Proceedings No 281, March 1982.

magnitude variations between the estimate and reality. Examples discussed include an early estimate for the 1100 copper orebody at Mt Isa, produced by an external party, and the initial mineral resource estimate for an epithermal gold vein project in PNG.

By contrast, incorrect application of geostatistical estimation parameters for an estimate with adequate geological domaining may produce local differences in the mineral resource estimate. These differences may be important for detailed design and scheduling but generally these estimation parameters alone do not produce significant global estimate differences. For example, different software packages with different rotation conventions can result in confusion and hence errors in the transfer of estimation parameters from one package to another. In several instances, correction of the parameters and re-estimation were shown not to alter the global estimate within the accuracy of the relevant significant figures associated with the estimate.

Geological mapping in civil engineering

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Geological mapping is vital to the success of civil engineering projects. In the power point presentation examples are used to illustrate the wide variety of projects, scales and applications of geological mapping in engineering. The wider role of geology in engineering is also discussed and the presentation ends with some comments on the rewards of a career in engineering geology.

In nineteenth century Britain, the role of geological mapping in civil engineering was superbly demonstrated by William Smith. If you are going to build structures on and in the ground it is essential to know the physical properties of the ground and how the ground might respond to what you do it (e.g. load, cut, dewater etc.). The branch of engineering dealing with the ground is now referred to as geotechnical engineering. The best geotechnical engineers today still understand the significance of the complexity and variability of real ground to their engineering decisions and the important role of geologists and geological mapping in successful projects.

Geological mapping in engineering is not an end in itself. The starting point is always to understand the project, what is going to be done to the ground and what engineering and geological questions need to be answered for that particular project. Even if it is exactly the same site we will ask different questions, develop different models and carry out different investigations for different projects (e.g. quarry compared to a canal). In many engineering projects in rock (and for some in soil) it is the defects (e.g. faults, joints) that dominate the engineering behaviour of the rock mass. In these projects, understanding the structural geology (the origin, distribution, continuity and other physical properties of the defects) is the key and will be the main aim of the geological mapping. Test pits may be used to fill gaps in outcrop, and carefully targeted cored boreholes may be used to confirm or revise the model and provide vital information at depth.

Geological mapping for engineering involves the traditional skills of all field geologists. Projects can be anywhere, and the basic tools of the geological compass, spade and sometimes hand auger are widely used. Most engineering geologists I know regard themselves as general practitioners (GPs) with some basic knowledge of most aspects of geology rather than specialists and are able to work effectively from first principles in any geological environment. Such GPs bring in and use specialist help as required for particular projects (e.g. petrologists, pedologists geophysicists etc.). A good proportion of planned engineering projects get built so engineering geologists involved in initial geological mapping often have the opportunity to follow up with test pits and drilling to check their predictions and improve the geological model. Geological mapping during construction when the site is opened provides an invaluable learning experience and finally there is the satisfaction of being involved in a successful and useful project.

Geohazards—their identification and management

Greg Kotze[1]
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Geohazards comprise a range of phenomena, being predominantly landslides, rockfalls, debris flows (or mudslides) and of course earthquakes. Australia is relatively stable tectonically and significant earthquake occurrences in Australia are relatively rare. The same cannot be said however, about landslides and rockfalls.

In 2007, the Geoscience Australia Landslide Database documented 84 significant landslide events historically Australia wide, collectively responsible for atleast 107 deaths and 141 injuries. Landslides and rockfalls have caused environmental degradation and hundreds of millions of dollars worth of damage to residential and civil infrastructure.

This presentation focuses on landslides and rockfalls, as they are the types of geohazards that are most likely to be encountered on a day to day basis around Australia. Landslides and rockfalls occur in green field and natural environments—as a result of natural processes—and they also occur in developed or urbanised areas, due directly or indirectly to human activity.

Over recent decades, the risks to people and property posed by landslide and rockfall hazards around Australia, have become progressively more acknowledged. This has come about due to several highly publicised tragedies, including the rockfall at Gracetown in Western Australia in 1996, which injured 3 people and claimed 9 lives and the Thredbo landslide in 1997, which destroyed 2 ski lodges and killed 18 people—becoming the worst landslide disaster in Australian history. It is fair to say that those 2 tragedies had significant impacts, on both public and governmental perceptions of 'geohazards' in Australia.

The need to firstly identify and secondly to manage geohazards, has become apparent at all levels of government. Various mapping programs and a range of management and planning policies have been developed, predominantly by local governments in steep coastal and mountainous regions and by state government departments with significant infrastructure or public exposure in 'geohazardous' terrain. Momentum continues to gather in this regard and the requirement exists for the engineering geological and geotechnical fraternities to provide quality mapping input and suitably experienced assessments, by which prevailing geohazards can be identified and managed.

The presentation includes examples and case studies of landslide and rockfall hazards in various settings. It also describes and illustrates hazard mapping techniques and various aspects of policy formulation, to facilitate the identification and management of geohazards.

SESSION 03EB (ENVIRONMENT)

Australia's involvement in IODP: what it means for our scientists

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In January 2008, Australia joined the Integrated Ocean Drilling Program (IODP), along with New Zealand in the ANZIC Consortium (www.iodp.org.au). IODP gives us access to an array of drilling vessels that are capable of taking continuous cores of sediments and rocks in almost all our marine environments, and up to 5 kilometres below the seafloor, to address many geoscience questions. The Australian IODP Office is at ANU, with Neville Exon as Program Scientist, and Sarah Howgego as the IODP administrator.

Australian IODP members are fourteen universities and three government agencies, and most funding comes from the Australian Research Council. Australian scientists from all member organisations can work on coring proposals designed to solve global geoscience problems or questions related to deeply buried extremophile microbes, can apply for shipboard or shore-based positions, and may get involved in various national and international research committees.

IODP's key research areas are spelt out in the 'Initial Science Plan' (www.iodp.org/isp) and are:

- Deep biosphere and ocean floor. This deals with 'extremophile' microbes which live below the seafloor and with gas hydrate
- Environmental changes, processes and effects
- Solid earth cycles and geodynamics

There are exciting opportunities for Australian scientists to take part in IODP research expeditions in our region and beyond. We have access to positions on up to six expeditions per year. ANZIC also has several voting and non-voting positions in IODP committees. Four Australians were involved in North Pacific coring expeditions in early and middle 2009. Among these Australians was the first microbiologist to participate from this country. There were two Australians aboard a Neogene sea level expedition in the Canterbury Basin off New Zealand in late 2009, and one Australian aboard a Cenozoic pre-glacial to glacial climate history and paleoceanography expedition to Wilkes Land off Antarctica in early 2010. Also in early 2010, three Australians will be involved in a study of post-glacial sea level rise in the Great Barrier Reef, including our first IODP co-chief scientist, Jody Webster from Sydney University. Other opportunities have come up in 2010, and an outline of the more interesting expeditions scheduled in 2010 and 2011 will be given at AESC.

The ANZIC Science Committee, chaired by Stephen Gallagher at Melbourne University, prepared a white paper for the INVEST science planning meeting in Bremen in late September, and a number of Australians made important contributions at that large IODP meeting. An Australian (Richard Arculus) and a New Zealander (Peter Barrett) are on the key committee developing a Science Plan for the new 10-year phase of IODP, beginning in late 2013. Geoff Garrett (ex-CSIRO) is on a committee reviewing the last three years of IODP science arrangements and making recommendations for the future.

The development of new IODP proposals for the study of global science problems in our region is very important if we are to get full benefits from our membership. There will be a workshop immediately after AESC entitled 'Southwest Pacific Geology with emphasis on IODP drilling'. The Southwest Pacific has many geoscience problems of global significance to resolve, and many potential IODP proposals could be developed. In recent years we have lacked adequate seismic capacity to do most site surveys from an Australian vessel, although the *Southern Surveyor* did provide vital data for the shallow drilling of the Great Barrier Reef expedition. This situation will improve when the new Australian research vessel comes into service in 2013, but its seismic system will be relatively limited, so that we will continue to rely on foreign seismic vessels or equipment, plus industry seismic data where it is available.

Australian scientists can become involved in developing drilling proposals, or apply to participate in drilling legs as shipboard or shore-based investigators (see www.iodp.org). Applications for involvement should be made through www.iodp.org.au. Extensive under-utilised core resources in our region and elsewhere are available through IODP itself (www.iodp.tamu.edu/curation/repositories.html). The vast repositories of existing ODP and DSDP cores can be accessed by any *bone fide* researchers (www-odp.tamu.edu and www.odplegacy.org).

Preliminary results from IODP Expedition 317 (Canterbury Basin, New Zealand)

C Fulthorpe, K Hoyanagi, P Blum and IODP Expedition 317 shipboard scientists, Robert (Bob) Carter[1]
[1]James Cook University

IODP Expedition 317 (November 4, 2009 to January 4, 2010) drilled a transect of four shelf-upper slope sites off eastern South Island, New Zealand (Canterbury Basin), in water depths between 85 m and 344 m. The expedition was aimed at understanding the relative importance of eustasy and tectonic and sedimentary processes in controlling the development of continental margin sedimentary cycles (sequences). Drilling concentrated on late Miocene to Recent stratigraphy, during which period the high rate of sediment supply from the nearby, uplifting Southern Alps resulted in a high-resolution record of depositional cyclicity that was influenced by north-flowing ocean currents.

The objectives of the expedition were to:

- date seismic sequence boundaries, and sample sediment facies, to estimate eustatic amplitudes
- drill the Marshall Paraconformity (early Oligocene, ~32–28 Ma) in the offshore basin
- constrain the erosion history of the Southern Alps
- determine sediment drift depositional histories, and the paleoceanographic record.

Sedimentary sequences were cored in a transect of three sites on the continental shelf (landward to basinward, Sites U1351, U1353, U1354) and one site on the continental slope (U1352). The drilling transect provides a record of depositional cycles across shallow water shelf environments that were directly affected by

local relative sea level change. Seismic sequence boundaries have been identified in cores from each site and can be correlated with lithological boundaries. This record can be used to estimate the timing and amplitude of global sea level change and to document the sedimentary processes that operate during sequence formation.

Sites U1353 and U1354 provide a high resolution record of recent glacial cycles covering the Holocene and late Quaternary in a continental shelf setting. Site U1352, located on the continental slope, represents a complete section from modern slope terrigenous sediment to hard Eocene limestone, with all associated lithologic, biostratigraphic, physical, geochemical, and microbiological transitions. The site also provides a record of ocean circulation and fronts during the last ~35 m.y. The early Oligocene Marshall Paraconformity was the deepest target of Expedition 317, and marks the regional expression of current erosion or non-deposition associated with the initiation of thermohaline circulation and the proto-Antarctic Circumpolar Current.

Nineteen regional middle Miocene to Pleistocene sequence-bounding unconformities were identified from high-frequency sequence stratigraphy on the shelf-slope sediment prism of the offshore Canterbury Basin (U1-19). The unconformities are related to three larger seismic units, whereas sequences comprise predominantly highstand deposits (U5-8), or indicate exposure during sea level lowstands (U9-19). Each unconformity is typically accompanied by a significant hiatus. The three Expedition 317 shelf sites U1351, U1353, U1354 provide significant high-recovery sections through the Holocene and late Quaternary for high-resolution studies of recent glacial cycles in a continental shelf setting. The smaller scale cycles penetrated by Expedition 317 drilling are in part similar to the Milankovitch-scale rhythms documented from nearby ODP Site 1119, and also to the New Jersey shelf, and correspond to 100,000 and 40,000 year rhythms. Cycles drilled during Expedition 317 have differing sedimentary architectures dependent upon whether they were deposited seaward (Site U1352) or landward (Sites U1353 and U1354) related to the inferred position of the lowstand shore line (~125 m). Site U1351 at 122 m water depth is located nearby the lowstand shore line.

The observed middle Miocene to recent sedimentary sequences are generally correlative with previous ODP drilling of sedimentary sequences for sequence stratigraphic and sea level objectives, particularly drilling on the New Jersey Margin (ODP Legs 150, 150X, 174A, and 174AX) and in the Bahamas (ODP Leg 166), but include an expanded Pliocene section. Completion of at least one transect across a geographically and tectonically distinct terrigenoclastic margin was the necessary next step in deciphering continental margin stratigraphy. Expedition 317 also complements ODP Leg 181 drilling, which focused on drift development, by providing the landward part of the Eastern New Zealand oceanic sedimentary system (ENZOSS).

Expedition 317 marked a new direction for IODP by incorporating drilling in shallow water on the continental shelf with unusually deep penetrations, and set a number of scientific ocean drilling records: (1) deepest sediment hole drilled in a single expedition (Hole U1352C; 1927 m) and second deepest hole in Deep Sea Drilling Program (DSDP), Ocean Drilling Program (ODP), and IODP history, (2) deepest hole on the continental shelf (Hole 1351B; 1030 m) and also the second deepest hole drilled in a single expedition (Hole 1353B; 614 m), (3) shallowest water depth for a site drilled by JOIDES Resolution for scientific purposes (Site U1353, 84.7 m water depth) and (4) deepest sample taken by scientific ocean drilling for microbiological studies (1925 m at Site U1352).

Reference

Expedition 317 Scientists, 2010. *Canterbury Basin Sea Level: Global and local controls on continental margin stratigraphy*. IODP Prel. Rept., 317. doi:10.2204/iodp.pr.317.2010. http://publications.iodp.org/preliminary_report/317/317PR.PDF.

Biogeochemical and geomicrobiological evidence for an ultra-deep anaerobic methane oxidation zone in the Nankai Trough sub-seafloor

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The microbially-mediated anaerobic oxidation of methane in seafloor sediments forms a key part of the marine sedimentary carbon cycle, and essentially limits the flux of methane to the deep oceans. This process is mediated by microbial consortia that predominantly utilise seawater sulphate as the terminal oxidant. In the

Nankai Trough, pore water biogeochemical data obtained during IODP Expedition 322 (NanTroSEIZE Subduction Inputs) revealed the existence of a deeply buried sulphate-methane transition zone at roughly 420 meters below seafloor, where no sulphate should theoretically exist. Preliminary calculations, however, support a ~20% seawater composition by volume for sedimentary pore fluids, probably due to marine crustal hydrogeologic circulation from distal recharge zones seaward of the Nankai Trough. Small amounts of methane (~200 uM) are produced either biogenically *in situ* or thermogenically within the accretionary wedge and then delivered by fluids migrating updip along the subducting Philippine Plate. The resulting hydrogeochemical conditions at IODP Drill Site C0012 support a reduced but still significant anaerobic methane-oxidation zone. From sediments within this biogeochemical 'hot zone', total extracted DNA concentrations increased nearly five-fold (to ~1 ng DNA/g wet weight sediment) above those from all other depths. Still, biomass is perishingly small, and occupies what may be a transient ecological niche for microbes that varies with variations in hydrogeological fluid circulation. Despite the extremely low biomass, microbes in this ultra-deep anaerobic methane oxidation zone clearly impact the sub-seafloor sulphur and carbon cycles. Identifying the microorganisms involved in anaerobic methane oxidation and sulphate-reduction, and characterising their species-specific activity, are the subjects of active research.

IODP Expedition 323 in the Bering Sea: environmental change over 5 million years recorded in deep-sea sediment

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IODP Expedition 323 in the Bering Sea drilled seven sites and recovered 5741 m of sediment core with the aim of elucidating high-resolution ocean and climate trends for the last five million years. The Bering Sea has extremely high surface productivity allowing recovery of sediment with abundant microfossils and other paleoceanographic proxies. Sites were located along the slope edge of the Alaskan continental margin in the region of the Arctic gateway and Umnak Plateau, and on Bowers Ridge, a submarine high, formed by an extinct and submerged volcanic arc.

The Arctic gateway sites had high sedimentation rates (up to 58 cm/k.y.) and despite penetration to 745 m, drilling reached only sediment dated at approximately 2.1 Ma. Although much of this sediment is terrigenous and derived from the Alaskan continent, benthic foraminifers and siliceous microfossils are adequately preserved, enabling future studies. The Bowers Ridge sites are separated by deep water from the Alaskan margin and its terrigenous sediment supply and have sedimentation rates up to about 12 cm/k.y., allowing recovery of sediment back to approximately 5 Ma.

The sediments recovered in the Bering Sea are a mixture of biogenic, siliciclastic and volcaniclastic material. The biological component comprises mainly diatom frustules with varying proportions of calcareous nannofossils, foraminifers, silicoflagellates, and radiolarians. The siliciclastic component is mainly mud, minor sand and isolated ice-rafted debris with clasts up to cobble size. Sedimentary features include decimeter- to meter-scale bedding defined by sediment colour and texture, fine millimeter-scale lamination consisting of alternating biogenic and terrigenous material, as well as bioturbation and minor slumping. The distribution of sedimentary components is controlled by changes in the biogenic, terrigenous, and volcanogenic sediment sources reflecting the changing environmental conditions (Milankovitch-scale and sub-Milankovitch-scale cycles) present during sediment deposition and proximity to the Aleutian arc.

Numerous ash beds, laminae and bioturbated mottles were described in the sediment. These are particularly abundant in the cores from the Umnak Plateau site adjacent to the Aleutian arc but occur in all holes drilled. Ash varies in grain size from fine to coarse and in composition from rhyolite to basalt based on colour and preliminary observations. Ash thickness in undisturbed sections reaches up to 35 cm in one core with a mode of 3 cm overall. However the intense bioturbation of much of the core makes estimation of original ash thickness difficult. Preliminary investigation of the relationship between ash and laminated intervals suggested no correlation.

Valuing EES education in Australia: where to from here?

Leah Moore[1]
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Applying our earth science and environmental science knowledge and expertise to the solution of a given science problem, or to clarify an aspect of our scientific work that was previously not well understood, is considered by most of us to be our core business. Most of the rewards (e.g. satisfaction of figuring out a solution to a problem, earning money, gaining promotion, publishing, earning peer recognition) are linked to how well we perform as earth and/or environmental scientists. Over a lifetime of service, this pursuit of science becomes more than a job, it comes to identify who we are. It follows that our values are, in part, framed by our practice of geoscience and our concern for matters relating to Earth's natural systems.

Given this context, it is interesting to observe how our attitudes toward teaching others about earth and environmental science (EES) are framed. For some, teaching students is a vocation about which they are as passionate as they are about their science. For others teaching and learning is something they have done with colleagues in a manner so informal that they have not overtly recognised their professional learning community even though it is at the centre of their working life. In reality most of our working environments, because of the nature of science, have this professional learning community aspect to them, recognised to varying degrees. But for many, sometimes even those in educational institutions, teaching others is secondary to their core business of researching, or finding the vectors to ore, or understanding groundwater systems or a myriad of other scientific endeavours.

Is it surprising then, that when it comes time to take responsibility for teaching children, or University students, or technical staff in scientific organisations, or land holders or other EES education stakeholders, we say that it is the 'education guy's' job? So let's take a look at the 'education guy's' world. If you are in a University environment at present you work your way up the promotion ladder by doing good science, publishing as many papers as you can, attracting grants and winning funds by graduating research students (who are also doing good science). Incidentally, many government agencies have similar drivers. You are encouraged to get sound student feedback on your teaching (in part because it attracts government funding) and increasingly there are grants for innovative and creative teaching. However, in science teaching faculties these are typically pursued by enthusiasts, and are certainly less avidly applied for than science grants. In part this may be because they are less lucrative, but mostly it is because this work is not valued as highly. In other words—the business of a science teaching faculty is to do science. But is it? Ideally we'd like to strike the balance between science research and teaching—but to do this the individuals within the faculty have to start valuing science education and research in science education more. To be fair, it is not that we don't think education is important—it's common sense that it is. But even within science teaching faculties the focus on science teaching is the 'science education guy's' job.

So what is happening in schools? From K-10 aspects of EES are integrated into the science programs. In senior years typically one of: earth and environmental science, geology, environmental science or geography, is taught in each state or territory. The configuration of what is taught varies greatly and there are as many curricula as there are education departments. From 2012 EES is one of four key science areas that will form part of the Senior Science National Curriculum and this creates an amazing opportunity for structured EES education across Australia. At the moment most EES (or similar) courses are established and taught by a single enthusiast in a high school, and about a third of these have qualifications in earth science. It is tough for teachers with no background in our science to teach EES, even with shared resources and the support of the 'education guy' from the local geological survey, geological society or industry supported geoscience education group. If we want to grasp the opportunity a nation-wide model for in-school geoscience education offers then we have to start valuing geoscience education to the extent that becoming an EES teacher is a vocation that tertiary students aspire to. We need to take initiatives like offering geoscience education subjects in teacher education programs. But remember there aren't enough trained EES teachers to teach in schools now—so it follows that you may not even have to remove your shoes to count the number of EES trained teacher-educators in Australia. This is where the science faculty comes in. If we value geoscience education enough, are prepared to accept that we need to learn how to become an educator in the same way that we learned to be a scientist (i.e. by getting qualified and gaining experience—not just by thinking that we can teach because

we know the content), and we communicate well with our education faculties, we can be a part of the solution.

Industry has a role to play as well. Many educationalists bemoan the fluctuating commitment of industry funds, field support and work experience options, aligned with the cycles of productivity that characterises the resources industry. And this does provide challenges that would be ameliorated if the peaks and troughs could be evened out somewhat. But almost more important at present is the unclear and mixed messages industry is sending to young people about what they are after in an employee. Do you really want a generation of spatial analysts and modellers or do you want people who can identify rocks and minerals well, use a compass and read maps and know how to get their hands dirty? Are you really prepared to do most of their training on-the-job so that they are up to date, or do you want them to come with a sound grounding and a breadth of geoscience and environmental science knowledge? Whatever it is that you want you need to start articulating it more clearly and putting your people, expertise and creation of experiential learning opportunities in front of students even more. Sustaining the 'industry-funded geoscience education support guy', providing resources for schools and allowing access to work sites should continue—but take care that outsourcing your responsibility to geoscience education does not go too far. To future-proof your workforce you need to understand what is happening in schools and Tertiary Institutions and be able to influence what happens there.

Changing a culture is a difficult thing but it is becoming increasingly clear that starting to overtly value our geoscience education and the education of others means that we will start to get the teachers and graduates and employees and lecturers and in-field extension officers and informed public that we want in our communities. If geoscience education is the 'education guy's' job—then we need to BE the education guy. This takes time, and humility, and courage—but the benefits are manyfold.

Correlation between school certificate performance and HSC performance at Knox Grammar School

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Universities have suffered from a lack of highly able students enrolling in the Earth Sciences for a number of years. Being able to target highly able students in the final year of their schooling may well have been difficult in the past due to lack of appropriate data and considering that students need to make choices regarding their university applications well before the HSC. Knox Grammar School is a non-selective boy's school and data collected over the last ten years shows a strong correlation between Band 6 performance at School Certificate and the attainment of Band 5/6 at HSC, regardless of which science strand they attempt. As many of these more able students attempt more than one science subject at HSC, it may allow universities to target these students earlier to better encourage them to consider a career in the Earth Sciences.

Engaging digital natives in earth science

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Educational pedagogy and practice have undergone a paradigm shift in the last few years. Today's 21st century education environments combine the traditional classroom with an interconnected, technology driven world challenged to engage the digital natives in our midst.

It is within this opportunistic environment more details on the makeup of the national curriculum have emerged with confirmation Earth and Environmental Science will indeed be included as the fourth science. As a consequence, questions are now being asked around the necessary planning and communication strategies that need to take place to ensure students as technological savvy users (or digital natives) are engaged at the primary and middle school level, translating into choice of this subject in the senior years and possible selection of Earth Science as a career pathway.

This paper examines a methodology used to communicate Earth Science education to the primary, secondary and tertiary levels and explores how others may use these learnings to foster an increased interest and take up in the subject.

Queensland Resources Council (QRC) is the peak representative body of the minerals and energy industry in Queensland. In line with its long term commitment to education it has embraced the technologies around 21st century education in supporting teachers and students in the teaching and learning of the sector with the view to encouraging students to consider a minerals and energy based career.

For fourteen years QRC delivered a face-to-face, for the most part, primary school level education program involving education officers visiting schools located principally in the south east corner of the state. Two years ago this program transitioned to an online format so that now through its e-learning environment www.oresomeresources.com teachers and students worldwide are provided with a suite of high quality educational resources across the key learning areas of Science, Maths and Technology. Housing over 300 items 'Oresome' provides up-to-date, relevant and curriculum aligned resources including interactive maps and 3D animations and movies.

To support this and further encourage the take up of minerals and energy related topics and subjects, QRC offers a teacher and pre-service teacher professional development (TPD) program that presents teachers and pre-service teachers with opportunities to participate in face-to face and online workshops, supplemented by wherever possible, hands on experiences and field trips. In line with 21st century education technologies, this approach utilises web 2.0 technologies such as social networking sites, blogging, online chats and webinars.

The participation of QRC member companies and other stakeholders in these endeavours has been paramount to the program's success. Such engagement provides opportunities for organisations to afford meaningful assistance to the education sector as well as profiling as potential future employers. By working directly with teachers, both an insight into the minerals and energy industry is communicated as is practical information which is then passed onto students.

Despite some technological constraints, the program has been welcomed by the educational community. Users of the program now have an increased understanding of the resources industry and have developed a more informed base from which to make decisions. Regardless of their geographical location, time poor teachers are able to participate in TPD without leaving their school and access high quality educational resources at their finger tips. Pre-service teachers have also embraced the approach and shown considerable enthusiasm in not only the uptake of the resources and services but in the development of the resource content. An unexpected spin off has been in informing public debate particularly on topical issues such as climate change, low emission technologies and the emissions trading scheme. The educational resources developed to demystify these areas have proved relevant to the wider community including media, government and industry. As a result of the program's success QRC has now become recognised as an industry leader by state educational authorities and other Queensland based industry bodies in online learning and education.

In considering the methodology around Earth Science education and an expanded role in education by industry and other supporters of Earth Science, the experience of QRC provides a pointer to a new model of engagement.

SESSION 03DB (DYNAMIC EARTH: RESTLESS EARTH)

A subduction model for the formation of the New England oroclines

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The southern New England belt in eastern Australia (from Brisbane to Newcastle) shows three tight curvatures of the orogenic structural grain, commonly referred as the Texas, Coffs Harbour and Manning oroclines. The exact timing of oroclinal bending is debated but there is sufficient evidence that constrains their formation to the Latest Carboniferous—Early Permian (300–260 Ma) (Klootwijk, 2009). The geodynamic process responsible for their formation, however, is unknown. In most previous models (e.g. Murray et al., 1987; Offler and Foster, 2008), the formation of the Texas/Coffs-Harbour orocline has been attributed to mega-drag folds associated with major displacement along a ~N-S sinistral strike slip fault. While this model explains the apparent kinematics of the Texas/Coffs-Harbour Z fold, it does not agree with major geological observations from Early Permian rocks in the southern New England belt. In particular, a strike-slip model cannot explain the (1)

apparent opposite sense of movement of the Manning orocline (dextral) relative to the Texas/Coffs-Harbour (sinistral); (2) the extent of magmatic processes that occurred simultaneously with oroclinal formation (300–250 Ma) (Shaw and Flood, 1981); and (3) the widespread evidence for extension during the Early Permian (295–270 Ma). The latter event affected most of eastern Australia and involved rifting and development of sedimentary basins, probably in a back-arc setting (Korsch et al., 2009). In the southern New England belt, ongoing generation of S- and I-type granites indicates that subduction continued, however, in an overall extensional setting. In the context of this geodynamic setting, an alternative tectonic model is proposed, in which the development of the oroclines is attributed to the dynamics of a retreated subduction system that is not supported by sufficient plate convergence. This results in slab segmentation and rollback of narrow slab segments, giving rise to curved and narrow subduction systems from the type seen today in the Banda arc or the western Mediterranean region (Rosenbaum and Lister, 2004). The tectonic response to slab rollback involved extension in the back-arc region, hence the deposition of Early Permian basin sediments, enhanced magmatism, and oroclinal bending by rotations of crustal blocks around vertical axes.

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Subduction dynamics, lateral slab edges, intraplate volcanism and mantle plumes

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Most volcanism on Earth is associated with plate boundaries, in particular spreading ridges and subduction zones (arc volcanism), and can thus be explained in a plate tectonic framework. Intra-plate volcanism, however, cannot directly be explained with plate tectonic theory. Intraplate volcanism in various places on Earth is frequently explained with the plume model. In this model a relatively fixed hot thermal (or thermo-chemical) plume rises from the lower mantle (potentially the core-mantle boundary) to the surface and, as the overlying plate moves with respect to the plume source, produces a linear hotspot track along which the age of volcanoes progressively changes. This model has been applied to linear volcanic chains such as the Hawaii-Emperor Ridge, Louisville Ridge and Nazca Ridge in the Pacific, the Ninety-East Ridge in the Indian Ocean and the Walvis Ridge in the Atlantic Ocean. Other intra-plate volcanism that does not occur in linear chains and does not show a preferred age progression in a specific geographical direction is more difficult to explain with a plume model, and might require an alternative explanation.

One example of enigmatic intraplate volcanism is located in Sicily in the Mediterranean, which took place at ~5.5–1.1 Ma on the Iblean plateau and at 0.5 Ma to Present to form Mount Etna. This volcanism is located in close proximity but is laterally offset with respect to the Eolian magmatic arc and the Calabrian subduction zone, where Ionian oceanic lithosphere is subducting north-westward below Calabria. The intraplate volcanism can therefore not be interpreted as arc volcanism. Previous work, primarily based on the geochemistry and petrology of the volcanics, suggests that the volcanism results from a plume, either originating from the lower mantle or from the 670 km discontinuity. The volcanism in Sicily and surrounding seas, however, does not align along a linear chain and shows no lateral age progression. Another model suggests that the volcanism results from lateral mantle flow from underneath Africa through a slab window, but it is not clear how lateral mantle flow can cause volcanism.

Here it is proposed that Mount Etna and the Iblean volcanics are related to decompression melting of upper mantle material that is flowing around the south-western Ionian slab edge to accommodate ESE-directed rollback of the Ionian slab that started at ~8 Ma. New three-dimensional fluid dynamic models of progressive subduction demonstrate that rollback-induced mantle return flow occurs in a quasi-toroidal fashion with a component of downwelling directly below and above the slab, and a component of upwelling next to the subduction zone with maximum upwelling observed next to the sub-slab region and reduced upwelling next to the mantle wedge region. Significant upwelling is observed at 90–430 km depth and extends 55–660 km away from the projected distance of inferred arc magmatism at the slab edge. The models can thereby explain the large spatial separation of up to 400 km between volcanism in Sicily and the magmatic arc during the last ~5.5 Myr, the contemporaneous activity of arc magmatism in the Tyrrhenian Sea and volcanism in Sicily, the petrology and geochemistry of the volcanics in Sicily, and the low S-wave anomaly at ~300 km depth below Sicily as observed in an S-wave mantle tomography model.

Mantle instability, surface uplift and volcanism behind active plate margins of the Pacific

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Surface uplift of continental margins has an important impact on our environment yet it is a process that is poorly understood. It is widely thought that behind convergent plate-boundaries vertical motions are primarily due part of convergence being accommodated by crustal thickening. There are, however, an increasing number of cases being documented where rapid (~ 5 my) uplift has occurred yet shortening is either absent or not obviously linked, in time, with the uplift episode. Examples include the Andes, the Rockies of western USA, western North Island of New Zealand, parts of the Lord Howe Rise and the highlands of New Guinea. Alternate mechanisms for such rock uplift include the removal of thickened, mantle lithosphere by flow-like instabilities. This type of mechanism can result in the sudden (~ 1–5 my) release of gravitational potential energy that has accumulated over periods of 30–40 my.

Late Cenozoic vertical movements, coupled to seismically determined lithospheric structure, in New Zealand provide a test of these contrasting mechanisms. Although New Zealand does not have the scale of surface uplift that say the Andes or Rockies has, rock uplift is as high, or higher, and New Zealand has a marine geological record that provides a clear history of vertical movements for the past 5 my.

Teleseismic P-wave advances for earthquakes recorded on a dense array of seismographs in central South Island, New Zealand, require high seismic velocities in the upper mantle beneath the Southern Alps. These advances are interpreted to represent an excess of cold, thickened, mantle lithosphere forming directly below the crustal root of the alps in the last ~ 10 my. About 1400 m of suppressed elevation, or 'negative dynamic topography', for central South Island is calculated from the modelled excess mass of lithospheric thickening. Supporting evidence for such a thickening comes from a -30 mgal isostatic gravity anomaly associated with the Southern Alps. In contrast, the central and western North Island displays positive dynamic topography and a positive isostatic gravity anomaly of ~ 65 mgal. Here the land surface of the Australian plate stands at a relatively high elevation (up to 1 km asl) given its measured crustal thickness (~ 25 km), and seismic evidence points to the mantle lid of western and central North Island being attenuated or absent. Geological evidence shows a rapid uplift of the western North Island starting at about 5 Ma. These contrasting, yet roughly coeval, vertical movements for two parts of New Zealand are difficult to explain within the context of plate tectonics. They can, nevertheless, be attributed to different stages of a common process—i.e. uniform thickening of the crust and mantle lithosphere (central South Island), then rapid, possibly convective, removal of the mantle lithosphere after ~15–30 my of shortening (western-central North Island).

Further tests of uniform mantle thickening beneath central South Island is currently being carried out with an offshore US-NZ study of shear-wave splitting.

Origin and interpretation of valley networks in Sinus Sabaeus, Mars

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The modern exploration of the planet Mars is driven by the search for water reservoirs on this extremely dry planet. On Earth valley networks primarily form by runoff of rain water from surrounding catchments. In these cases they are more properly defined as channel networks. In dry climates, however, surface runoff is insufficient to explain the development of the channels, and groundwater seepage can become the dominant factor. Martian water reservoirs could exist at depth, and valley networks could represent the typical surface expression of these aquifers.

Small valley systems, with complex, multiply branched patterns, form valley networks that cut extensively through the ancient crust of the Martian southern hemisphere. Due to their morphological similarities with the channel networks forming terrestrial drainage systems, the ancient Martian valley networks have often been interpreted to imply one or multiple periods of wet climates on Mars in the Noachian era. This interpretation is however not unique, as geomorphic and scaling relations do not conclusively support the notion that Martian valley networks were carved by surface water, regardless whether originating by meteoric processes or springing by point sources. Even accounting for deformations of valley network morphologies due to erosion subsequent to their formations, recent studies (e.g., Som et al., 2009) indicate that width–, distance– and slope–area relations do not satisfy the scaling parameters typical of terrestrial drainage patterns, thus suggesting that morphology alone cannot be unequivocally invoked to indicate a fluvial origin for the Martian valley networks. Furthermore alternative explanations for the surface features displayed by some valley networks, such as those in the Tyrrhena and Amenthes regions, have been provided, including volcanic and tectonic processes (e.g., Leverington, 2004; Caprarelli et al., 2007, and refs therein).

We attempt to resolve ambiguities in the interpretation of valley network morphologies by placing the observed features in a comprehensive geological context. We are conducting a detailed geological study of the ancient Sinus Sabaeus region on Mars, in the longitude and latitude ranges 0˚ to 40˚E, and 40˚S to 0˚. Here we present our preliminary results and a map summarising our interpretation and synthesis of major geological events. We collected and processed: (1) Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) Mission Experiment Gridded Data Record (MEGDR)—resolution 128 pixel/deg (463 m/pixel); (2) MGS Mars Orbiter Camera narrow angle (MOC-NA) imagery—resolution 1–5 m/pixel; (3) Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS) daytime infrared BTR (band 9) and night-time infrared data—resolution 100 m/pixel; and, where available, (4) Mars Express (MEX) High Resolution Stereo Camera (HRSC) imagery—resolution 10–25 m/pixel, and altimetry—resolution 100 m/pixel. We used ArcGIS to map and analyse the datasets.

Most networks in the study region are deeply eroded, rendering calculations based on geomorphic parameters pointless. Generally valley alignments along major tectonic directions suggest a primary role for endogenic processes in their formation. This does not exclude the possibility that flowing water may have further carved the valleys, but the features we have studied thus far do not show obvious signs of fluvial deposits that might lend support to such interpretation. At this stage of our investigation we cannot exclude that groundwater seepage may have enhanced complexity and dimensions of the networks. Relative stratigraphies based on impact crater counting were useful in drawing geological maps of selected areas, and indicate that the region was characterised by a complex sequence of events. Further studies are under way to gain a comprehensive picture of the geological evolution of the area. Ultimately it is by piecing together detailed pieces of information that we will be able to reach sound conclusions in regards to the features observed in this region, including the origin of valley networks.

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New surface clutter simulations of Mars Express MARSIS data support extensional tectonic history of Pickering Crater (Mars)

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Pickering is an approximately 150 km diameter crater located about 1500 km SW of Arsia Mons, the oldest of the Tharsis volcanoes. It is located along the SW termination of Daedalia Planum, a vast volcanic expanse on the Tharsis Rise, the plateau on which the three Tharsis volcanoes (oldest to youngest: Arsia, Pavonis and Ascraeus) are located. Tectonism played a fundamental role in the formation of the rise, which is also surrounded by major tectonic units, including the Thaumasia Plateau, Valles Marineris and Coprates Rise. Tectonic processes had a major role in shaping the Martian western hemisphere, but recent lava flows have covered older structures.

Pickering Crater lies within Noachian terrains (Scott and Carr, 1978). The origin of the crater is unknown, but it could have been formed by caldera collapse or by impact. After its formation the region underwent pervasive fracturing in the NE-SW and NW-SE directions. This produced the irregular fretted character of the crater rim. This episode of deformation probably occurred under a wrench (strike-slip) tectonic regime with a principal compressive stress oriented either N-S or E-W, the orthogonal arrangement of the conjugate fractures rendering stress determination ambiguous. After this discernible episode of tectonism, the crater was infilled and flooded by lavas. Only relatively young (late Hesperian—early Amazonian) NE-SW striking grabens can be observed on the surface of the volcanic rocks (Caprarelli and Leitch, 2009). A long period of geological activity remains buried under the surface.

The Mars Express (MEX) Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) is a low-frequency (1.8, 3, 4, 5 MHz) radar capable of ground-penetration. The instrument records echoes returning to MEX from Martian interior depths as big as 5 km at nadir, well within the crust. We used data from MARSIS orbits 4921 and 4932 to search geological structures deep under the surface of Pickering Crater. The orbital parallel tracks run along the eastern side and the central portion of the crater, respectively. After accounting for the effects of high intensity nadir surface reflections and off-nadir clutter, new simulations confirmed the presence of a low-angle N-dipping reflector of approximate horizontal length of 10 km at depths 0.5–1 km below the surface in both orbits, already inferred in earlier examinations of the data based on purely geometrical parameters (e.g., Caprarelli et al., 2008a-b).

Because the orbit tracks do not intersect, no unique structural reconstruction is possible. However, Mars Orbiter Laser Altimeter (MOLA) Precision Experiment Data Records (PEDR) orbit 10664 intersects MARSIS orbit 4921 in the eastern portion of Pickering Crater. Here surface features provide a picture consistent with the presence of the subsurface reflector shown by MARSIS data. Plausible tectonic scenarios can be defined and further constrained by published geological reconstructions (Caprarelli and Leitch, 2009). Crustal extension underpins the models.

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Mid- and low-latitude layered deposits on Mars: geological significance

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Thick layers of rocks cover a total area of approximately 3,000,000 km^2 at sub-equatorial latitudes on Mars. They exhibit fine, nearly horizontal layering, and are present as isolated plateaus of what were once more extensive deposits. Diverse geological processes produce layered deposits, either in sub-aerial or sub-aqueous environments: the Martian layered deposits have been variably interpreted as due to aeolian, volcanic, or lacustrine deposition (e.g., Caprarelli and Pondrelli, 2008). Since 1997, NASA and ESA orbiter missions have

collected spectral data from visible to thermal infrared wavelengths. The data showed that the deposits contain phyllosilicates, sulphates and hematite (e.g., Squyres et al., 2004; Gendrin et al., 2005; Bibring et al., 2006; Chevrier et al., 2007). On Earth these mineral species form by water/rock interaction. Their presence in the Martian sub-equatorial regions indicates that substantial quantities of water must have been present on the surface or underground when the minerals were formed, suggesting that at least some time in the geological past Mars experienced a wet climate. However, one all-encompassing process of formation of alteration minerals and layered deposits at mid- and low-latitudes on Mars remains elusive (Chojnacki and Hynek, 2008), suggesting that the mineralogical record reflects multiple and sequential geological processes. Hence these deposits must be studied in the context provided by comprehensive geological reconstructions.

Here we present preliminary results and geological interpretations from our ongoing study of Martian mid- and low-latitude layered deposits. We selected small sub-equatorial areas straddling the eastern hemisphere crustal dichotomy, in the MC-14 (Amenthes), MC-15 (Elysium), MC-22 (Mare Tyrrhenum) and MC-23 (Aeolis) quadrangles, where earlier and current studies conducted by our group (e.g., Caprarelli et al., 2007; de Pablo and Caprarelli, 2010) provide good geological constraints. We collected and processed: (1) Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) Mission Experiment Gridded Data Record (MEGDR)—resolution 128 pixel/deg (463 m/pixel); (2) MGS Mars Orbiter Camera narrow angle (MOC-NA) imagery—resolution 1–5 m/pixel; (3) Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS) daytime infrared BTR (band 9) and night-time infrared data—resolution 100 m/pixel; (4) Mars Express (MEX) High Resolution Stereo Camera (HRSC) imagery—resolution 10–25 m/pixel, and altimetry—resolution 100 m/pixel. We used ArcGIS to map and analyse the datasets.

Most layers appear in locations close to circular features with morphological characteristics consistent with volcanic constructs. This suggests that the layered rocks may be of volcanic origin, perhaps formed by deposition and lithification of volcanic ashes. The identification of ancient calderas in this region (Caprarelli et al., 2007) supports this interpretation. Some layers are enigmatic: it is not yet clear whether the layered features are due to deposition or to erosion (e.g., Caprarelli and Pondrelli, 2008), and often appear associated to sub-glacial features. In this context they might represent lacustrine environments, but additional and detailed studies of higher resolution datasets, such as Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) imagery (resolution 0.25 m/pixel), and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) imagery (spatial resolution 20 meter/pixel) will be necessary to conclusively interpret these features. In the next steps of our study we will collect, process and interpret higher resolution and spectral data to define relative stratigraphies and rock compositions. This will further constrain our knowledge and understanding of the sequences of geological processes that shaped the sub-equatorial regions of Mars.

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Slope morphology of Twin Peaks, Mars Pathfinder landing site

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Development of slope form over time has long been a concern of geomorphologists, One approach involves field measurements to test ideas about slope evolution starting from the assumption that observed slopes represent different stages of an essentially similar evolution [1]. Space is substituted for time, and a number of slopes, assumed to be of increasing age, are measured and placed in an evolutionary sequence (e.g. [2], [3], [4]).

[3] showed that slope angles are modally distributed, with the modal angles controlled by the materials (regolith) of which the slopes are formed, and by the processes operating on them. Data can be obtained directly from field work or from digital elevation models (DEM) derived from remote sensing investigations [5]. DEMs are particularly useful to study inaccessible planets, such as Mars, where on site observations are restricted to only a few landing sites. Here we present a study of slopes on the Twin Peaks, two small hills located near the Mars Pathfinder landing site at the mouth of the Ares and Tiu flood channels. The streamlined forms and terraces of the Twin Peaks were taken to indicate catastrophic flood conditions that were believed to be prevalent in the area [6]. It was also suggested that the northernmost peak was topped by floodwater, causing its flatter appearance. Other researchers postulated alternative geomorphological origins for the features observed at the Pathfinder landing site. Processes such as ice flow or deposition were proposed as being the principal cause of most of observed features, by analogy with similar features observed on Earth [7]. Here we propose that the slopes on the Twin Peaks may provide an indication of the processes that shaped them after they were formed.

The southern Twin Peak is a conical hill rising 38 m above the local terrain. A portion of the Pathfinder super panorama was used to analyse the hill-slope morphology. The camera horizon was used as a baseline and all slope angles were measured from this. The hill comprises four separate regions including the top of the hill, which is convex in shape. The convex nature of the hilltop is a common if not ubiquitous feature of hills regardless of their origin. It is related to the creep processes that frequently dominate the tops of hill slopes. In this case it was probably caused by heating and cooling during the Martian diurnal cycle, by the action of soil water, or a combination of both.

All slope sections were observed to be similar in length. The slopes nearest the hill top measure 21˚ and 22.5˚ respectively on the north and south sides of the Southern Twin Peak. Mid way down the hill the next sequence of slopes have north and south angles of 9˚ and 15˚ respectively. Shallow end-slopes measure 4˚ and 5˚ north and south respectively. Similarity of slope angles and lengths indicates symmetry, suggesting that the rocks are the same all around the hill.

Our analysis suggests that slope angles are controlled by a combination of the materials of which they are formed and the processes that are operating on them. Their primarily symmetrical outlook indicates no structural control, suggesting that the hill is formed by flat-lying or massive homogeneous rocks. This being the case, slope morphology results from shallow processes related to mass wasting and surface erosion, although it is obvious from the difference in slope angle between the upper and lower slopes that there is a difference either in lithology across the section of the hill, that the erosional effects were different, or that the surficial processes acting on the slopes were different.On Earth slopes frequently evolve by lower facets expanding upwards at the expense of the facet above, a process defined as slope retreat and replacement—lower slope facets replace upper slope facets. Therefore we conclude that the second possibility is more likely. The mid slope region marks a departure from symmetry with a 6˚ difference between the two sides. This may indicate separate processes operating on either side of the hill. Further investigation is currently under way to clarify the nature of the mid-hill slope differences. Additional studies are also being conducted to determine the sequence of lithologies forming the peak.

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Simulation, analysis and modelling in AuScope

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Computational modelling is often referred to as the 'third branch of science' ranking alongside experimentation and development of theoretical explanations in the construction of an understanding of the natural world (e.g. Pool, 1992, Science, v256, pp44).

The solid Earth sciences rely heavily on computation as the principle means of studying the time-evolution of otherwise agonisingly slow processes that can be observed only where they have been serendipitously preserved in the geological record.

The computational codes which are the engines of models and simulations of natural processes have reached a level of complexity that they require specialist teams of (software) engineers and mathematicians to construct, test and maintain; expertise which comes from outside the specialist scientific domain of application. They are properly considered the basic infrastructure needed for certain disciplines to progress.

AuScope SAM provides such an infrastructure to solid earth scientists in Australia and integrates with the data grid also provided through AuScope. We will show a number of examples where AuScope's SAM infrastructure has been used to create new scientific knowledge at the cutting edge of the Earth Sciences.

AuScope earth imaging—progress with geotransects

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A major component of AuScope activities in Earth Imaging has been directed to elements of a geotransect program, with reflection profiles, passive seismic and magnetotelluric components. Much of the reflection work has been done in cooperation: a 200km spur was added to a major survey in Northern Queensland undertaken by GSQ/GA in 2007 and AuScope supported 200 km of the 580 km GOMA (Gawler-Officer-Musgrave-Amadeus) profile from the southern Northern Territory into South Australia in 2008 that was also funded by GA/PIRSA/NTGS. In November 2009, AuScope carried out approximately 200km of reflection lines from Western Victoria into South Australia across the southern Delamerian, with support from GSV. As a result there is now almost continuous reflection coverage across the Delamerian into much of the Lachlan Fold belt. Planning is in train for joint GSWA and AuScope work in mid-2010 across the Capricorn orogen to link from the Pilbara to the Northern Yilgarn.

In addition a program of passive seismic deployments has been made to provide supplementary 3-D information around reflection profiles. A suite of deployments have been made in the Gawler and Curnamona cratons, and instruments are currently in place in a swath that will eventually extend from Mt. Isa to the Queensland coast. Magnetotelluric measurements are being made along the southern Delamerian profile.

By good fortune, the AuScope deployments have been able to be linked with separately funded activities (mostly ARC funding), so that a north-south array of broad-band instruments along the Stuart Highway provides a complement to the GOMA profile. Passive seismic deployments in north-western New South Wales, in part at the same time as the Curnamona array, significantly increase the potential for determining 3-D structure. Similar linkages have also been secured in magnetotelluric work.

The AuScope National Virtual Core Library—establishment and achievements

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The AuScope NVCL was established to facilitate wide ranging earth science research into the mineralogy and composition of the top two kilometres of the Australian continent, using the millions of metres of core stored in State and Territory Geological Survey and company core libraries. Traditionally these libraries are physically visited by a small number of geologists wishing to compare and understand the characteristics of mineral deposits sampled over the last 50 years during past exploration programs and now deposited with the Surveys for public use. In addition, cores drilled through public stratigraphic programs, oil and gas exploration, and basin analysis programs are also stored. Such visits are based primarily on visual, experiential and subjective analysis and often require expensive travel to the distributed core libraries.

The AuScope NVCL component's goal is to radically improve the ease, user experience and knowledge derived from these past drill core holdings, plus future drilling, to contribute to the other AuScope objective, a more robust and objective four-dimensional earth model of the Australian continent.

Using a new generation of Australian-developed hyperspectral logging technology, CSIRO's HyLogging™ Systems, each State and Territory Geological Survey has been equipped to mineralogically log and image as much of their archived core as possible, to interpret the contained mineralogy, and to database the outputs so they can be interrogated and published via the Internet, in a consistent and standard manner.

Phase 1 of the project involved CSIRO designing and constructing seven HyLogger-2 generation instruments. This phase utilised investment from the Federal Government's NCRIS program and the CSIRO. Phase 2 involves each Geological Survey hiring or assigning staff to operate these instruments in each jurisdiction's core libraries, and interpreting the spectral results using TSG-Core software developed by the CSIRO. This part of the project involves substantial ongoing investment by each Geological Survey. Phase 3 comprises the building of a series of distributed relationship databases and their associated infrastructure in each jurisdiction. These databases are built by synchronisation with the TSG-Core processing software. Using web services technology (Phase 4) these databases are then able to be interrogated by users anywhere in the world and the logged data and images visualised, explored and partially downloaded from the Internet, or delivered by disk on request. Phase 4 is being developed in partnership with the AuScope Grid component. Every one of these Phases poses significant new territory and challenges across a number of quite different disciplines.

At this time six Geological Surveys have operational NVCL nodes based in each capital city, namely Brisbane, Sydney, Hobart, Adelaide, Perth and Darwin. The Melbourne node will be established in late 2010. After training phases, involved with establishing procedures and protocols for standardised logging, the geological survey teams are now logging several hundreds of metres per day. Issues that have arisen at this stage include manpower and scheduling derived from moving large amounts of core around day-in, day-out, plus dealing with sometimes very old and severely degraded cores. Notwithstanding these set-up challenges over 100,000 metres of cores from hundreds of drill holes have been logged and new mineralogical findings documented. The difficulties involved in consistently interpreting geology, as well as host rock, metamorphic and alteration mineralogy, by conventional visual means, is gradually be replaced by the more objective HyLogging strategy and is producing long lasting digital records that will be available for generations to come. Many examples will be given in the paper.

In several States and Territories new collaborative, publically-assisted drilling programs are also providing new, up-to-the-minute cores that are now required to be logged, thus keeping the NVCL potentially fresh and relevant.

Once the cores are logged a validation phase is also commonly undertaken to clarify, on selected subsamples, the mineralogy evident in the HyLogged cores. This is being conducted using a variety of supporting analytical techniques such as XRD, SEM, electron microprobe, thin section petrography, etc., and is an important part of confirming and justifying confidence in the NVCL.

The logging priorities in each State/Territory are defined by the AuScope Geotransects program and with the intent to cover the nation's 'classic' ore deposit types and stratigraphic sequences. The NVCL logging infrastructure is also available by arrangement for students, individual researchers and research consortia, (e.g. AMIRA, MERIWA, CRCs, etc.), as well as industry. Discount rates are available to researchers.

The NVCL goes far beyond logging alteration mineralogy. Mineralogical and lithological characterisation can be used in many other pursuits, for example, in oil and gas exploration and formation characterisation, for basin analysis, for geothermal research, for geometallurgical characterisation, for studies on the carbon sequestration characteristics of subsurface formations, indeed anywhere where an improved and objective understanding to the geology and past geological processes, and 'stratigraphic' correlation is required.

The AuScope NVCL offers an unprecedented collaboration between Federal and State agencies, CSIRO and industry, and in time for every earth scientist who wishes to augment their research by using the sensing, data or knowledge infrastructure. Please find out more by visiting http://www.auscope.org.au/content.php/category/id/15.

Mineralogical validation of the AuScope NVCL

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The AuScope National Virtual Core Library (NVCL) is being built from nodes in each Australian State and Territory Geological Survey using voluminous mineral spectroscopy of hundreds of thousands of metres of legacy cores. The mineral spectroscopy is undertaken using hardware and software HyLogging™ technologies and the results, in the form of logs and images, are being databased and intended for Web publication. Three critical steps underpin the collection and utilisation of these data: calibration, validation and explanation. The outcomes of these three steps bear importantly on the confidence and benefits that can be ascribed to the outputs and, ultimately, to the downstream utilisation of the geological knowledge contained in the logs and databases by the wider earth science community.

Calibration ensures that the spectroscopy is conducted according to comparable and traceable standards and is provided as part of routine measurement processes. Validation is the process whereby the spectroscopically-estimated mineralogy is confirmed by a series of independent processes on representative sub-samples. These two steps are critical to having the confidence to go to the third stage. Explanation is the final step that ascribes interpretation and meaning to the observed mineralogical results in terms of geological processes, paragenesis and potential benefit to some branch of the earth sciences, and commonly utilises integration with other geological observations and measurements. This paper concerns itself with the second of these steps based on experiences gained so far from operation of the NVCL.

In the day-to-day research and building of the NVCL validation has multiple purposes. It is not only about confirming that mineral x really does occur at location y, but does so with some probability, and that estimates of the proportions of minerals in an assemblage are more or less correct in some relative or absolute sense. Results of this then not only feed into downstream use but backwards to improvements in the measurement technology and algorithms and software that provide these estimates.

Armed with the broad brush spectroscopic and mineralogic domains spatially evident in HyLogged drill holes we have used various techniques to validate the outputs. These have included so far, replicate measurements, thin section petrography, x-ray diffraction, SEM, electron microprobe and multi-element geochemical measurements. These have been focused mainly on confirming the mineralogy of spatially coherent domains and also on specific mineral samples where often something unexpected has become evident. Examples are given below. Multiple validation techniques are often needed as not all methods are truly reliable for all cases; e.g. separation of some clay species by XRD is often also difficult and infrared spectroscopy may in fact be the better method.

The potential to map stratigraphically-significant enstatite distribution in high-grade, complexly folded gneiss at the Challenger gold mine, South Australia, was an unexpected find using the HyLogger. A recurring and distinctive spectrum, not present in the TSA training library, was confirmed by petrographic investigation to the presence of the orthopyroxene.

Petrology, microprobe and SEM have been used to validate the HyLogging of alteration minerals associated with IOCG-style mineralisation in Emmie Bluff drillhole, SAE6. A distinct spectral response for dickite and illite, noted in the cover sequence of Pandurra Formation sandstone, was confirmed by XRD and SEM. With calibration, the paragenetic sequence of kaolinite/dickite and variously crystalline illite/white mica, reflecting depth of sandstone burial, could be reliably mapped using the NVCL HyLogger.

HyLogging petroleum core is a new direction for GSWA. Recently acquired spectral data for several kilometres of petroleum core from the Canning Basin has provided information about litho-stratigraphic unit boundaries (especially between carbonate group minerals), porosity, and water content.

To study the 3D distribution of alteration of the Minnie Spring molybdenum mineralisation in the Gascoyne Province, WA, 1500 metres of core were HyLogged with support from petrographic and XRD analyses. The pervasive development of a phengite-Fe/Mg chlorite-epidote assemblage overprinted an early stage of muscovite formation. This propylitic and sericitic alteration is spatially associated with quartz-pyrite-molybdenite veins that are tracked by illitic phengite and calcite.

Validation in Queensland and Tasmania has included further confirmation of dickite in sedimentary sequences, and much more common gypsum identification than previously seen. Strategies are also being developed in several States to confirm small mineral proportion estimates and better understand the lower limits of detection in complex multi-component mixtures, particularly those including small carbonate fractions.

SESSION 03RC (RESOURCES: AIG SYMPOSIUM)

Forensic petrology

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Petrology, from Greek petra (rock) and logos (knowledge) studies the origin and formation conditions of rocks using textures, microstructures, mineralogy and mineral chemistry as well as bulk composition and classification. It is the basis for important theories/models of crustal and mantle processes. Most petrology is indeed forensic in the sense of sleuthing a story from clues that rocks provide.

The thought of forensic petrology conjures up images of vicious murder investigations and other serious crimes of human kind. Indeed there are some famous Australian examples. In 1960 forensic petrology helped to convict the kidnapping murderer of schoolboy Graeme Thorne. His parents were asked for a sizable ransom after an Opera House lottery win. Sand on Graeme's clothing was confirmed as pink-coloured lime mortar (by Horace Whitworth, Mining Museum) and matched sand on the floor of the murderer's garage. Sand on another murder victim contained quartz and unusual brackish-water shell fragments matching the sand at Narrabeen, helping the police investigation. Identification of rocks thrown through train windows and of stolen bush rock aided other police investigations.

Other examples are unusual and unexpected. When concrete telephone poles were damaged by exploding fragments X-ray diffraction showed the concrete contained brucite. It formed from hydration of powdery synthetic periclase, generating pressures of 4kbar (> twice the strength of materials in the concrete). Other important projects involved aggregate mixes which lay outside the optimal size fraction envelope required for use in long-life all-weather concrete. Petrological examination discovered deleterious minerals and explained the sizing deficiency.

On a continental scale, our study of mantle garnets from diatremes along 2000km of eastern Australia, and importantly from a diamond project near Bingara NSW (Rimfire Pacific Mining NL), shows many contain spectacular decompression exsolution microstructures; rutile, ilmenite, apatite and pyrrhotite rods exsolved along crystallographic directions in garnet; Cr-spinel in clinopyroxene and rutile in orthopyroxene. These ultra-high-pressure minerals crystallised as homogeneous grains, up to 250km deep in the mantle within Palaeozoic-Mesozoic subduction slabs, then decompressed in buoyant slab fragments exhumed upwards through the mantle when subduction ceased. Mineral chemistry indicates decompression at 600–1000°C; temperatures near the mantle-crust boundary. These clues suggest the 'conventional' double-layer crustal structure (Phanerozoic low grade rocks/crystalline basement) of eastern Australia grew mainly by repeated additions from below of decompressed slab, stabilising a skin of arc volcaniclastics. We proposed 'exhumation accretion' to the lower crust as an important continent-building process analogous to upper crustal subduction accretion.

On a prospect scale, samples from a Mozambique coal development are unusual arkosic and mixed carbonaceous and micaceous silty continental sediments. Petrological clues indicate deposition in a subsiding swampy basin (?fault trough) containing significant plant remains forming carbonaceous claystones and coal. A

nearby high relief granitic terrane was indicated since rapid influx (possibly by local floods) contributed significant unsorted, granitic lithic detritus that mingled with fine grained carbonaceous sediments.

On the scale of individual ore deposits, a scheme of zoned hydrothermal alteration mineralogy, pioneered by Terry Leach and routinely used by petrologists, has led to success in gold and base metal ore location. Also important are textural and fluid inclusion studies of quartz in hydrothermal and tectonic/orogenic deposits.

Metallurgical problems also can be addressed by petrology. Mine geologists at Cobar reported abundant Cu in assays, but only minor chalcopyrite was identified in drill core. A quick study revealed abundant non-magnetic pyrrhotite was actually cubanite.

Evidence from textures, mineralogy and chemistry of nuggets can determine sources of PGM and gold in placer deposits at Fifield, NSW (B.J. Barron and G.S.Teale for Rimfire). Exsolutions in PGM were quenched at different temperatures, possibly in a nearby or underlying, mantle-derived, fractionating intrusive complex. Two compositions are dominant; isoferroplatinum (minor Os-Ru-Rh) and osmiridium (minor Pt-Ru-Rh). This suggests two sources—one platinum rich and another iridium-(osmium) rich. Gold nuggets are from a nearby hydrothermal source (4–15%Ag; chalcopyrite, galena, Zn-bearing pyrite, pyrrhotite inclusions). Leached gold nuggets show micro-pseudobreecia structures, and gold (<0.05%Ag) is re-deposited as specks in adjacent oxidised host. A third nugget type, characteristic from another locality, is isoferroplatinum containing unusual PGE-bearing sulphide inclusions, some with arsenic. Here, distinctive chemistry of gold nuggets (~5% Ag; Co-As-Ni sulphide inclusions) suggests a mantle source for some elements—possibly shared with sulphide-bearing PGE.

Forensic petrology therefore is versatile and broad based, utilising many techniques to study enigmatic rocks and solve problems on different scales. It is a challenge to live long enough to address its many and varied projects.

Groundwater dependent ecosystems

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Groundwater dependent ecosystems (GDEs) are generally considered to be flora and or fauna that rely on groundwater to some degree to survive or maintain some ecological function.

An outcome of the 1994 Council of Australian Government's Water reform framework was that water allocation planning is required to protect ecosystems that have an important function or conservation value, of which GDEs are included.

The prolonged dry conditions across much of southern Australia for over a decade have corresponded with an increase in groundwater use. This presents substantial challenges for GDE policy development in Australia when developing management plans including GDEs for entire river catchments or aquifer systems.

This challenged is exacerbated by the understanding that GDEs generally confined to iconic GDEs, such as the mound springs of the Great Artesian Basin and the Banksia woodlands of Western Australia, when recent research suggest their distribution is significantly greater.

This paper presents an overview of the current understanding of GDEs, including

- What are groundwater dependent ecosystems?
- Where do they occur?
- How do they interact with groundwater?
- How are they identified?
- Can they be integrated into management plans?

Professionalism in the geosciences through the Australian Institute of Geoscientists

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The Australian Institute of Geoscientists (AIG) is a professional society which enables members to demonstrate their professional status in the community. By joining AIG, a geoscientist makes a commitment to maintain high professional standards. AIG members are known to the industry at large as graduates in geoscience who have gained at least five years of professional experience (verified by two sponsoring AIG members) and who have committed to comply with the AIG's Code of Ethics. Members of the AIG are eligible to act as Competent Persons for reporting to the Australian Stock Exchange and to act in a similar capacity in countries which have endorsed the AIG as a Recognised Overseas Professional Organisation in their jurisdiction.

A further step in professionalism is to achieve registration through the AIG's Registered Professional Geoscientist (RPGeo) scheme. Acceptance as an RPGeo confirms that the geoscientist is skilled in one or more specific fields of geoscience, and that the person is committed to maintain standards of expertise through ongoing professional development. The scheme allows employers to identify persons who are able to fulfil certain work requirements.

The registration scheme operates through the grades of membership of the Institute. This method was adopted after multiple phases of consultation with AIG members during 1992 to 1996. Given the option of choosing between not establishing a scheme of registration, establishing registration as a new grade of membership or establishing registration separate to membership, AIG members voted in favour of the membership mechanism. Appropriate changes to the AIG constitution were approved by the members of the AIG at an Extraordinary General Meeting held in Perth in May 1996. The processing of applications for registration was published in April 1997.

AIG members benefit from the availability of registration as a grade of membership because registration completes a logical scale of progression in professional status from Student Member to Graduate Member, then to Active Member and finally to Registered Professional Geoscientist. The initial stages (Student and Graduate) reflect the acquisition of academic training and initial experience. The latter stages (Active and RPGeo) reflect the acquisition of significant professional skills and applied experience. Registration with the AIG identifies exactly which areas of specialisation apply to various members of the geoscience industry.

Self-regulation is important in many industries. Registration within the geoscience profession is available through the AIG's registration scheme, which provides members with stature in the community comparable with other professionals and ensures the highest standards of practice by all Registered Professional Geoscientists. RPGeo acceptance also defines the particular skills of each geoscientist.

No legislation in Australia requires geoscientists to be registered. In Canada and the USA, geoscientists are registered in specific states in order to practise. The voluntary AIG system provides nationwide registration should legislation ever be introduced in Australia. Registration will facilitate professional recognition for AIG members who choose to work overseas.

AIG members may be accredited as Registered Professional Geoscientists in one or more of twelve fields of expertise. Members seeking two or three fields often require additional referee reports.

The AIG system of registration entails verification by four peers who testify to their direct knowledge of the applicant's professional experience in the particular fields of expertise in geoscience in which the applicant wishes to register. Two referees must be AIG members. Other referees must be members of recognised learned or professional societies. All RPGeo applications must go through the same rigorous process. RPGeos must undergo Continuing Professional Development and maintain a written record of these activities which may entail attendance at workshops or conferences, publication of data and concepts, as well as technical reading. These records are subject to regular audit by the Registration Board.

A Certificate of Registration and RPGeo stamp is issued to each member granted RPGeo status. The post-nominal RPGeo may be employed on business cards, letters and curriculum vitae. Geoscientific reports may signed by the author adjacent to placement of the registration stamp.

The AIG encourages its qualified members to acquire RPGeo status. Professionals who participate in formal accreditation demonstrate a commitment to maintaining technical skills, and inform clients and/or employers of their specialist fields of expertise.

Geoscientists—our relevance in the age of technology

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The preparation of this abstract underwent a number of iterations. Where to start on discussing the relevance of geosciences in the age of technology? An age where many people in our society rarely reflect upon the study, exploration and interpretation (and yes, perhaps some educated guesswork) required to understand our natural history, identify and extract the resources upon which we rely and allow us to build the infrastructure that characterises modern society. It's not all about the latest gadgets, is it?

Perhaps the following definition presented in Wikipedia provides a good starting point.

> it (geology) encompasses the study of the composition, structure, physical properties, dynamics, and history of Earth materials, and the processes by which they are formed, moved, and changed. The field is a major academic discipline, and is also important for mineral and hydrocarbon extraction, knowledge about and mitigation of natural hazards, some engineering fields, and understanding past climates and environments.

This definition demonstrates the diversity of our field and the numerous contributions that the study of geosciences has made to society (both ancient and modern), some of which are:

- the history of geology, the key milestones and important figures in geological research and development
- the importance that many mineral discoveries had in the exploration of our continents, establishment of civilisations and society development
- urban renewal in the form of contaminated site assessment, remediation and management
- hydrogeology and (ground)water resource management
- geotechnical studies for building and natural risk management
- our understanding of the natural wonders of the world, the geological processes required for their creation and their importance to culture and tourism
- the importance that resource and mining companies have on the financial markets and the numerous other industries that rely on the skills of geoscientists.

As you can see, it is difficult to identify what is the most important contribution of geoscience to society and many are in fact related. However, it certainly can be stated that all that geoscientists have played a major role in our understanding of the earth and the development of human civilisation and will continue to be important for our future. It is up to us to continue to foster interest in our field and relay this message to future generations of scientists (and non scientists too).

Magnetostratigraphic records from Eocene-Miocene sediments cored in the Equatorial Pacific: initial results from the Pacific Equatorial Age Transect (PEAT) IODP Exp 320/321

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Integrated Ocean Drilling Project (IODP) expeditions 320 and 321 were part of a single drilling program known as the Pacific Equatorial Age Transect (PEAT). PEAT was designed to recover a composite Pleistocene–Eocene sedimentary succession from beneath the Equatorial Pacific high productivity zone in order to construct a continuous paleoclimatic, paleoceanographic, and paleoenvironmental record for this period and to validate and improve the astronomical calibration of key climate events and the Geological Time Scale.

During PEAT, 6141 meters of sediment were recovered from 23 holes at 8 coring sites (initial results at http://iodp.tamu.edu/publications/PR.html). Age models and sedimentation rates were determined from bio-magnetostratigraphic datums. Initial paleomagnetic results from Expedition 320 comprise measurements at 56,222 intervals along c. 2000 split-core sections. Progressive alternating field (AF) and thermal demagnetisation of discrete samples revealed shallow magnetic inclinations, consistent with the paleoequatorial coring locations. Magnetic polarity zonations were recognised by the downhole mapping of 180° alternations in declination on split core data. The resulting magnetostratigraphies were used to develop initial age models at each drill site and yield 803 absolute ages ranging from 51.743 Ma (the base of Chron 23n.2n at Site 1331) to the present (Chron C1n; 0 to 0.783 Ma at Site U1335). Numerous short polarity intervals were also identified which may correspond to short term fluctuations of the geomagnetic field.

We present an overview of the PEAT program and will discuss the initial efforts in constructing magnetostratigraphies and how, together with bio-, chemo-, and cyclo- stratigraphies, the data will be used to refine and extend the astronomical calibration of the geologic timescale.

Sr, Nd and Pb isotope data from the Shirshov Massif of the Shatsky Rise, north-west Pacific

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The Shatsky Rise is a large volcanic plateau in the north-west Pacific that formed between 140–150 Ma in a relatively short time period on the Pacific oceanic crust (e.g. Nakanishi et al., 1999, Mahoney et al., 2005). The plateau formed during a time of frequent magnetic reversals allowing for the tectonic regime in the vicinity of the plateau to be reconstructed. Magnetic lineations in the oceanic crust indicate that the plateau formed along the trace of a triple junction of oceanic spreading ridges (Nakanishi et al., 1999). This observation makes the Shatsky Rise the ideal location to test competing theories for the formation of oceanic plateaus: 1) A deep origin, oceanic plateaus are formed by the impact of a deep derived mantle plume head with the oceanic crust. 2) A shallow origin, oceanic plateaus form at rapidly extending plate boundaries, such as triple junctions, by melting of fissile and fertile upper mantle material relative to typical depleted MORB mantle.

Shirshov Massif is the northernmost of the large seamounts within Shatsky Rise. It is a subcircular edifice, ~100 km in diameter that formed along the trace of the triple junction. The Shirshov Massif represents a waning phase in the evolution of the Shatsky Rise, intermediate between the main phase of plateau formation the Tamu Massif to the south-east and the much lower levels of magmatism represented by the younger Papanin Ridge to the north-east. In the parlance of the plume head hypothesis, Shirshov Massif is in the transition between plume head and tail.

During IODP Expedition 324 Hole U1346A situated on the northern flank of the Shirshov massif was drilled, penetrating relatively thin sediment cover and into the igneous basement. Two volcanic units were recognised,

a 1.6m volcanic debris flow and a 50.1m thick succession of pillow lavas (and/or inflation units) that represent a single volcanic event (Shipboard Scientific Party, 2009).

Here we present Sr, Nd and Pb isotope data from basalt samples recovered from the Shirshov Massif in IODP Hole U1346A. We compare the isotope data to previous analyses from the Shatsky Rise (Mahoney et al., 2005), to other oceanic plateaus and to estimated mantle end member compositions in order to assess the nature of the mantle material that melted to form the end stage plateau volcanism of the Shatsky Rise. These data will be used to assess the nature of the mantle source components of the end stage Shatsky Rise plateau development as recorded in the Shirshov Massif basalts.

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Antarctic ice shelf and ice stream processes based on geomorphic features imaged by sidescan sonar, Prydz Bay, Antarctica

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Antarctic ice shelves and fast flowing ice streams are key drainage features of the Antarctic Ice Sheet and their behaviour determines the sensitivity of the ice sheet to climate change and sea level rise. Some fast flowing ice streams are thinning rapidly and could be the 'soft underbelly' of the East Antarctic Ice sheet. Processes across the grounding zone are important in understanding the retreat behaviour of ice streams but are poorly understood because of the difficulty of accessing the region. The Antarctic Shelf preserves geomorphic features and sedimentary structures left by ice retreat which can provide insights into processes in and close to the grounding zone. Sidescan sonar records from Prydz Bay image a range of features that reflect changes in processes across the Amery Ice Shelf grounding zone during retreat after the Last Glacial Maximum. The major features identified are:

- Mega-scale Glacial Lineations—Linear ridges of sediment formed by moulding of mobile subglacial sediment parallel to ice flow.
- Flutes and Mega flutes—Smaller linear ridges moulded by ice flow.
- Inter-flute dunes—Large bedforms formed by bottom currents flowing the grounding zone in the sub-ice shelf cavity.
- Transverse steps—Ice flow parallel ridges that terminate in steps running oblique to normal to the ice flow direction.
- Sinuous ridges (Eskers)—Gently sinuous ridges that run generally parallel to obliquely across fluted surfaces.
- Polygonal crevasse infills—Irregular polygonal ridges on the crest of grounding zone wedges.

The presence of fluted and mega-scale glacial lineations indicates that the ice moved over an unfrozen, deforming bed in the zone up stream of the grounding zone. For most of the Amery Ice Shelf, the inter-flute dunes reflect strong thermohaline circulation in the ice shelf cavity. Sand and gravel recovered in cores from beneath the Amery Ice Shelf indicate significant current speeds, possibly enhanced by tidal pumping.

The sea floor in the Lambert Deep on the western edge of the Amery Ice Shelf lacks inter-flute dunes and has the transverse steps, esker and polygonal ridges. These features represent subglacial features preserved from

reworking by the large scale sea floor geometry which prevented a strong thermohaline circulation developing. Transverse steps in the bed indicate the presence of subglacial cavities at the bed between patches of grounded ice as the ice approached the grounding zone. The presence of an esker indicates water flowing in a subglacial tunnel. The polygonal ridges are similar to those formed where surging glaciers have stagnated. The heavily crevassed ice rests on the sea floor and sediment is squeezed into the basal crevasses. The stagnant ice then lifts off the sea floor, preserving the polygonal ridges. This at least implies periods of stagnation before the ice flowing into the Lambert Deep retreated from successive grounding line positions.

The sea bed geomorphic features in Prydz Bay revealed by sidescan sonar demonstrate that the grounding zone of the Amery Ice Shelf comprised areas of ice moving on deforming till. Cavities show that it was partially grounded. The polygonal ridges suggest episodes of stagnation and even surging behaviour of part of the system. Once the ice retreated from the Bay, thermohaline currents enhanced by tidal pumping were strong enough to rework the sediment into dunes and sandy lags.

Applying geoscience to map benthic habitats through space and time: George V Shelf, East Antarctica

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Physical and biological characteristics of benthic communities are analysed from underwater video footage collected across the George V Shelf during the 2007/2008 CEAMARC voyage. Benthic habitats are strongly structured by physical processes operating over a range of temporal and spatial scales. Iceberg scouring recurs over timescales of years to centuries along shallower parts of the shelf, creating communities in various stages of maturity and recolonisation. Upwelling of modified circumpolar deep water (MCDW) onto the outer shelf and cross-shelf flow of high salinity shelf water (HSSW) create spatial contrasts in nutrient and sediment supply, which are largely reflected in the distribution of deposit and filter feeding communities. Long term cycles in the advance and retreat of icesheets (over millennial scales) and subsequent focusing of sediments in troughs such as the Mertz Drift create patches of consolidated and soft sediments, which also provide distinct habitats for colonisation by different biota. These physical processes of iceberg scouring, current regimes and depositional environments, in addition to water depth, are important factors in the structure of benthic communities across the George V Shelf. The modern shelf communities mapped in this study largely represent colonisation over the past 8,000–12,000 years, following retreat of the icesheet and glaciers at the end of the last glaciation. Recolonisation on this shelf may have occurred from two sources: deep-sea environments and possible shelf refugia on the Mertz and Adélie Banks. However, any open shelf area would have been subject to intense iceberg scouring. Understanding the timescales over which shelf communities have evolved and the physical factors which shape them will allow better prediction of the distribution of Antarctic shelf communities and their vulnerability to change. This knowledge can aid better management regimes for the Antarctic margin.

Reconstruction of the southern Indian Ocean environment over the last 40ka using radiolarian (protista) proxies

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Census counts of planktonic micro-fossils, most commonly forams but also diatoms, radiolarians, and others, have frequently been used as proxies for the reconstruction of palaeo temperatures and, less often, salinity, both at the sea-surface. This study demonstrates that radiolarians are proxies for a wider range of oceanic physico-chemical properties and from the surface to depths of at least 500 metres below sea level. This finding has been employed to reconstruct palaeoenvironmental in the southern Indian Ocean over the last 40k years.

Transfer functions were generated from census counts of surface sediments from Indian Ocean core tops correlated with the physico-chemical properties of the region obtained from the World Ocean Database, 2005 (Boyer *et al.,* 2006). The transfer functions were employed to reconstruct palaeoenvironmental conditions spanning the last 40k years for four Indian Ocean cores: two, MD88-769 [46°04'S 90°06'E] and MD88-770 [46°01'S 96°27'E], from south of the Subantarctic Front, a third, MD94-102 [43°30'S 79°50'E], from just north of the Southern Subtropical Front, and a fourth, MD94-103 [45°35'S 86°31'E], from between these two fronts.

Reconstructions of temperature, salinity, dissolved oxygen, and nitrate, and phosphate concentrations for a range of water depths have proved possible.

The changes of the oceanic environment over the last 40k years, as suggested by these reconstructions, will be discussed. It will also be suggested that the scope for the reconstruction of the palaeoenvironment using plankton is significantly greater than previously thought.

SESSION 03SC (SOCIETAL: EDUCATION)

Data Metallogenica—the next generation

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Data Metallogenica (www.datametallogenica.com) involves progressively building the global web-based encyclopaedia of ore deposits. It is a not-for-profit community enterprise owned by AMIRA International on behalf of the minerals industry.

The initial seed funding from 1999 to 2004 to do this via AMIRA International projects (P554 and P554A) was provided by over 100 large and small companies plus government groups such as Geoscience Australia, all Australian state and territory geological surveys, the USGS, Geological Survey of Canada and several provincial surveys, plus professional groups such as the Geological Society of Australia, the Society of Economic Geologists, the Australian Institute of Geoscientists, the AusIMM and similar associations in Canada and Southern Africa, the PDAC and AME BC. The initial phase involved purchasing and moving the original physical collection of representative samples from Canada and expanding it by 40% to cover over 3000–4000 deposits through 70,000 samples around the world, digitally photographing at high quality and placing on the web, together with spectral mineralogy of alteration for about 10% of the collection. Self-supporting growth since then has greatly increased the coverage of supporting data such as reports, maps, sections, photographs of field, core and petrography, as well as a full listing of all Australian geological theses from the Australian Geoscience Thesis Database (P874). About 70 full PhD and MSc theses from around the world have also been added to date. Much of the high quality material in DM is original, unique and irreplaceable.

The next phase of building the global encyclopaedia of ore deposits will involve much faster growth of several main activities through increased annual funding through a new AMIRA project (P1040):

Data Additions—an extremely large backlog of high quality supporting digital technical material has already been accumulated from many sources, mainly companies, surveys and research groups for individual deposits and global overviews, the main limiting growth factor being labour to add the material to the web. This growth is very likely to continue, and may be augmented by geochemical analyses of relevant parts of the collection, as well as regional geological overviews.

- Global Geoscience Thesis Database—a progressive building of a digital listing of geological theses from other areas around the world (P1018) to supplement the upgraded Australian version
- Website Upgrade—improved, simplified and expanded navigational arrangement of material on the web, as well as increased and sophisticated searchability
- Expansion Of Physical Collection—continued growth of coverage and photography from missing key deposits around the world
- Increased Interaction With Other Databases—assessment and implementation of linked web facilities with other supporting quality international databases.

The purpose of DM is to be a major global resource for education and training as well as reference for all economic geologists. It is accessible anywhere, anytime and is of particular value in developing countries in Asia, Africa and South America where many new mines will be developed in the future. It is designed for local (field) dial-up access if required. It is also a permanent repository of valuable and fragile past data, rapidly being lost, and has the capacity to expand to include mining, mineral processing, environmental and other

data in the future. DM is already a major resource; its long term potential and value for the minerals industry is almost incalculable.

The educational benefits of an international seismic monitoring network in schools—the 'SISMOS à l'École' project at Telopea Park School, Canberra

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Earthquakes are both disconcerting and fascinating because of their suddenness, the terrible destruction they can generate and because they still remain largely unpredictable. This is why emphasis must be placed on education, especially in the school system where causes and effects of these hazards are studied to help us understand the Earth and its natural processes. Trying to explain earthquakes entails studying the inaccessible, scrutinising the Earth's depths and understanding the planet's internal dynamics. In this respect, seismology is a source of complexity and fascination. Scientific culture is thus at the heart of seismic risk instruction.

All this is included in the 'SISMOS à l'École' (http://sciencesalecole.obspm.fr/), 'Sciences à l'École' (www.edusismo.org) curriculum, an initiative of the French Ministry of Education which implements a program allowing a natural risk culture to be engaged through a scientific and technological approach. The original and innovative aspect of this program is that it gives students the opportunity to install a seismometer in their school. The recorded signals, reflecting regional or global seismic activity, feed into an online database, a genuine seismic resource centre and a springboard for educational and scientific activities. The network—numbering some fifty stations installed in metropolitan France, the overseas departments and territories and French high schools abroad—is the development of an experiment conducted in the Alpes-Maritimes region in France more than ten years ago.

Telopea Park School/Le Lycée Franco-Australien de Canberra recently joined this international network. A seismic station was installed within the school on July 25, 2008. At that time, it was the 44th station of the network, the 3rd in the Southern Hemisphere and the 1st in the Asia-Pacific area. This station has provided very interesting recordings from the Asia-Pacific area that have complemented those from other stations. Data from this station are accessible at http://canb.telopea.act.edu.au. The 'SISMOS à l'École' program encourages students to become 'ambassadors' of natural catastrophe preparedness in their school, in their families and more broadly in their local community. This project has benefited all the students in the school (French and Australian) and, more generally, the other members of the school community. This is part of a broader challenge to encourage students' interest in science and to steer them towards scientific studies and professional careers.

This project has developed strong links with local and international partners in economical, educational, scientific and cultural fields. Currently, several partnerships have already been established. The project has benefited from the generous financial contributions of the Embassy of France in Australia and of the Australian French Association for Science and Technology (AFAS). The European Commission's Delegation to Australia has also supported the project as it represents the extension of the early European seismic network called EduSeis. A scientific partnership has been established with Geoscience Australia through the program called 'Scientists in Schools' and the Research School of Earth Sciences (RSES) of the Australian National University (ANU). Both these organisations are bringing scientific expertise and human resources to the project.

The installation of the seismic station in Telopea Park School/Le Lycée Franco-Australien de Canberra exemplifies how the development of simple devices and the design of concrete experiments associated with an investigative approach make it possible to instil the students with a high-quality scientific culture and to educate future citizens about risks. In this presentation, we discuss the basis behind the SISMOS à l'École project, the installation of the seismic station at Telopea Park School and how this program can be used in Australian schools and included in the curricula of educational programs established to increase the awareness of earth sciences.

Education and public awareness today for the geoscientists and geoscience challenges of tomorrow

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Geoscience Australia's education and public event programs play a pivotal role in promoting awareness of geoscience within the education sector and general community. As custodian of the nation's geographical and geological data and knowledge, Geoscience Australia provides advice and information to a range of stakeholders including Government, industry and the community.

Geoscience Australia's education and public programs promote the agency's role through the provision of accessible, current, relevant geoscience information and awareness-raising events for a range of audiences and occasions. Authentic, purposeful learning opportunities for school-aged students are also offered by Geoscience Australia's on-site Education Centre. Through these programs Geoscience Australia works to promote awareness of geoscience to:

- cultivate an interest in and understanding of geoscience in our students and the broader community
- improve scientific literacy in our students and the broader community
- engage students and the broader community in geoscience
- encourage students to choose further study and careers in science and geoscience
- promote awareness of Geoscience Australia's activities with all stakeholders.

To ensure context and relevance, the range of awareness-raising activities on offer aligns with Geoscience Australia's mission as well as current geoscience topics and relevant syllabus outcomes. This presentation will consider a selection of Geoscience Australia's education activities and events and highlight some of the contextual issues faced, as well as opportunities created in providing accessible information to diverse stakeholder groups.

Within Geoscience Australia, established education and public events programs enjoy agency wide support from planning stages through to delivery. They showcase the cross-disciplinary nature of geoscience, use authentic scenarios and involve Geoscience Australia's data, technology, equipment and geoscientists. Collaboration underpins many of these programs and will be discussed in the context of some new and emerging opportunities.

The agency also contributes to science education and awareness activities in the wider community and will continue to work with professional and industry bodies to develop new geoscience-awareness initiatives.

To ensure wide application and engagement with all state science curricula and syllabuses, new education activities are being created with explicit physics, chemistry, biology and/or mathematics focus. Geoscience Australia's new education activities will also be discussed in relation to the relevant 'big ideas of science' and the Australian National Curriculum.

Geoscience Australia's education and public awareness activities continue to play a vital role in addressing one of the long term challenges facing Australia—the significant and persistent decline of geoscience students and university graduates. Discussion will be encouraged particularly regarding the intended and actual impact of geoscience education and awareness raising activities.

The benefits to student learning of participation in marine research cruises

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Experiential learning, a teaching technique that incorporates such things as field work, work-based training, simulations and group work is a critical component of learning and teaching in the geosciences in Australia. Depending on the experience and its construction in terms of learning outcomes, it may be more valuable to the learner than many formal learning contexts. Experiential learning is learner-centred, active and related to the life and life experiences of the student. The learning activity is context-based as closely related to real-

world activities. As such it is a form of situated cognition. Opportunities are rare however, both in Australia and overseas, for student participation in experiential-based curriculum and more so for international research-based marine investigations particularly at undergraduate level. Examples of this type of activity include the Ocean Drilling Program Undergraduate Student Trainee program, which ended in 2003, and the UOS program which began in 2004. This type of program is an excellent means of providing students with new oceanographic and scientific skills while gaining a range of both technical and interpersonal generic skills. Participation in research cruises places the student in a learning environment that engages their full attention. The student must make their own decisions and experience the results of these decisions. The program inspires not only the student involved, but also others with whom they come in contact at their home institution.

This research examines the results of surveys conducted in 2007 and 2008 after legs of the UNESCO and Geoscience Australia–funded multi-week University of the Sea program. There were 18 students involved in the program in 2007 and 10 completed the survey; in 2008 there were 24 students and 14 completed the survey. Students apply to participate in the program and are selected on ability and the need for a spread across participating countries and universities. Over both cruises there were approximately 40% final year undergraduate and 60% postgraduate students. The respondents were 50/50 male/female in 2007 and 64/36 male/female in 2008.

All students on the 2007 and 2008 cruises were invited to complete a questionnaire. Participation was voluntary and anonymous and students could choose to return uncompleted questionnaires. The questionnaire included both quantitative and qualitative data including questions about participant demographics. There were fifteen rated responses, using a 'strongly agree' to 'strongly disagree' Likert scale, and nine open-ended questions. The rated response questions covered aspects such as the aims and objectives of the cruise, how effective the students found the learning experience, their access to scientific staff as teachers and mentors and whether they considered the experience valuable to their future career.

Almost all students thought the cruise was a very valuable learning experience, valued the hands-on aspect, the practical skills training and the opportunity to interact with scientists, and considered that the cruise was effective for enhancing interpersonal skills. However several thought that more could be done to equip them prior to the cruise and that more structure could be provided in the learning environment including the use of lecture programs and targeted technical skills development. While many of the concerns of the students can be addressed in future programs, for example by having the students present results part way through the trip or by scheduling more debriefing sessions to update progress and discuss skills development, they must also realise that the primary aim of the cruises on which they participate is to gather scientific data and that this is within the broader objectives of the funding agency. The cruise is not planned as an educational tool for the students; they benefit by simply participating in the experience. The scientists and technicians on the cruise are not present as student supervisors but may be viewed as 'teachers' by the students. This distinction needs to be made much clearer to the students in their initial information package to avoid misunderstanding in the future.

SESSION 03DC (DYNAMIC EARTH: RESTLESS EARTH AND EARTH STRUCTURE)

Reconstructing the early Jurassic to present Pacific and proto-Pacific basins: implications for circum-Pacific plate margins

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The margins of the circum-Pacific consist of some of the most geologically active regions in the world with a long but often discontinuous history of subduction, arc volcanism, continental and back-arc extension and other types of anomalous magmatism. The interpretation of these geological processes relies on a detailed plate tectonic history of the adjacent ocean floor in order to link the onshore geological record with offshore oceanic processes. Previous plate tectonic models of the Pacific basin have largely focused on identifying magnetic lineations and deriving relative plate motions between either presently active plates or extinct plates where both flanks of the spreading system have been preserved. Other approach to constrain plate tectonic models has been through the interpretation of onshore geology, in particular examining anomalous volcanism

and geochemistry associated with ridge subduction events, crustal shortening rates and events, large-scale crustal deformation and ore-deposit formation. While these previous regional studies and approaches have been valuable in deciphering plate motions and reconciling them with the geology of the circum-Pacific, plate tectonic models of the entire Pacific basin incorporating a absolute reference frame, spreading histories of all the major plates and importantly, the restoration of now subducted crust has been lacking.

We present a new, self-consistent and quantitative plate tectonic model of the entire Pacific basin from the early Jurassic (200 Ma) to the present. We use an updated set of magnetic anomaly identifications to construct seafloor spreading isochrons for all the major plates in the Pacific domain and compare our results to the World Digital Magnetic Anomaly Map (WDMAM). We have reconstructed the Pacific basin using a global set of finite rotations for the Pacific, Phoenix, Farallon, Izanagi, Kula, Aluk, Antarctic, Juan De Fuca, Bauer and several other microplates as well as plates associated with major and well constrained ridge jumps. In addition, we incorporate spreading in the Ellice Basin and spreading associated with the Osbourn Trough, related to the break-up of the Ontong-Java, Manihiki and Hikurangi Plateaus. Our plate model is based on an absolute reference frame using moving Indian/Atlantic hotspots and a True Polar Wander corrected reference frame for times prior to 100 Ma. For the Pacific plate, we use a fixed Pacific hotspot reference frame for times prior to 83.5 Ma. In addition, we have restored now subducted oceanic crust of all the major plates that once operated in the Pacific basin, using evidence of ridge subduction events from the onshore record and the rules of plate tectonics.

Our synthesis of Pacific plate motions will help to resolve long-standing inconsistencies between the geological and seafloor spreading record and will place greater constraints on the plate boundaries surrounding the Pacific plate back to 200 Ma. This has implications for understanding plate driving forces, the growth of ocean basins and the relationship between geologic plate boundary processes and can be used as surface boundary layer input into geodynamic models. In the context of the Australian plate, our updated plate reconstructions provide tighter constraints on the nature of the subducting crust east of Australia during a period of extensive arc volcanism (early Jurassic-mid Cretaceous) and the transition to a passive margin setting at ~100 Ma.

Timor collision: deformation and tectonic implications

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New biostratigraphic dating places the collision between the Australian Plate and the Banda Arc at 10.9–9.8Ma. Colliision produced a complex intercalation of thrust slices from both the Australian Plate and Banda Arc sides of the plate boundary. Initial thrust emplacement occurred between 9.8–5.5 Ma, producing, amongst other things, a series of south-directed thrust slices of material from the Gondwana and Australian Margin megasequences. These thrusts produced complex antiformal thrust stacks that generally include Triassic limestones from the Gondwana Megasequence as the highest structural unit. Thrust stacks preserve elements of the Gondwana and Australian Margin megasequences, including the remnants of the collided 'Timor plateau', analogous to the offshore Exmouth Plateau of the present day. Emplacement of these thrust slices and subsequent loading of the crust caused remobilisation of underlying Triassic mudstones, which were emplaced in the Viqueque region prior to 5.5 Ma. These remobilised muds form diapirs and melange deposits, containing blocks of Australian-derived materials. After a tectonic quiet zone from 5.5–4.5 Ma, further thrust emplacement occurred.

Intercalation of Australian-derived material with material from the Banda Terrane has been complicated by probable over-folding of Banda Terrane thrust slices, resulting in unpredictable outcrop locations, probable inverted stratigraphy at some locations, and complex structural interactions. Late to Recent high-angle strike-slip faults control much of the present-day topographic expression of the island, including the exposure of the strike-parallel chain of limestones 'fatus' that extend across the island. At least one of these fatus limestones occurs in the restraining bend of an extensive left-lateral strike-slip system.

We present new data for the timing of collision in the Timor, and the implications for a ~ 8 Ma collision in this region of the Banda Arc, and on Timor.

The role of lower crustal flow in the formation of subaqueous Archaean continental flood basalts

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Potentially higher sea levels do not fully explain why subaqueous flood volcanism on top of continental crust was common throughout the Archaean. One possible way of maintaining basaltic piles several kilometres thick below sea level is via gravity-driven lower crustal flow of hot continental crust. In this study, we run numerical experiments to determine the relaxation time of a topographic load emplaced on continental crust as a function of Moho temperature. We use a visco-plastic model in which the viscosity depends on temperature. We apply the results of these models to the Fortescue Group, in the Pilbara Craton. Data regarding the eruption time and stratigraphic thickness of the Maddina Formation basalts, together with sedimentary structures pointing to shallow initial and final depth of emplacement, constrain the relaxation time for this section of the Fortescue Group continental flood basalts to between 0.75 and 2 Myr. According to our modelling results this translates into a Moho temperature range of 610 to 690°C for continental crust 40 km thick (580 to 665°C for continental crust 30 km thick). This is significantly higher than the present-day Moho temperature range of 400 to 500°C for Archaean cratons, suggesting that the studied continental lithosphere has cooled by approximately 200°C over 2.72 Ga. The observation that many Archaean continental flood basalts failed to emerge despite their thickness suggests that gravity-driven lower crustal flow of hot continental crust was an efficient process that maintained continents below sea level throughout the Archaean.

Melting of carbonated eclogite at 9–20 Gpa—implications for carbonate mantle metasomatism

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The exotic and rare rock types—kimberlites and carbonatites—are undoubtedly of mantle origin and are sometimes considered to be genetically related, but the compositions of their parental melts and the conditions of melting are still widely debated. Because of hydrothermal alteration of oceanic basalt, large amounts of carbonates are subducted together with ocean floor basalts reaching upper and lower mantle conditions. Little experimental work has been performed to constrain the high pressure phase and melting relations of carbonate-bearing basalt (eclogite at high pressures) and none of the previous studies exceeded the pressure of 10 GPa (*1–4*).

In this work we present the study on carbonated eclogite at 9–20 GPa. The goal of the study was to experimentally investigate the possible role of carbonated eclogite in genesis of kimberlites and related rocks. We aim to locate the solidus and partial melt compositions of carbonate-bearing eclogite as functions of pressure, temperature and SiO_2 content. Multi-anvil experiments were conducted on the 3000 ton press in Tohoku University, Sendai. The experiments were conducted under the range of pressures and temperatures of: 9, 13, 17 and 20 GPa at 1200, 1300, 1400 and 1600°C. The experimental compositions were two synthetic mixes GA1 (*5*) to which 10% of calcite (10%cc) was added, and Volga+10%cc which is identical to GA1 but with 6.5% less SiO_2. GA1+10%cc models altered oceanic crust, recycled into the convecting mantle via subduction. Volga+10%cc models subducted mafic crust, which may have lost a siliceous component during dehydration and/or silicate melting in the subduction zone. All the experiments were conducted in the Au_{25}-Pd_{75} capsules with 12–48 hours run durations in most cases.

The mineral assemblages in the runs differed depending on the pressure. At 9 and 13 GPa, the major phases were garnet, clinopyroxene, carbonate (mainly calcitic), high-pressure modified form of rutile (only at 9 GPa) and stishovite (only at 13 GPa). Garnet was the most abundant phase in all the experimental runs. At 17 GPa clinopyroxene was no longer stable; the mineral assemblage consisted of marjoritic garnet, carbonate and K-hollandite, which contained most of the K. Stishovite was observed in most of the runs. With the increase of pressure up to 20 GPa, CAS and Ca-perovskite appeared in some on the low-temperature experiments.

Carbonate was present either as calcite or magnesite, while potassium partitioned in the Si-rich phases, garnet or clinopyroxene at 9–13 GPa and K-hollandite at 17–20 GPa. We have not detected any K-rich phase neither at 9 nor at 13 GPa.

In most GA1+10%cc and a few Volga+10%cc runs crystallised diamonds were observed. The possible explanation to that is an increase in iron (III) in garnet. Since Fe^{3+} in garnet may increase with pressure, some Fe^{2+} can reduce carbonates to diamond. However, this requires further investigation.

The low degree melts are highly carbonatitic changing their compositions towards more silica-rich melts with increasing temperature at the same pressure.

The solidus is relatively flat in P-T space but it remains at higher temperatures than the hottest estimated subduction geotherm (*6*), in good agreement with previous, lower pressure studies (*3, 4*). Thus subducting carbonates in eclogite may reach the deeper convecting mantle where they may partially melt to produce carbonate-rich liquids which could have a role in fertilising the surrounding peridotite mantle and producing enriched magmas.

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Experimental evidence of high pressure stability of Na-rich amphibole in subduction zone environments

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Porous flow transport of aqueous fluids and hydrous melts derived from the subducted slab into the overlying mantle wedge is expected to lead to the formation of hydrous phases in the peridotite. However, at relatively high pressures of 30–45 kbar, corresponding to a sub-arc depth of ca. 100–150km, most hydrous phases such as amphiboles, chlorites and serpentines, are no longer stable [1]. Phlogopite would seem to be the only phase capable of hosting water, but this phase would dominate the budget of alkalis and many of the trace elements characteristic of arc volcanism. In order to explain the full trace element pattern of arc lavas, complicated mixing processes would have to be postulated involving high-pressure and low-pressure hydrous peridotite contributions.

We have experimentally investigated the interaction of a hydrous sediment melt with mantle wedge peridotite. To investigate fluid-mantle interactions in a sub-arc P-T range fine grained natural San Carlos olivine was mixed in a ratio of 3:1 with a pre-synthesised, trace element doped, hydrous felsic glass formed in the subducted slab at 800°C, 35 kbar [2]. One end of the capsule was filled with carbon spheres in order to collect quenched fluids and melts at the end of the run. Synthesis piston cylinder experiments were carried out in gold capsules for a week in the range 800°C–1050°C and 25 to 45kbar, which covers the average P-T range for the mantle wedge above subducted slabs.

The main outcome is that alkali-rich amphibole (Mg-katophorite) can be a stable hydrous phase from 25 to 45kbar with a temperature range up to 1000°C. Mg-katophorite is highly sodic (from 6 to 7.5 wt% Na_2O) but relatively poor in potassium and calcium. Amphibole is in equilibrium with olivine, orthopyroxene, phlogopite and aqueous fluid or melt. At high pressure (>40kbar), garnet is also present and in the lower pressure range (<30 kbar), aspidolite (Na-mica) occurs as the main sodium-bearing phase. The high water and Na contents of this ultramafic system depress considerably the peridotite solidus, which can be as low as 900°C at 25kbar. At higher pressure (30–40 kbar), the amphibole stability field overlaps the solidus, producing the paragenesis ol+opx+phl+amph+melt. Therefore, the breakdown of amphibole at this pressure leads to partial melting of the peridotite. Above 40 kbar, clear evidence of a solidus cannot be found. Fluids in the carbon-sphere traps

show a continuous transition from aqueous fluid to hydrous melt with increasing temperature, which suggests that the conditions are above the second critical endpoint and a wet solidus is no longer defined.

At subsolidus conditions, trace elements are strongly fractionated between amphiboles and micas. Amphibole carries most of the REE, divalent LILE and some HFSE (Y, Zr, Hf), whereas micas are poor in REE but host large amounts of LILE (Rb, Cs, Ba). Some HFSE such as Nb and Ta are depleted in both amphiboles and micas and remain preferentially in the fluid phase. At supra-solidus conditions, the silicate melt is the main host of LILE and REE, such that its trace-element pattern is very similar to that of the initial slab-derived input.

This set of experiments provides evidence that alkali amphibole has a stability field to much higher pressures than amphiboles found in lherzolites. It shows that such amphibole can play an important role as a carrier of trace elements in the upper mantle. In addition, such water-rich and Na-rich peridotites show a solidus considerably lower than the surrounding anhydrous mantle. Melting of such peridotites during amphibole breakdown could liberate significant amounts of alkali and LREE trace elements in the subcontinental or sub-arc mantle. In natural environments, sodic amphiboles have been described in mantle xenoliths from the East African rift. These are metasomatised refractory peridotite containing Mg-katophorite and phlogopite, similar to the assemblage in our experiments. The metasomatic agent is inferred to be an alkaline hydrous melt [3] similar to the slab melt we used in our experimental study. Our experimental findings reveal new possibilities for fluid and trace-element transport from the slab to the locus of partial melting in the mantle wedge.

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SESSION 03LC (LIFE AND SOLAR SYSTEM: PLANETS WET AND DRY)

NASA's Lunar Crater Observation and Sensing Satellite: mission overview and first science results

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The LCROSS (Lunar Crater Observation and Sensing Satellite) mission's objectives were to study a permanently shadowed region near a pole of the Moon. Science goals included investigating the presence or absence of water on the Moon as well as furthering our understanding of other species trapped in these regions. The LCROSS mission launched with the Lunar Reconnaissance Orbiter in June 2009 and used the Atlas V Centaur Earth departure upper stage of the launch vehicle as a ~2300 kg kinetic impactor. The Centaur successfully impacted the Moon within the Cabeus Crater near the lunar south pole. The impact occurred on 9 October 2009 and created an ejecta plume whose properties, including water ice and vapour content, were observed by the shepherding spacecraft (S-S/C) plus Earth- and space-based telescopes. Following a similar trajectory of the Centaur, the S-S/C flew through the Centaur impact plume and then the ~700 kg S-S/C also impacted the Moon.

All science instruments aboard the LCROSS shepherding spacecraft successfully collected data during the final descent to the lunar surface. The LCROSS payload consisted of nine science instruments including one visible wavelength context imager provided by Ecliptic Enterprises Corporation, two near-infrared (1–1.4 micron/1–1.7 micron) cameras from Goodrich Sensors Unlimited, one mid-infrared (5–9.4 micron) thermal imager from Thermoteknix Systems, Ltd., one mid-infrared (5–15 micron) camera from FLIR Systems/Indigo Operations, a custom-built highly sensitive total luminance photometer (0.4–1 micron), a UV-visible spectrometer (260–650 nm) provided by Ocean Optics, and two compact low power near-infrared spectrometers (1.2–2.4 micron) built by Polychromix.

This paper will focus on results from analysis of the shepherding spacecraft data during its final descent through the impact plume created by the Centaur impact. In particular, discussion will focus on the LCROSS plume that resulted from the lunar impact as well as the detection of water within the LCROSS plume. Interest

in the possible presence of water ice on the Moon has both scientific and operational foundations. It is thought that water has been delivered to the Moon over its history from multiple impacts of comets, meteorites and other objects. The water molecules migrate in the Moon's exospheric type atmosphere though ballistic trajectories and can be caught in permanently shadowed polar cold traps that are cold enough to hold the water for billions of years. The LCROSS mission is providing key information on the enigmatic permanently shadowed regions of our Moon.

The bulk composition and thermal structure of the CoRoT-7b exoplanet

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CoRoT-7b is the latest discovery of the CoRoT space telescope and the first observed transiting super-Earth. Therefore, CoRoT-7b represents a milestone for the field of planetary science. For the first time, both the planetary radius R_P and mass M_P of a low-mass (< 15 Earth masses) extra-solar planet were precisely determined. In units of Earth equivalents, these are $R_P = 1.68 \pm 0.09\ R_{Earth}$ [1] and $M_P = 4.8 \pm 0.8\ M_{Earth}$ [2], respectively. Hence, the average compressed density of CoRoT-7b is $\rho = 5.6 \pm 1.3$ Mg m^{-3}. This value is comparable to the Earth's (5.515 Mg m^{-3}) and suggests terrestrial-type bulk composition of a super-Earth-sized exoplanet. This class of planets is of particular interest for planetary researchers because of the potential to be inherent habitable.

In this study, we model the internal structure of CoRoT-7b using mass and energy balance constraints. We examine various interior candidate compositions under the assumption of a fully differentiated planet. The following two equations of state (EoS) have been implemented into our model and compared: (a) the generalised Rydberg EoS [6] as an empirical fit to experimentally obtained data, and (b) the reciprocal *K*-primed EoS [7] which is an equation constructed to fit the preliminary reference Earth model (PREM) [8] especially well.

To self-consistently calculate the radial distribution of temperature within the planet we adopt a mixing length formalism [3]. This concept was derived from consideration that the Stokes' viscous drag is balanced by the buoyancy force operating on a parcel and has been recently applied in planetary sciences, e.g. [4, 5]. By using this approach, we are able to study temperature effects on the interior structure and to investigate the possible existence of a magma ocean on top of the planet's mantle, dependent on the planet's ability to homogenise the surface temperature.

Our model calculations imply that the deep interior of CoRoT-7b is predominantly composed of dry silicate rock, similar to the Earth's Moon. A central iron core, if present, would be relatively small and less massive as compared to the Earth's (core mass fraction 32.6 wt.-%). This result suggests that CoRoT-7b may have originated in the iron-depleted region beyond the snowline and lost its volatile mass fraction when subsequently moving towards its primary. In addition, the calculated temperature profile has only a marginal effect on the structure of the planet as a whole. Nevertheless, our results indicate that temperature variations would affect the viscosity and, therefore, strongly influence mantle convection pattern and pressure-induced phase transitions. Our results also show that a partly molten near-surface magma ocean could be maintained, provided surface temperatures were sufficiently high and the rock component were mainly composed of Earth-like mineral phase assemblages.

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Bulk chemistry and habitability of the rocky planets that are probably in orbit around Alpha Centauri A and B

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The rocky planets of our Solar System are devolatilised pieces of the Sun. For example, when we compare the bulk elemental abundances of the Earth with those of the Sun, we find that the relative abundances of the refractory elements (Mg, Si, Fe, Ca, Al, Ni, Cr, Ti, Co, V, Sc) are identical (within observational and model uncertainties) to those of the Sun [1]. We also find that the most volatile elements (H, He, Ne, Ar, Kr) are depleted in the Earth by many orders of magnitude compared with the Sun. Moderately volatile and moderately refractory elements show intermediate levels of depletion depending on how volatile or refractory the element is. The other rocky planets of our Solar System also follow this pattern. Thus, if rocky planets are in orbit around other stars, the first order estimate we can make of their chemical compositions is that they will be devolatilised pieces of their host stars. Thus, to first order, their bulk elemental composition will be different from the Earth's, to the extent that their host star's elemental composition is different from the Sun's. In other words, volatile element depletion and refractory element retention, within the habitable zones of other stars is likely to be an almost universal result of planet formation.

We have compiled the most comprehensive elemental abundance data for Alpha Centauri A and B and applied this logic to make estimates of the chemical composition of any rocky planets in orbit around Alpha Centauri A or B. These estimates allow us to make crude predictions about mantle convection, magnetic fields and water content of these potential planets. We will present our predictions and their implications for the habitability of these planets. We will also introduce the concept of a chemical habitable zone. It has not escaped our attention that these may be the first planets beyond our Solar System that humanity may be able to explore and colonise.

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Water vapour abundance in the lower Venusian atmosphere

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Understanding the Venusian atmosphere is key to understanding the evolution of Venus and other terrestrial planets. The Venus atmosphere is complex. Not much is understood about the development and maintenance of the runaway greenhouse effect that generates surface temperatures 500K above the planet's effective temperature, the temperature Venus would have in radiative balance without an atmosphere. The mechanisms that produce atmospheric rotational speeds 60 times faster than the surface at the cloud tops are similarly not well understood. Water vapour in the lower atmosphere plays an important role in heat transfer and is pertinent to both the above examples. Detailed studies of water vapour abundance and distribution throughout the lower atmosphere of Venus are therefore needed in order to develop accurate chemical, radiative and dynamical models.

The Venus surface and lower environment are obscured at visual wavelengths by a planet wide cloud cover and with surface pressures almost 100 times that of the Earths, the lower atmosphere is difficult to study. In 1984, it was discovered that the clouds and upper atmosphere of Venus were relatively transparent at near infrared wavelengths (Allen and Crawford, 1984) and that radiation originating from the surface and lower levels of the atmosphere pass relatively unimpeded. This discovery provided a method by which the surface and lower atmosphere of Venus could be studied remotely.

Ground-based spatially resolved near infrared spectroscopic observations of the Venusian night-side have been obtained from Siding Spring Observatory at each inferior conjunction from 2002 to 2009. Observations have been made using the IRIS2 instrument on the Anglo-Australian Telescope and CASPIR on the 2.3m ANU telescope. Recent improvements in ground-based near-infrared instruments allow a substantial improvement in the spectral and spatial resolutions that can be achieved.

The atmospheric window at 1.18 µm contains absorption by water vapour. Previous earth and space based observations obtained at lower spectral resolutions have modelled and compared the shape of the 1.18 µm atmospheric window to obtain estimates of water vapour abundance (Meadows and Crisp, 1996; Bézard et al., 2009) and there have been recent improvements in high temperature line lists improving the accuracy for radiative transfer models (Bailey 2009). In this study absorption bands located at 1.174 µm, 1.178 µm and 1.182 µm, are modelled using the radiative transfer program VSTAR to analyse water abundances in the Venusian lower atmosphere. The results will be presented and compared to previous ground-based detections and recent studies from the Venus Express VIRTIS instrument.

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SESSION 03TC (TOPICAL: AUSCOPE SYMPOSIUM)

Minerals Down Under National Research Flagship: linking AuScope to the broader minerals industry value chain

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The CSIRO Minerals Down Under National Research Flagship was launched in 2007 to tackle medium- to long-term challenges facing the Australian mineral industry across the value chain from exploration and mining through mineral processing within the framework of an economically, environmentally and socially sustainable minerals industry. This broad research portfolio provides an ideal environment to link the AuScope research platforms to applications across the industry and, perhaps more importantly, to unlock the value of data integration between traditionally discrete parts of the minerals value chain.

Despite the potential benefits of data integration, it remains an elusive goal within research and industry. Many studies use only a small subset of available data types in an integrated manner, often maintaining the traditional 'silos' of exploration, mining, processing and mine closure. Integrating data across the entire minerals value chain is an expensive proposition involving multiple disciplines and, significantly, multiple data sources both internal and external to any single organisation. Differing vocabularies and data formats, along with access regimes to appropriate analysis software and equipment all hamper the sharing and exchange of information. In spite of the many intuitive arguments for data integration, the large investments required also demand a clear understanding of the practical benefits to be unlocked. As a result, the cost of data integration is itself a barrier to the research required to justify the investment in data integration.

AuScope has addressed the challenge of data exchange across organisations nationally and established an AuScope community earth model. The model contains a wide variety of live and updated data types. The data standards and infrastructure platforms that underpin AuScope provide important new datasets and multi-agency links independent of software and hardware differences. AuScope has thus created an infrastructure, a platform of technologies and the *opportunity* for new ways of working with and integrating disparate data at much lower cost. An early example of this approach is the value generated by combining geological and metallurgical data sets as part of the rapidly growing field of geometallurgy. This not only provides a far better

understanding of the impact of geological variability on process outcomes but also leads to new thinking on the types and characteristics of data sets collected at various stages of the exploration and mining process.

The Minerals Down Under Flagship is linking its research activities to the AuScope infrastructure and exploiting the technology internally to create a platform for integrated research across the minerals value chain and improved interaction with industry. Referred to as the 'Minerals Down Under Earth Model', the system will be fully interoperable with the AuScope Earth Model with secured access to allow confidential collaboration with industry when required. The Flagship is altering its work practices based on the AuScope approach and developing new ways to deliver research outcomes and interact with its industry partners. Specific examples include:

- Discovering all open access reports published by Minerals Down Under that lie within a given tenement or geologic unit boundary. This will unlock a wealth of historical data that has traditionally been difficult to access on a geographic query basis and greatly improve the accessible knowledge base for many exploration tenements.

- Web and open standards based access to Flagship and partner derived open file information through the Minerals Down Under Earth Model. This allows real time collaboration between disciplines and research/industry partners and immediate access to the latest research outcomes. For example, integration of information from State water records linked to laterite geochemistry provide the opportunity to understand the complex interplay between groundwater's and the regolith profile. Import feedback loops between disciplines and a broader understanding of the potential value of data sets will eventually lead to a fundamentally different approach to data collection.

- More complex workflows involving simulation and analysis being available as on-demand secure computational services directly to industry working against industry supplied data are also under consideration.

The CSIRO Minerals Down Under Flagship is building on the AuScope infrastructure to transform the way that data and data products are identified, shared, integrated, and reused, to unlock the benefits of true integration of research efforts across the minerals value chain.

Implementing spatial information services at GeoScience Victoria

Paul McDonald[1]
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GeoScience Victoria (GSV) is the Victorian government custodian of geoscience data and knowledge. Since 2004 it has been working toward delivering data held in its information systems using web-based data delivery mechanisms (web services) that conform to international standards for both content and format.

The primary driver for this is twofold: to ensure that the vast holdings of detailed scientific data and interpretations GSV and its stakeholders have captured are honoured during delivery; and to ensure that GSV's data delivery systems can be seamlessly integrated into computational systems distributed across Australia and the world, regardless of how each individual organisation stores and maintains its data.

As a result, users of our data should spend much less time re-formatting and manipulating data once it is received. They will be able to use the same process when acquiring data from other organisations that use the same standards. Much more time can be spent on modelling and analysis of data that hosted in Victoria and elsewhere, with all data sources integrated seamlessly. Data from other domains, using the same base standards, can also be combined and interpreted. Potential uses for the data range from the obvious, such as regional or localised 3D modelling, exploration project generation and environmental geoscience, to newer, multidisciplinary areas, such as the impact of geology-related activities on agriculture and fisheries.

To achieve this goal, GSV has been collaborating with agencies from North America, Europe, Asia and Australia to develop the GeoScience Mark-up Language (GeoSciML). GeoSciML defines how geological interpretations and observations should be structured when delivered via Open Geospatial Consortium (OGC) compliant web services. This work is integrated with existing standards for borehole and field observation data, and has also been extended to develop an Australian model for earth resources. At the time of writing GSV has deployed

web services delivering geological interpretations, earth resource information and borehole locations. It is now working towards delivering enhanced borehole data, field observations and geochemistry.

Despite these well defined standards, the technology required to set up the web infrastructure was either immature or unavailable until relatively recently. AuScope's development of the spatial information services stack has provided us with the technology necessary to deploy our web services. In addition, AuScope provided expertise to all other Australian geological surveys to set up new Earth Resource web services. This expanded the community of data providers beyond those who are involved standards development, to a significant group of operational data providers.

The collaboration with AuScope has enabled a move from standards with exciting potential to fully operational data delivery systems based on web services. These services deliver data describing a rich variety of geological phenomena and are now ready for use by both the geoscience community, industry and the wider research community. How the data are used is now limited only by the individual user's needs or capabilities, the format and content are no longer a limiting factor.

Developments in the analyses of geodetic GPS data

Christopher Watson[1]
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Local, regional and worldwide global positioning system (GPS) networks have long been used to monitor geophysical processes which vary spatially throughout both the temporal and frequency domains. It is now possible to estimate position at the 1–2 mm level with data obtained from geodetic quality GPS receivers, comparable to those being installed across the Australian continent as part of the AuScope geospatial component.

The improved precision obtainable from GPS offers new insights into the surface expression of a range of geophysical signals. These improvements have resulted from not only improvements in the tracking network, but incremental improvements in such things as the modelling of the propagation of the GPS signals through the atmosphere and deformation of the surface of the Earth from atmospheric and ocean mass loading effects. Assessing the influence of these incremental advances across a diverse parameter set requires a systematic approach and incurs significant computational burden. Geodetic GPS coordinate time series that are generated from any given analyses often exhibit complex nonlinear behaviour which reflect a combination of real world signal and systematic artefacts caused by such things as aliasing of high frequency periodic motion and errors within the processing models or solution strategies.

In this presentation, we describe the AuScope GPS analysis workflow that provides for the integrated analysis and visualisation of GPS data and subsequent solutions. The workflow aids in the efficient selection and processing of GPS data and includes a novel visualisation of the analysis outputs. This visualisation assists in the comparison of subtlety different solution sets, with the result being a tool that aids in the scientific development of the technique, thereby contributing to the improved understanding of global geophysical processes.

By way of application, we present results from the novel application of GPS to hydrology. We present results comparing time series of hydrologically induced deformation of the Earth's crust, as determined using GPS, which those estimates from space based gravity measurements from the Gravity Recovery and Climate Experiment (GRACE). This application serves to highlight the benefits of dense networks of GPS sites whilst outlining some of the current areas of development within the discipline.

Virtual Rock Labroatory: enablng computational minerals science research

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The Discrete Element Method (DEM) is a powerful and oft utilised numerical tool for minerals science research, particularly for fundamental studies of rock breakage and laboratory-scale simulations of comminution processes. Its power stems from the discretisation of rock into a large number of constituent particles interacting via simplified laws for elasticity, friction, breakage and other phenomena. DEMs capture

naturally the self-organisation associated with damage evolution and fragmentation, without the burden of dynamic re-meshing required by continuum-based breakage models. DEM permits investigation of the internal dynamics leading to damage and final failure of rocks—features often beyond direct observation. However DEM research is generally stifled by the computational demand imposed by the method.

The ESyS-Particle DEM simulation software (https://launchpad.net/esys-particle/) was developed by the Australian Computational Earth Systems Simulator (ACcESS) MNRF with ongoing software development funding from AuScope Ltd. specifically to address the computational limitations of existing DEM software. ESyS-Particle provides a parallel DEM simulation engine optimised for high-end supercomputers such as the Australian Solid Earth Simulator (UQ) and the iVEC supercomputer (CSIRO, WA). ESyS-Particle is the most advanced freely available parallel DEM simulation software as evinced by a rapidly expanding global user-base.

One of the key features driving its popularity is the scripting interface that permits rapid construction of new models without changes to the core engine of ESyS-Particle. Whilst the scripting interface is undoubtedly the favoured mechanism for using ESyS-Particle by power-users with programming skills, the lack of a graphical user interface detracts a broad community of end-users familiar with commercial simulation software. The Virtual Rock Laboratory (VRL) has been constructed with this user-base in mind. VRL is a web portal that enables users to execute ESyS-Particle simulations on the AuScope computational grid. Requiring only a JavaScript-enabled web browser, the portal can be accessed from anywhere in the world. It contains intuitive interfaces for constructing simulation scripts, submitting them to a supercomputer, monitoring the progress and downloading the results—all from within the portal. VRL's dialogue-based Script Builder makes it possible to create new simulations without any prior programming experience.

In keeping with the mandate of AuScope to provide state-of-the-art research infrastructure for use by the Australian geoscience research community, the VRL has been tailored for use by postgraduates and researchers without in-depth knowledge of numerical modelling principles. The Workflows implemented in VRL provide the key components for applied numerical modelling aimed at understanding the physics of rock breakage and fragmentation. We have utilised the analogy with a physical rock laboratory to guide development. Users select the type of rock breakage experiment they wish to perform (e.g. a uni-axial compression experiment), provide input parameters such as the material properties and physical dimensions of the rock sample to test, then request execution of the simulation on the AuScope Grid. Once a simulation is completed, the user is informed and the VRL provides tools for visualisation and analysis of the simulation results. We will demonstrate the features and workflows implemented in the Virtual Rock Laboratory with emphasis upon its application for minerals science research.

Scientific results from the AuScope Geospatial infrastructure

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AuScope is one of the capability areas funded under the National Collaborative Research Infrastructure Strategy (NCRIS). The philosophy behind NCRIS is to provide the research infrastructure—and people to operate it—to enable Australian and international scientists to undertake world class research that could not be acomplished without the provision of the infrastructure.

The AuScope Geospatial component comprises three new Very Long Baseline Interferometry systems, new gravimeters, a network of Global Navigation Satellite System (GNSS) sites, upgrades to satellite laser ranging systems and high performance computing hardware. The purpose of this talk is to present some of the research outcomes that have been achieved to date through the use of AuScope infrastructure. Results will be shown that exploit the availability of GNSS observations at new sites across the continent (continental drift, crustal strain, hydrological loading), gravity observations made with new instruments as well as from studies that have utilised the AuScope Terrawulf II computer processing facility. Owing to the fact that the rollout of AuScope Geospatial infrastructure is ongoing, some of the scientific outcomes expected in the future will also be discussed.

The Australian geothermal industry—an overview

Catherine Stafford[1]
[1]Granite Power Limited

The last 5 years has seen the Australian Geothermal Industry rapidly expand from literally a handful of participants to a community of 54 companies exploring for geothermal energy nationwide. The growth in the uptake of geothermal licences in Australia continues: as of January this year there were a total of 409 licences and licence applications in Australia covering an area of over 432,000 km^2 with the forecast expenditure for exploration and development of these projects for the period 2002–2014 being over AU$2.1 billion ([1]).

The Australian Geothermal Industry predominantly focuses on amagmatic-type resources, and in that respect differs from mature 'conventional' geothermal exploration and development projects such as found in the Philippines and New Zealand. In terms of energy for power generation, rather than direct-use, there are two types of geothermal systems being sought in Australia:

- Hot Sedimentary Aquifers (HSA): These are generally shallower targets (~3–3.5 km depth); have lower temperatures, but essentially do not require enhancing/engineering of the rock to create a suitable reservoir and sufficient flow rates.

- Enhanced Geothermal Systems (EGS): These are deeper hotter systems (~3.5–5.5 km depth); often in crystalline basement rock; essentially requiring enhancing or engineering (by mechanical or chemical means) to create a reservoir and flow.

Within Australia, the most advanced HSA project is that of Panax Geothermal in the Penola Trough of the Otway Basin (SA). This proof-of-concept project is currently being drilled to reservoir depth ([2]). The most advanced EGS project is that of Geodynamics in the Cooper Basin (SA). This project has already accomplished proof-of-concept following six years work resulting in fluid circulation between the injection and production wells following reservoir stimulation. The next step is the commissioning of the already constructed 1 MW pilot plant ([3]).

This growing industry is supported by the newly incorporated Australian Geothermal Energy Group (AGEG, established 2006) and the national industry association the Australian Geothermal Energy Association (AGEA). Together these bodies, via a joint Geothermal Reporting Code Committee, have developed the 'Geothermal Reporting Code, the Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves' (2008). This is the first geothermal reporting code to be developed in the world.

As with any establishing industry there are necessarily new developments in techniques and technology and adaptations of existing techniques and technology borrowed from other resource industries. In the Australian Geothermal Industry this has been aided by the establishment of twelve Technical Interest Groups (TIGs) within AGEG. These expert lead research and development groups focus on diverse topics including: Exploration and Well Technologies; Direct-Use; Outreach; Reservoir Development and Engineering; Well Construction; and Power Plants.

There have also to date been several government funded initiatives together totalling over $264 million, to end 2009 ([1]), leading to the establishment of specialist geothermal research centres e.g. Queensland Geothermal Energy Centre of Excellence; WA Geothermal Centre of Excellence; SA Centre for Geothermal Energy Research; varied projects such as seven 'proof-of-concept' geothermal drilling projects (Panax Geothermal, Geodynamics, Petratherm, Green Rock Energy, Greenearth Energy, Hot Rock, Torrens Energy) funded by the Australian Federal Government Geothermal Drilling Program; and seven projects funded by the Australian Federal Government Renewable Energy Development Initiative (REDI) including the development of 'Granex' power exchange technology jointly through Granite Power and the University of Newcastle and the development of a 3D thermal modelling program for Torrens Energy.

The growth of the geothermal industry is currently a global phenomenon. Several of the new technologies, methods and protocols required to drive this global industry forward, have already come and will continue to come out of Australia.

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Industrial minerals: big but not sexy!!

Ted Ambler[1]
[1]Somerset Mining Pty Ltd

'Industrial minerals' have been estimated by the UN to represent almost 25% of the world trade in minerals. But what are industrial minerals? Whilst often referred to as 'non-metallic' minerals, industrial minerals are rocks or minerals used principally for their physical properties, but commonly for their chemical properties and sometimes for a combination of both. Generally, there is limited mineral processing involved in preparation of the mineral for the market. Construction materials such as sand and crushed stone should be included in the general definition of industrial minerals.

A key difference between mining for metallic minerals and mining for industrial minerals is that the former typically recovers for sale a very small proportion of what is mined, whereas in the latter, typically, what is mined is sold. An Industrial Mineral typically has a relatively low unit value which means that processing options are limited and logistics become critical. Industrial minerals do not travel far as a general rule. Operations are commonly small, with relatively low capital investment requirements. There are many exceptions to these 'rules' with mineral sands, fertilisers, sulphur etc being notable exceptions.

However, the markets for industrial minerals are huge. In Australia, approximately 150 million tonnes of construction materials are produced annually. World trade in Ground Calcium Carbonate has been estimated to be around 60 million tonnes and for limestone, used to produce cement, around 4.6 billion tonnes.

The industrial minerals practitioner must have a clear understanding of the target market and the means of getting the mineral from the deposit to that market—with some exceptions there are no world markets for industrial minerals as there are for metals or metal concentrates. As with any mineral commodity, resource assessment is critical. Tonnage and grade are just as important when it comes to industrial minerals as for any other mineral deposit. Assessment of the deposit must be done in light of the target market requirements, and the geologist needs to understand how the mineral being assessed will work in the customer's particular process—minerals from different deposits vary in their behaviour—'limestones aint just limestones'. The testing methodologies and client needs require a different approach to resource assessment.

Iluka Resources heavy mineral exploration in the Eastern Eucla Basin, South Australia

Ian Warland[1]
[1]Iluka Resources Ltd

In September 2004, Iluka discovered the Jacinth deposit wholly contained within Iluka's tenement Exploration Licence (EL) 2900. Ambrosia was discovered some weeks later located approximately 2km north of Jacinth. Jacinth and Ambrosia are located on the eastern edge of the Eucla Basin in South Australia.

Several Australian companies have explored for mineral sands within the Eucla Basin over the last 20 years. BHP and Geo Peko explored during the late 1980s to the mid 1990s primarily for rutile and ilmenite.

The National Minerals Sands, Swan Reach NL and Geo Peko Joint Venture had some success with the discovery of mineralisation at the Immarna Prospect approximately 40km north of Jacinth in the early 90s. The Joint Venture drilled a number of other mineralised intercepts, the best being hole EB119. Here they intersected 2m @ 27% HM. Although this intercept was relatively deep at 40 metres it contained over 50% zircon in the assemblage.

Iluka applied for tenement EL2900 in 2001 after recognising the high potential for zircon rich, beach placer deposits hosted in Eocene sands of the Ooldea Range. Early reconnaissance creek sampling, confirmed the high zircon assemblage of the heavy mineral in the area.

In 2003 B. Hou, P. Heithersay, from Primary Industries and Resources South Australia published a paper titled 'Evolution of beach placer shorelines and heavy mineral deposition in the eastern Eucla Basin, South Australia'. The paper highlighted the prospectivity of the Eucla Basin, in particular the Ooldea range.

After approvals were received, drilling commenced in September 2004 on tenement EL2900, and Jacinth was discovered 3 weeks later. The initial work followed up the intersection at EB119 and then moved towards the Ooldea scarp to test a prospective topographic feature. Jacinth was found in position analogues to the Western Australian HM deposits Eneabba and Yoganup.

Jacinth and Ambrosia are classic beach placer deposits containing a high-grade strand with a lower grade dunal, halo or possibly younger transgression above it. Jacinth mineralisation extends over 4km along strike and up to 1km at it's widest. It is up to 30m thick and over much of its length mineralised to surface.

There are approximately 9.5 million tomes of heavy mineral between the two deposits containing over 4.5 million tonnes of zircon. Jacinth and Ambrosia have a zircon to titanium ratio of about 10 times the global average making it arguably the highest-grade zircon deposit in the world.

Iluka has constructed a $390 million project to enable exploitation of the Jacinth and Ambrosia deposits. The mine opened officially in February 2010 and at full production will produce approximately 300,000 tonnes of zircon per annum over 10 years.

Heavy mineral occurrences in the Eucla Basin vary greatly in mineral assemblage from the zircon rich Jacinth, Ambrosia and Tripitaka deposits to the ilmenite dominated Typhoon and Mojave prospects. The mineral assemblage and heavy mineral grade depend on several factors such as the type of source rocks, sediment load, depositional setting and degree of reworking by waves and wind energy.

Deposits such as Jacinth, Ambrosia and Tripitaka may have been subjected to several phases of reworking during fluctuating sea levels. The mine exposures at Jacinth will provide an opportunity to complete a detailed geological study of the deposit to help unravel it depositional history and any post depositional modification.

Iluka has about 50,000sqkm of tenure in the Eucla Basin to explore. Since the initial discoveries of Jacinth and Ambrosia, several other heavy mineral occurrences have been found by Iluka; including the Tripitaka deposit, Gulliver's, Typhoon, Dromedary and Mojave prospects. The Eucla Basin is shaping up to be a world class heavy mineral province that should provide a wealth of minerals for years to come.

The joys of having rocks in your head

Greg Mortimer[1]
[1]Consultant

As one of the early batch of geology graduates from Macquarie University, Greg Mortimer was blighted through his geological career with a strong desire to explore the great mountains and remote ends of the of the world. This light lecture looks from the top of Mt Everest to the Transantarctic Mountains and High Arctic archipelago, and considers the importance of the mind-set of the geologist and geological thinking.

SESSION 03ED (ENVIRONMENT)

Antarctic and Southern Ocean influences in global Late Pliocene cooling

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`During the Early Pliocene (4.5–3.2 Ma) Earth's average surface temperature was 3–4°C above present and atmospheric pCO_2 was ~400 ppmv. This century Earth will reach comparable levels of atmospheric pCO_2 and

temperature, and the warm Pliocene epoch is becoming increasingly important as analogue for the assessment of future scenarios of polar ice sheet melt and its influence global sea-level rise.

Early Pliocene climate was characterised by reduced meridional and zonal temperature gradients leading to permanent 'El Nino-like' conditions in the equatorial Pacific Ocean. The marine-based West Antarctic Ice Sheet (WAIS) was reduced to terrestrial remnants, Greenland Ice Sheet had deglaciated, and interglacial global sea-level was up to 25m above present.

Subsequent cooling culminated in Northern Hemisphere continental glaciation by ~2.7 Ma, and has been attributed to declining pCO_2 in combination with favourable orbital geometries, closure of the Panamanian Seaway, and enhanced poleward oceanic heat transport and precipitation. Conspicuous by its absence in global Late Pliocene cooling scenarios is the role of Antarctic cooling and ice sheet dynamics.

Data from a well-dated, marine sediment core (AND-1B) from beneath the Ross Ice Shelf, together with other geological and geophysical data from the Antarctic margin, provide evidence of major expansion and cooling of the Antarctic Ice Sheet beginning at 3.4 Ma. This high latitude cooling likely resulted in several positive feedbacks leading to step-wise expansion of sea-ice between 3.3 and 2.0 Ma, northward movement of the westerly wind field, and associated intensification of oceanic frontal systems (e.g. Polar Frontal Zone and the Subtropical Front). Such changes may have significantly reduced Atlantic meridional over-turning circulation and ocean heat transport to the Arctic preconditioning the world for bipolar glaciation (~2.7 Ma) and heralding the onset of the Quaternary.

Structure and evolution of the Hunter Ridge, North Fiji Basin, south-west Pacific: results from three voyages of R/V 'Southern Surveyor'

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The North Fiji backarc basin (NFB) began opening ~12 Ma in response to subduction reversal along the Vanuatu section of the Proto-Vitiaz arc. The triangular shape of the basin reflects ongoing (since ~5 Ma) southward propagation of the backarc spreading centre in response to westward roll-back of the Vanuatu trench and eastward roll-back of the Tonga trench. The south-east boundary of the Basin is formed by the submarine Hunter Ridge, which extends from ~ 172 oE to ~ 179 oE between islands of Hunter and Kadavu. This area has been mapped and sampled during the SS10/2004, SS08/2006 and SS03/2009 voyages of the R/V 'Southern Surveyor'.

The south-west end of the Hunter Ridge is a volcanically active area that accommodates the the oblique southward propagation of the North Fiji Basin spreading centre. Multi-beam seafloor bathymetry acquired during the voyages reveals that the processes occurring during this stile of propagation of the backarc basin involve sequential formation of 50–100 km long rift zones that split the crust of the Hunter Ridge along its strike. Initially such rift zones form as narrow (2–3 km wide) well-defined grabens with incipient magmatic activity. Then the graben widens to form a robust magmatic rift with clear volcanic centres and incipient spreading. Finally, the rift undergoes rotation and evolves into a N-S aligned robust spreading segment. This process on one hand results in the rifted blocks of the Hunter Ridge being incorporated within the backarc crust, and also leads to extensive deformation of the residual crust of the Hunter Ridge itself.

Volcanic rocks erupted during rifting within each segment include a large spectrum of subduction-related magma compositions from backarc basin basalts to boninites, calc-alkaline basalts and high-Mg adakites. All magma series have very primitive, high MgO endmembers. There is clear petrographic and geochemical evidence for extensive mixing between high-Mg adakitic and backarc basin magmas in this area, which results in formation of primitive magmas with typical calc-alkaline and boninitic affinities. This mixing process we believe is applicable to the genesis of calc-alkaline magmas world-wide.

Seafloor mapping also revealed the highly deformed nature of the entire Hunter Ridge crust, identical to that observed at the southern end of the Ridge. This puts important constraints on the tectonic history of the Ridge and questions the currently accepted view that the Ridge represents a relatively young (3–7 Ma) volcanic arc formed above a northward subduction zone of the South Fiji Basin crust under the North Fiji Basin crust. Instead, it may represent a deformed block of the Proto-Vitiaz arc crust, which was initially positioned

between its Vanuatu and Fiji segments. Recovery of a range of intrusive rocks from the deepest scarps on the Ridge will allow dating of the volcanism using a U-Pb technique.

A large number of small, young (post-deformation) volcanic cones were identified along the entire Ridge length and on the adjacent seafloor of the North Fiji Backarc Basin, suggesting that both are currently undergoing extension.

Mapping the seabed between the Hunter and Matthew Islands, discovered large fresh N-S oriented lava fields on the seafloor south of the Matthew Island, indicative of active extension in this area, possibly also related to southward propagation of the North Fiji Basin.

Volcaniclastic sediments formed by submarine hydrothermal eruptions in the Manus Basin, Papua New Guinea

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Whereas hemipelagic ooze dominates the Manus backarc basin floor, dark grey to black volcaniclastic sands and silts occupy a 7x4 km mudline 'apron' surrounding far-eastern SuSu Knolls, a group of hydrothermally-active submarine volcanoes (South Su, North Su, and Suzette). Thin layers of similar sediment overlie hemipelagic ooze in an adjacent 2050m deep basin. These volcaniclastic sediments resemble subaerial or water-lain tuffs at terrestrial stratavolcanoes and might be interpreted as such in ancient sequences, but here they exist at water depths of 1150m to 2100m, remote from potential sources on land.

The mudline volcaniclastics have similar bulk chemical compositions throughout their dispersal area. Moderately well sorted, they are composed predominantly of sharply angular fragments of glassy to devitrified microlite-rich andesitic lava, and shard-like grains of plagioclase curiously shaped by conchoidal fracture rather than cleavage. Orthopyroxene, clinopyroxene and Ti-magnetite clasts are less abundant. Clay-altered lava fragments also occur and widespread trace constituents include quartz-sulphide vein fragments, composite sulphide clasts, and alunite grains. Quenched juvenile material is lacking. Large blocks of conspicuously porphyritic parental lithologies and altered equivalents dominate the 1150 mbsl crest of youthful North Su, considered the most likely source for the volcaniclastics. Subtle petrographic features such as presence of highly siliceous residual glass in lava clasts rule out derivation from alternate explored features in the region, except otherwise-unlikely South Su. Maximum grainsizes of plagioclase and volcanic clasts are greatest in surface sands on North Su (1.5–2 mm) and decrease semi-systematically to about 0.3 mm at apron fringes.

In gravity cores, grabs, and diamond drill cores at Suzette (including Nautilus Minerals Inc. Solwara 1 project at ~1500 mbsl) the mudline volcaniclastics are ~0.6m thick and show mild upwards-fining grading. They variously overlie similarly enigmatic volcaniclastic units, locally derived hyaloclastite beds, and fine pumiceous rhyolite ash layers (sourced from Rabaul mega-eruptions?). Within the Solwara-1 hydrothermal site both mudline and deeper sediments are cemented by opaline silica or even sulphides. Partial replacement of clasts by barite and sulphides also occurs. Some deeper sediments are pervasively altered. Fragments of pyrite-chalcopyrite-marcasite several cm across with concentric chimney-like structures are scattered in the volcaniclastic sediments. Overlap between hydrothermal and volcano-sedimentary processes is further exemplified by a dredged Suzette chimney with orifices clogged by mineralised volcaniclastic sediment.

Absence of juvenile components denotes derivation of the volcaniclastics by gas-driven rather than magma-driven eruptions. The unusual conchoidal fracturing of former plagioclase phenocrysts suggests fragmentation following explosive shock. Chimneys that vent 325ºC 'flashing' fluid at North Su imply an internal hydrothermal system on the point of phase separation and which would expand violently if pressure were suddenly reduced. North Su lies only 10 km from a seismically active transcurrent microplate boundary (Weitin Fault) from which a series of normal faults strike towards SuSu Knolls, so plentiful scope exists for sporadic pressure release within the edifice by uplift, cover removal or earthquake-induced fracturing, with consequent flashing and sweeping of fine volcaniclastic debris spalled from the walls of instantaneously expanded hydrothermal conduits that cut fresh and altered volcanics with sulphide veins.

This debris has been dispersed 2 to 3.5 km in a submarine environment where water resistance would rapidly diminish eruptive kinetic energy and where bottom currents are minimal. Build-up near the source followed by slumping and transport in submarine mass flows may explain deeper sediments at Solwara-1 and those in the

adjacent basin, but for the mudline volcaniclastics this process appears ruled out by failure to channelise down 'valleys', by deposition over high-standing neighbours, and by lack of clast abrasion and absence of large lava blocks.

An alternate dispersal process via large-scale hydrothermal 'flashing' at the source is creation of a hot, buoyant eruption column able to rise through seawater and spread laterally before cooling and condensation of any incorporated vapour caused collapse and deposition of the contained sediment. Turbulence in the column may explain the lack of significant separation of mineral components and the relatively moderate grainsize grading of the ultimate deposit, but not the degree of sorting which must reflect source processes. Apparent incorporation of chimney fragments at Solwara 1 requires further investigation.

SuSu-like volcaniclastic 'aprons' are lacking at other volcanic constructs within the eastern Manus Basin. These are mostly built by more effusive eruptions.

SESSION 03DD (DYNAMIC EARTH: RESTLESS EARTH AND EARTH STRUCTURE)

Through a glass darkly: imaging the Earth's interior from the surface

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In the Earth Sciences a common process is to try and extract meaningful information from noisy and inadequate data. Often assumptions must be introduced in order to retrieve any information at all, and inevitably the influence of those assumptions on conclusions is an important question. An example is seismic imaging of the Earth's interior where earthquake travel times, or waveforms, are fit by adjusting parameters controlling an Earth model. Typical assumptions in seismic tomography include knowledge of the error characteristics of the data, and also the style of parameterisations used to represent the subsurface, e.g. including lateral heterogeneity or not, the number of unknowns and length scales of allowed variation. The two questions of 'how well to fit the data?' and 'how many unknowns to include in the model?' are ubiquitous in inference problems. They are also related, since it is well known that data can be fit better by introducing more degrees of freedom (or unknowns) into the model.

In cases where both the noise in the data and the number of unknowns in the model are poorly known in advance, how does one proceed? Should restrictive, and possibly unwarranted, assumptions be introduced in order to make problems tractable, or should we simply give up? The answer to both questions is no. It turns out that in many cases its is entirely possible to proceed without fixing the number of unknowns or level of required data fit in advance. In this presentation an approach will be described where both of these assumptions are relaxed and yet robust results are achieved. We show that its possible to let the data decide how well to fit the data and how many unknowns to use in the model. We do this through a sampling based approach which involves generating many candidate solutions rather than seeking a single model through optimisation. The ideas here are quite general and can be readily applied to other problems where we would prefer to relax arbitrary and often unjustified assumptions about the number and type of unknowns. In this presentation the methodology will be described in general terms and illustrated with examples from seismic imaging.

Architecture of the Prydz Bay region, Antarctica, from magnetotellurics

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During the summer of 2008/09, measurements were taken at 34 magnetotelluric (MT) stations along profiles totaling approximately 180 line km in the Prydz Bay region of Antarctica. Prydz Bay comprises several regions of coastal outcrops with distinct geological histories, including the Vestfold Hills and the Rauer Group of islands. The primary aim of the MT survey was to image the boundary between the Vestfold Hills and the Rauer Group. The Vestfold Hills are dominated by 2520–2480 Ma orthogneisses that experienced granulite-grade metamorphism prior to 2470 Ma. They were intruded by several generations of dykes during the Paleoproterozoic and Mesoproterozoic. The Vestfold Hills have not been pervasively affected by high-

temperature Neoproterozoic events, probably related to Gondwana amalgamation, that permeate much of the Prydz Bay region. The Rauer Group, which lies adjacent to the Vestfold Hills, preserves a significantly different geological evolution. The oldest rock package in the Rauer Group comprises 3300–2800 Ma tonalitic orthogneisses, layered igneous complexes and paragneisses. 1060–1000 Ma orthogneisses are interleaved with the Archean rocks in places, and the entire region is affected by 550–500 Ma metamorphism. The contrasting geological evolutions of the two regions suggest that they do not share a common history and were juxtaposed probably at either c. 1000 Ma or at c. 550–500 Ma during the amalgamation of Gondwana. The contact between the two regions is covered by the Sørsdal Glacier near the coast and by the Antarctic ice cap further inland and can therefore not be sampled directly. To image the contact, the MT survey was focused over the inland extension of the Sørsdal Glacier with station spacings of 2.5 km to 5 km. Both broadband and long-period measurements were taken to constrain the structure from the near-surface to the upper mantle.

MT is a passive electromagnetic geophysical technique which uses the earth's time-varying magnetic field as its source field. It is applicable to Antarctic environments as its passive nature results in no environmental impact and since the frequencies contained in the source field enable signal penetration through thick ice. However, data collection in the Antarctic does pose several challenges. MT methodology assumes that the source field is a plane wave, with fluctuations in the vertical magnetic field only occurring due to lateral resistivity gradients in the earth. At locations close to the magnetic pole, this assumption may not hold. The vertical magnetic field was measured at most MT stations and these data were combined with permanent magnetic observatory data from the nearby Davis, Mawson and Casey stations to analyse the activity in the vertical magnetic field and the impact of this on the MT data. Electrical noise from statically charged ice particles blowing over the MT electrodes has been proposed to pose significant challenges to collecting high-quality MT data in polar regions. Weather data from the Woop Woop weather station, located at the northern end of the MT profile, were collected in order to compare wind speed and direction with electrical noise. Finally, the high contact resistance of ice poses a challenge to data collection and pre-amps were utilised to boost the signal collected at the electrode. Along-strike measurements were taken on ice-covered and ice-free regions to analyse the effects of ice on the measured signal.

Magnetotelluric surveys across major Archean tectonic boundaries in southern Western Australia

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The results of two large-scale magnetotelluric surveys in southern Western Australia are reported. The Balladonia to Kambalda survey extends across the boundary between the Archean granitoid-greenstone rocks of the south-eastern Yilgarn Craton and continues on to the adjacent Proterozoic Albany-Fraser Orogen. The second survey extends across the south-central Yilgarn Craton from Hyden to Norseman.

The Balladonia survey was designed to elucidate the deep structure of the suture zone between the Archean and Protozoic. The data show the Albany-Fraser Orogen is largely allochtonous, having been thrust north-west of the Archean rocks along detachment structures in the middle and upper crust. The data allow the location, at depth, of the Yilgarn Craton's boundary to be established. There is also evidence for Protoerozic suspect terrains in the lower crust. The locations of the major crustal boundaries and major faults has important implications for nickel and gold mineralisation in the area, both of which are spatially related to such features.

The Norseman survey crosses greenstone belts (Southern Cross, Lake Johnston) which are known to be significantly older than those exposed near Norseman. The survey was designed to identify any intervening palaeo-suture zone. The survey also crosses the presumed southern extension of the Ida Fault and Koolyanobbing shear zones. It is expected to be able to establish their dip and depth extent. Both are associated with major gold deposits. These data have only just been acquired but their quality is very good and initial inversion results are expected in the few months.

The Capricorn orogen: crustal structure and evolution from a passive seismic transect

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The Capricorn Orogen of Western Australia preserves geological evidence for several episodes in the early tectonic history of the Australian continent. It joins the extensive Archaean Pilbara and Yilgarn Cratons to form the West Australian Craton, and is hence a highly significant architectural legacy of the geodynamic evolution of Australia. During mid-2006 to mid-2007, an extensive passive seismic experiment was carried out in which high-fidelity broadband seismic stations were deployed from the northern Pilbara in a north-south transect extending to a point approximately 100 km south-west of Meekatharra. This long transect samples the Pilbara Craton, Capricorn Orogen, and the Narryer and Murchison Terranes of the Yilgarn Craton. Additional seismic stations were deployed in a second, shorter transect which ran eastwards from Marble Bar to a point approximately 50 km east of Telfer, and hence crossed the Rudall-Paterson Orogen. Station separation on both transects was nominally 40–45 km.

The field deployment was a natural development of previous, reconnaissance-level deployments which spanned the West Australian Craton at the scale of the main terrane groups (Reading et al., 2007). During this earlier work, the variability of the Capricorn Orogen in terms of crustal structure was identified, but the station density was not sufficient to define the variability of structure within the Capricorn. The traverses that are interpreted in this study allow constraints to be placed on the crustal architecture at several points within this complex, multi-episode orogen. The crustal structure is determined by using earthquake records from teleseismic events which sample the upper mantle and crust beneath the recording stations. Seismic receiver functions are calculated to remove source and source-side path influences on the waveform, with a refinement to the technique that also removes the effect on the seismogram of the receiver-side free-surface and hence enables a better performance of the adaptive inversion algorithm. Upper crustal structure is also deduced from waveforms derived from the cross-correlation of ambient seismic energy between stations and is combined with the mid- and lower crustal, and upper mantle structure derived from the receiver function analysis.

We find that the architecture of the lithosphere for stations in the southern Pilbara, Capricorn and northern Yilgarn shows incremental variation between stations with a deepening Moho from north to south across the traverse. Characteristic seismic wavespeeds are variable with a slightly reduced lower crustal wavespeed being characteristic for the stations located within the Capricorn Orogen. The broad receiver function arrivals associated with the Moho beneath the Capricorn indicate a transitional lower crust to upper mantle layer in contrast to the sharp Moho that characterises the Pilbara and more southerly Yilgarn. Upper crustal structure deduced from ambient seismic energy technique shows some correlation with ancient basin structures. The stations across the Rudall region, moving away from the Pilbara Craton, show complexity in crustal structure and an increasingly ill-defined Moho. The processes of continental evolution associated with ancient orogens such as the Capricorn and the Rudall clearly influence the whole depth of the crust and the nature of the crust to upper mantle transition.

Reference

Reading AM, Kennett BLN and Goleby B, 2007. New constraints on the seismic structure of West Australia: Evidence for terrane stabilization prior to the assembly of an ancient continent? *Geology*, v. 35, p379–382, doi:10.1130/G23341A.1

SESSION 03LD (LIFE AND SOLAR SYSTEM: PLANETS WET AND DRY)

Early mantle depletion on a small igneous asteroid: new evidence from Nd isotopic compositions of basaltic eucrites

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Eucrite meteorites are among the oldest basalts in the Solar System. They are thought to sample the primary crust of asteroid 4Vesta based on remote sensing spectroscopy and plausible mechanisms for delivery of the

meteorites to Earth. Previously (AESC 2008) we reported on the petrography and major+trace element geochemistry of a suite of 13 samples of basaltic eucrite meteorites that had been collected in Antarctica. Textures of these basalts indicate variable cooling rates and depths of emplacement, with some samples having rapidly quenched textures consistent with surface flows while others have a coarser-grained, subophitic texture with pyroxene exsolution lamellae indicating slower cooling at greater depths (probably <5 km).

Major element compositions of all samples cluster near the experimentally-determined peritectic, consistent with melt compositions. Trace element compositions, however, showed considerably greater variability, with REE patterns ranging from LREE-enriched with negative Eu anomalies to LREE-depleted with positive Eu anomalies. Oxygen isotopes support derivation of all of these samples from a single parent body. We interpreted the LREE-depleted group as a new variety of non-cumulate basaltic eucrite possibly derived from a plagioclase-enriched source region that formed during early planetary differentiation, but concerns over terrestrial alteration and weathering of LREE-bearing phosphates as an alternative explanation persisted, due in part to the presence of a large positive Ce anomaly in one of the LREE-depleted samples (PCA80252).

In order to address the relative roles of early planetary differentiation vs. terrestrial alteration in producing the LREE-depletions, we conducted a ^{147}Sm-^{143}Nd isotopic study on whole rock samples of these eucrites. Five samples of Main Group eucrites have relatively flat REE patterns with small negative Eu anomalies and near-chondritic ^{147}Sm/^{144}Nd (0.1938–0.2006, average = 0.1958 vs. CHUR = 0.1960–0.1966) and ^{143}Nd/^{144}Nd (0.512556–0.512653, average = 0.512596 vs. CHUR = 0.512630–0.512638; εNd(0) = -1.6 to +0.3). Four samples of LREE-depleted (Group 2) eucrites, including PCA80252, have subchondritic ^{147}Sm/^{144}Nd (0.2001–0.2605) and elevated and variable ^{143}Nd/^{144}Nd (0.512787–0.514570; εNd(0) = +2.9 to +37.7). Two samples of trace element-enriched eucrites (Stannern trend and transitional) have LREE-enriched patterns (^{147}Sm/^{144}Nd = 0.1880–0.1894), deep negative Eu anomalies, and 'crustal' values of ^{143}Nd/^{144}Nd (0.512386–0.512478; εNd(0) = -3.1 to -4.9).

Most of the samples fall close to a 4.5 Ga reference line, but they do not form a valid whole rock isochron. Importantly, the Group 2 sample with the large positive Ce-anomaly (PCA80252) is the most discrepant, with much lower ^{143}Nd/^{144}Nd than would be expected for its ^{147}Sm/^{144}Nd (T-CHUR = 1.8 Ga, where T-CHUR is a model age calculated relative to chondritic evolution). In contrast the two most LREE-depleted Group 2 eucrites (EET90020, MET01081) have T-CHUR = 4.5–4.6 Ga. The remaining Group 2 sample (PCA91078) has an unrealistically old T-CHUR of 6.3 Ga. T-CHUR model ages of the other eucrites are also highly variable, i.e. Main Group = 0.6–6.7 Ga, and Stannern/transitional = 3.4–4.4 Ga).

We conclude that the ^{147}Sm-^{143}Nd systematics of some basaltic eucrites have been subtly (and some not so subtly) altered by terrestrial weathering. In the case of PCA80252, the LREE-depletion is accompanied by a young T-CHUR model age, a large Ce-anomaly, and other trace element signatures of weathering such as elevated Sn abundances. In contrast, the strong LREE depletion observed in other samples of basaltic, non-cumulate eucrites appears to be a primary feature based on the realistic T-CHUR model ages and the absence of other indicators of alteration. This implies the formation of LREE-depleted source regions on the eucrite parent body very early in its history, possibly by either fractional melting or magma ocean crystallisation, and continued melting of these depleted sources to produce the Group 2 basaltic eucrites. The four 'best' samples from this study, which includes one Main Group, two Group-2, and one Stannern trend eucrite, give a whole rock isochron age of 4543 $\pm$ 21 Ma, suggesting that igneous differentiation occurred within about 20 Ma from the origin of the Solar System.

Lu-Hf system in the bulk silicate earth: the effects of non-chondritic composition and ^{176}Lu accelerated decay

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The accuracy of interpretation of the Lu-Hf systematics depends on how well we know the composition of the bulk silicate Earth and the rate of decay of ^{176}Lu to ^{176}Hf. Both of these parameters were recently subjects of controversy and proposed revision.

Precise determinations of the ^{176}Lu decay constant (λ^{176}Lu) by age comparison using carefully selected terrestrial rocks and minerals (Scherer et al. 2001, Söderlund et al. 2004) and meteoritic phosphates (Amelin 2005) yielded the λ^{176}Lu value of 1.867×10^{-11} a^{-1}. These studies revealed that the previously used value, based

on analyses of eucrite meteorites (Patchett and Tatsumoto 1980) is about 4% too high. However, recent Lu-Hf studies of meteorites (Blichert-Toft et al. 2002, Bizzarro et al. 2003) report the apparent decay constant values that agree with the eucrite value. This 'conundrum of the ^{176}Lu decay constant' was explained by an extensive gamma ray irradiation that caused accelerated decay ('burn-out') of ^{176}Lu in early Solar System condensates (Albarède et al. 2006). Alternatively, it may be a result of interaction of supernova-derived cosmic rays or neutrinos (Thrane et al. 2007, Meyer et al. 2008).

Using the initial Hf isotopic composition derived from a Lu-Hf isochron for the angrite Sahara 99555, Connelly et al. (2009) estimated a Solar System initial ^{176}Hf/^{177}Hf that is ca. 4.5 epsilon-units lower than the chondrite value (Bouvier et al. 2008). This offset is interpreted as a result of cosmic ray irradiation that pre-dated chondrite accretion, whereas the interiors of the angrite parent body and the Earth that accreted earlier were shielded from irradiation, and preserved the lower initial ^{176}Hf/^{177}Hf. The present-day bulk silicate Earth ^{176}Hf/^{177}Hf= 0.282658 in this model is derived from the chondritic value of 0.282785 by shifting it down by 4.5 ε-units. The initial ^{176}Hf/^{177}Hf= 0.279668 is derived by extrapolating the present-day value 4567 Ma back in time using chondritic ^{176}Lu/^{177}Hf=0.0336.

It is also possible that the composition of the bulk silicate Earth was moved away from the original chondritic composition by very early differentiation accompanied with partial loss of differentiated material. This may occur through explosive volcanism in ca. 100 km planetesimals (Warren 2008), or through collisional erosion of differentiating planetary embryos (O'Neill and Palme 2008). These models predict that the Earth is depleted in incompatible lithophile material. Warren (2008) estimates Lu/Hf in the 'early depleted reservoir' at 1.09–1.33 times chondritic; O'Neill and Palme (2008) estimate Lu/Hf at 1.17 times chondritic. In the non-chondritic composition (non-CHUR) model, we use the ^{176}Lu/^{177}Hf=0.0393 (1.17 x chondritic). The initial ^{176}Hf/^{177}Hf=0.279794 is the same as the chondritic value. The present-day non-CHUR ^{176}Hf/^{177}Hf value of 0.283292 is obtained by forward extrapolation from the initial ^{176}Hf/^{177}Hf using ^{176}Lu/^{177}Hf=0.0393. The third model combines the effects of burn-out and a non-chondritic composition, yielding ^{176}Lu/^{177}Hf=0.0393 (the same as in the non-CHUR model), and the ^{176}Hf/^{177}Hf ratios shifted down 4.5 epsilon-units by burn-out, yielding present-day ^{176}Hf/^{177}Hf=0.283165.

A profound effect of the choice of the reference reservoir composition on $\varepsilon_{Hf}(T)$ values and hence on the data interpretation is illustrated using the zircon data from the Itsaq Gneiss Complex. In the standard CHUR model, the protolith of these rocks appears to be derived from slightly depleted mantle with $\varepsilon_{Hf}(T)\approx+1$ at ca. 3.8–3.9 Ga. Using the burn-out model makes the $\varepsilon_{Hf}(T)$ values strongly positive thus implying an extreme and very early depletion of the source. Choosing the non-CHUR model has the opposite effect: it makes the $\varepsilon_{Hf}(T)$ values strongly negative, and leads to interpretation of the Itsaq source as an enriched crustal or mantle reservoir that separated from the primitive mantle before 3.9–4.0 Ga ago. In the model that combines non-CHUR and burn-out, their effects are partially compensated, making the $\varepsilon_{Hf}(T)$ values at 3.8 Ga about 1.5 epsilon-units higher than the values in the CHUR model, and nearly identical at 3.4 Ga.

Uncertainty in the composition of the bulk silicate Earth is currently the greatest obstacle to accurate interpretation of terrestrial mantle differentiation and crustal growth. Chondrite composition is not necessarily a suitable proxy to the ratios of refractory lithophile elements such as Lu/Hf and Sm/Nd in bulk silicate Earth, whereas the proposed alternative estimates are strongly model dependent and therefore potentially inaccurate. New approaches to the accurate determination of the bulk Earth composition are necessary.

The tectonics of tiny worlds: Enceladus and the spectrum of planetary dynamics

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In the spectrum of tectonic regimes for solid terrestrial planets, Earth is commonly assumed to be an end-member in terms of its large size and active tectonic regime. The association between these two features is under attack by recent observations on many of the outer solar system satellites, suggesting they too possess of active surface dynamics. In particular, the recent Cassini mission to Saturn revealed active cryovolcanism on Saturns icy-moon Enceladus. Despite it's small size (~500km across), tidal heating due to its non-synchronous rotation around Saturn is sufficiently powerful to melt the ice deep within its interior. However, Enceladus is puzzling for a variety of reasons; not only does the young south pole region exhibit geysers and high heat flows not observed anywhere else on the satellite, cratering statistics demonstrate a highly episodic distribution of surface ages, and the current observed heat loss exceeds the long-term tidal heat production by at least 3.5.

Here we present scaled numerical models of convection within Enceladus's icy interior, and demonstrate that Enceladus should be in a convective regime that involves catastrophic overturns of its lid, each lasting about ~10 million years, with a roughly billion periodicity. During these events, portions of the lid are recycled into the interior, causing transiently high heat loss in the active region. We demonstrate that such episodic lid recycling occurs for plausible lid strengths and Enceladus's estimated tidal energy supply. The localised nature of these catastrophic overturns, the billion year recurrence interval, and the anomalously high heat flow during such events, are all consistent with Enceladus's geological record and heat supply.

Such localised catastrophic overturns may also have operated on other satellites, such as Ganymede, Europa, Rhea, and Miranda, based on their cratering records. This suggests active tectonics on solid satellites or planets may not be as rare as presupposed, and also highlights the secondary effect of size on the tectonic regime. To a first order, tectonic regime is governed by a planet or satellite's thermal state, which controls not only the thickness of the brittle lid, but also the induced convective stress on the lithosphere, which is a function of velocities in the interior, and viscosity. Strongly tidally heated icy satellites may in many circumstances periodically generate sufficient driving stresses to break their stagnant lids, releasing pent-up internal heat in dramatic, short-lived events. Outer solar system missions to these tiny satellites give us important constraints on the spectrum of possible planetary dynamics, particularly regarding the tectonics of tiny worlds.

Meteoritic signatures in ≥3.7 Ga rocks from the Isukasia terrane (Greenland): present knowledge and future directions

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The 35 km long Isua supracrustal belt in the 3.9–3.6 Ga Isukasia terrane of southern West Greenland (Friend & Nutman, 2005) contains a northern ~3.7 Ga volcano-sedimentary arc assemblage juxtaposed by 3.66 Ga against a southern ~3.8 Ga volcano-sedimentary arc assemblage (Nutman & Friend, 2009). It is now shown to consist of a series of tectonic panels partitioned by 3.65–3.6 Ga mylonites (Nutman & Friend, 2009). All of the Isua rocks have only ever been metamorphosed up to the middle amphibolite facies, with one tectonic panel experiencing maximum temperatures of only ~550°C (Rollinson, 2003). Much of the belt was already strongly deformed by 3.6 Ga, but there are rare low strain domains including some within discrete tectonic lithons, wherein both volcanic and sedimentary structures have been preserved. Thus these rocks are the world's best candidates to look for impact/meteoritic signatures at the tail end of the putative 4.0–3.8 Ga Lunar LHB (Late Heavy Bombardment) event.

Isua igneous rocks (both metabasalts and metatonalites) show no W isotopic deviations from terrestrial values (Schoenburg et al., 2002; Iizuka et al, in press). On the other hand, some ~3.7 Ga metasedimentary rocks do show deviations (Schoenburg et al., 2002), which has been interpreted as indicating that Isua sedimentary rocks contain a component of fine-grained meteoritic material, either as direct infall, or recycled from exposed surfaces of eroding volcanic rocks. Interestingly, the unit where a W isotopic anomaly has been reported also contains fine-grained graphite particles with a depleted ^{13}C signature (Rosing, 1999). This has traditionally been interpreted to be a signature of early life (Rosing, 1999), but combined with the W isotopic anomaly, it could in fact be derived from meteorites. Additionally there is a preliminary report of high Ir abundances in Isua chemical sedimentary rocks (Jørgensen et al., 2009). Thus there is a body of diverse data suggesting that Isua sedimentary rocks might contain a high background meteoritic component at the tail end of a LHB.

In an Isua supracrustal belt domain of low strain, we have discovered that a series of pillowed and brecciated intermediate metavolcanic rocks with a SHRIMP U-Pb zircon age of 3.709 Ga are overlain by chemical sedimentary rocks, containing rare detrital zircons as young as 3.690 Ga (Nutman et al., 2009). The underlying volcanic rocks show geochemical evidence of weathering. The ~3.7 Ga (deformed and metamorphosed) unconformity between the volcanic and sedimentary rocks is our future first target to look for signatures of more concentrated meteoritic material. Also we are aware of a similar modified unconformity in the southern, ~3.8 Ga, portion of the belt, albeit here the rocks are more deformed. Geochemical investigation of such weathered volcanic—chemical sedimentary rock interfaces can be expected to yield higher concentrations of meteoritic material, than already proposed/reported from the sedimentary rocks.

Within another part of the Isukasia terrane, still at amphibolite facies and locally without intense deformation, in reconnaissance fieldwork we have found an assemblage of volcanic, sedimentary and gabbroic rocks intruded by granitoids with a SHRIMP U-Pb zircon age of 3.89 Ga. Planned detailed study of these rocks, which formed at the climax of the supposed LHB event, should provide further information on how this event actually effected Earth.

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SESSION 03TD (TOPICAL: AUSCOPE SYMPOSIUM)

Modelling across the scales: the data and resolution challenge

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The physics of many of our Nation's most pressing engineering and ecological problems involve simultaneous processes on multiple scales. These scales range from pore- to mine- to basin- to lithosphere scale, i.e. from nano metres to hundreds of kilometres. Examples of such processes include the predictive simulation of the heat extraction process from hot rock (dry or wet), the simulation of different CO2 sequestration technologies, ore body genesis, mantle models with self consistent plate tectonics and many more. The challenge is to resolve each scale to an appropriate degree of accuracy whilst allowing for the exchange, aggregation and disaggregation of information between the scales. The scale resolution and information exchange challenge requires the management of simultaneous, scale specific modeling technologies e.g. Lattice Boltzmann Methods (LBM) and particle methods on the micro-scale, with finite- element, difference or volume methods on the macro-scale, combined with efficient mesh adaption schemes. The third challenge (besides scale resolution and scale communication) with the potential to substantially increase the value to be gained from modeling and simulation is the self consistent integration of geoscientific data (gravity, magnetic, GPS, INSAR etc) into dynamic computational simulations of earth processes (Inverse modeling technologies) The computational realisation of the various algorithms, code and data integration, and the sheer size of the problems involved in terms of unknowns, represents a significant innovation in terms of regional modeling capability, an innovative challenge the AuScope SAM team (with its track record of delivery of strong outcomes) is uniquely poised to meet.

Advances in geochemistry, past, present and future

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Advances in geochemistry have often been heavily facilitated by analytical breakthroughs. For example, the publication in 1928 of the book by Norman L. Bowen that laid down the foundations to understand the formation and evolution of igneous rocks. Most of the magmatic processes that he proposed are still used and discussed today, and his search for which physical parameters to understand these processes are major themes of current research. However, whole rock analyses involved laborious wet chemical techniques. The development of fast XRF methods completely revolutionised this field allowing for faster and more detailed studies. Also at the time of Bowen's publication, radioactivity had been known for almost 30 years, yet determining accurate isotope ratios of natural rocks for the purposes of dating and understanding their

formation would not come until 1960s with technological advances in mass spectrometry that were largely developed for other purposes. The most obvious outcomes were constraining the age of the earth and the spawning of the field of isotope geochemistry as applied to both high- and low-temperature processes. Development of the electron probe and ICP-MS has similarly had major impacts on all fields of geochemical endeavor. More recently development of energy filters has allowed precise analysis of short-lived isotopes leading to a proliferation of studies of the time scales of physical processes on Earth. MC-ICP-MS has had a similar affect upon the use of the isotopes of the transition metals. In Australia the development of the SHRIMP fundamentally changed the way in which zircon dating was performed and this remains the instrument of choice worldwide for precision and spatial resolution. Looking to the future, the development of Ion Probe ability to analyze stable isotopes, increased spatial resolution, synchrotron applications and others will have major impact upon geochemical research and the broadening of its application. However, such equipment is expensive and strong geochemical groups in Australia, as elsewhere, tend to be clustered around a few well-equipped laboratories. It is therefore important to decide how to keep these laboratories at the cutting edge and to appraise the need for the establishment of new laboratories to seed research in other institutions. The key role that geochemistry has played in our growing understanding of geological processes is heavily underscored by the publication by Elsevier of the 7800 page, ten volume Treatise on Geochemistry in 2003. Continuing advances in the field will require commitment to investment in appropriate infrastructure.

The future of geodetic science: implications for Australia's infrastructure and investment

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Geodesy is the science of measuring and mapping the geometry, orientation and gravity field of the Earth including the associated variations with time. One of the missions of Geodesy has been to provide the foundation for high accuracy surveying and mapping, in effect underpinning the geospatial information sciences and industry.

Modern Geodesy involves a range of space and terrestrial technologies that contribute to our knowledge of the solid earth, atmosphere and oceans through earth observation of many parameters. These technologies include: Global Positioning System/Global Navigation Satellite Systems (GPS/GNSS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Satellite Altimetry, Gravity Mapping Missions such as GRACE, CHAMP and GOCE, satelliteborne Differential Interferometric Synthetic Aperture Radar (DInSAR), Absolute and Relative Gravimetry, Precise Surveying (Levelling & Traversing). A variety of services have been established in recent years to ensure high accuracy and reliable 'geodetic products' to support geoscientific research. The reference frame defined by Modern Geodesy is now the basis for most national and regional datums. The Global Geodetic Observing System (GGOS) is an important new international initiative. GGOS aims to integrate all geodetic observations in order to generate a consistent high quality set of geodetic parameters for monitoring the phenomena and processes within the 'System Earth'—the solid Earth, the hydrosphere (including oceans, ice-caps, continental water), and the atmosphere.

In parallel with this international initiative AuScope NCRIS Capability 'Structure and Evolution of the Australian Continent' has as one of its components the establishment of 'National Geospatial Reference Framework'. This is giving a significant boost to Australian, and international, geodesy through the installation of new VLBI antennas, absolute and relative gravimeters, and almost 100 new GNSS reference stations. GNSS technology is nowadays a crucial geopositioning tool for both Geodesy and Surveying and this is being increasingly recognised in the form of an expanding ground infrastructure of permanent reference GNSS stations. This paper will describe the background to Australian Geodesy, highlight some of the trends in international geodetic science, discuss the crucial link between geodetic infrastructure and technology on the one hand and the geospatial sciences (mapping, remote sensing and imaging, precise navigation) on the other hand, and speculate on what might be the implications for future geodetic/geospatial national infrastructure and capability investments.

Imaging beneath the Australian continent: infrastructure needs to meet the challenges of the 21st century

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For the last half century, Australia has enjoyed an enviable international reputation in solid earth geophysics, particularly in the field of deep seismic imaging on regional and continental scales. Much of this reputation has been built on the development of novel data inference techniques, innovative use of seismic recording equipment, and the advancement of new paradigms for describing the structure and evolution of continents. For example, the idea for deploying a rolling array of seismic instruments to eventually cover an entire continent with passively recording seismometers had its origins in the SKIPPY project, and resulted in the first high resolution images of mantle structure beneath a continent. This idea has now been adopted by USArray, a massive US$100M+ project designed to progressively cover continental USA with seismometers at a 70 km spacing.

In order to maintain its position at the coal-face of new developments and discoveries in seismology, Australia must continue to facilitate its researchers with the necessary resources to foster innovation. From an infrastructure point of view, there are a number of areas that can be targeted in order to maximise return. A traditional strength is our ability to deploy passive seismic arrays to record distant earthquakes in order to build 3-D models of Earth structure, usually at mantle depths. While this work should continue, the potential returns can be greatly enhanced by the use of new generation equipment capable of recording three component data over a wide range of frequencies (from mHz to a 1000Hz). This will allow a variety of other useful information to be recorded (e.g. local earthquakes, higher frequency microseisms generated by the oceans, atmosphere and cultural activity) that can be integrated with the distant earthquake information to image structure throughout the full thickness of the lithosphere. The ability to illuminate structure from the shallow crust all the way down to the base of the upper mantle will provide key information on the development of the continental lithosphere, and help contribute towards a regional framework for the future exploration of prospective regions. Moreover, instruments capable of recording high frequencies make them useful for detecting explosions, vibroseis and airguns, which are used for a variety of purposes including reflection profiling and wide-angle surveys. Thus, deployments which record both active and passive data help provide a basis for the seamless joining of information collected at the exploration scale, and at the regional scale. In the past, this has been one of the major stumbling blocks for greater collaboration between exploration and solid earth geophysicists. A new pool of at least 150 three component instruments is required to meet the needs outlined above.

A second research area that opens up a wealth of opportunity for Australian scientists is marine geophysics. Although land-based seismic imaging has a strong future, the fact that Australia is surrounded on all sides by vast tracts of submarine continental terrane and ocean basins that are largely unexplored means that opportunity for new research and discoveries abound. A fleet of at least 20 OBS's (Ocean Bottom Seismometers) will allow a new chapter to be opened in the history of seismic imaging in Australia. OBS's can be placed almost anywhere on the ocean bottom, allowing them to record a variety of information that is invisible to land-based instruments. Applications include improved imaging and understanding of active seismogenic regions such as subduction zones, many of which lie on Australia's doorstep, and pose major earthquake and tsunami hazards to Australia and its neighbours; imaging of submarine sedimentary basins, which is relevant to exploration; and improving our understanding of the structure of the Australian continent beneath the oceans.

SESSION 04RA (RESOURCES)

The Paterson AEM Survey, Western Australia: enhancing prospectivity using regional AEM data to image Paleozoic-Mesozoic paleotopography

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The Paterson AEM survey was flown over the eastern Pilbara Craton, the Paterson Orogen and the on-lapping Officer and Canning Basins in NW Western Australia between September 2007 and October 2008 as part of the Australian Government's Onshore Energy Security Program. The survey was designed to provide pre-competitive data to enhance exploration for uranium and other minerals. Flight lines spacings were 6, 2 and 1 km and 200 m for a total area of 45,330 km^2 targeting known deposits and other highly prospective rocks extending under cover. The survey data give new insights into the Paleozoic-Mesozoic paleotopography of the region, which is blanketed by Phanerozoic regolith including Permian glaciogene, Mesozoic and Cenozoic sediments, well developed weathering horizons and indurated materials. These insights have major implications for mineral prospectivity.

The survey has shown that the bulk of the Archean and Neoproterozoic basement rocks are generally resistive except for the Archean Jeerinah Formation (part of the Fortescue Group), adjacent to the Woodie Woodie Mn deposit, and the carbon- and pyrite-bearing facies of the Neoproterozoic Broadhurst Formation, which hosts the Nifty Cu deposit. Overlying Phanerozoic materials of the Canning Basin have variable conductivity: Permian glaciogene sediments are generally weakly to moderately conductive and can be mapped over large distances; Mesozoic sediments tend to be resistive to weakly conductive; and, Cenozoic sediments tend to be resistive (sand dune and sheets) or strongly conductive (saline sediments associated with modern salt lakes and paleodrainage systems including the Wallal, Percival and Disappointment Paleovalleys). The conductivities of Phanerozoic materials also change gradually from east to west across the survey area, most likely in response to mixing of fresh and saline groundwater from the east (more saline) to the west (less saline).

The AEM data set was inverted using a GA-developed layered earth inversion technique. The inversion also included development of a per cent data influence (PDI) surface which indicates the depth below ground at which the inversion becomes unreliable. The inverted AEM data was then interpreted with the aid of a database of over 4,300 public-domain exploration drill holes. The AEM data have been used to map the location of the major Paleozoic (sub-Permian) and sub-Mesozoic unconformities in 3D where conductivity contrasts permit: where weak to moderate conductors overlie resistive basement; and, where weak to moderate conductors overlie highly conductive basement. It is not possible to locate sub-surface geological features where strong conductors occur at the surface, e.g., around salt lakes. The PDI surface also gives a graphical indication of areas where EM techniques will and will not penetrate, making it a *de facto* 'AEM go-map'. Resistive areas have a lower-elevation PDI surface and are more amenable to detailed ground or airborne EM techniques; discrete conductors within the PDI surface may indicate the presence of alteration or mineralisation.

The survey has improved knowledge of the basement-cover relationships in the region including:

- the sub-surface extension of the highly U-prospective Paleoproterozoic Rudall Complex to the SE underneath the on-lapping Canning Basin
- the 3D distribution of Permian-filled paleovalleys in and around the Kintyre U deposit in the northern Paleoproterozoic Rudall Complex and elsewhere over Neoproterozoic rocks of the Yeneena Basin
- the extent and depth to Neoproterozoic rocks in the Anketell Shelf (including the nearby Telfer Au-Cu mine and other Au and base metal prospects). Wildcat drilling campaigns in the area historically have had only a 65% success rate of reaching Neoproterozoic rocks below cover

- the sub-surface extent of major mineralised Neoproterozoic rocks including the Broadhurst Formation underneath the on-lapping Canning Basin in the Paterson Range and Gregory Range areas.

The Paterson AEM survey has allowed more accurate depth-to-basement maps to be constructed and will improve prospectivity in the region by:

- imaging near-surface structure to enhance geological interpretation and exploration targeting
- indicating areas which are amenable to EM techniques using the PDI surface or 'AEM go-map'
- locating discrete conductors.

Exploring and developing placer and uranium mineral potential of the Eucla Basin and peripheral palaeovalleys

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The large areal extent of the Eucla Basin and adjacent palaeovalley network has resulted in a complex succession of marine and non-marine strata across a range of depositional environments. The Palaeogene-Neogene morphology and geology show many palaeolandforms including valleys, lagoons, estuaries, and coastal barriers, which are important because they contain significant mineral resources, such as placers and uranium. The remarkably preserved palaeoshorelines and palaeovalleys along the margin of the Eucla Basin, up to 380 km inland from the present shoreline, is highly prospective for placer and uranium deposits. Factors controlling these mineral distributions in the Eucla Basin and palaeovellys include sea-level changes and palaeoclimate, nature of the distal provenance rocks in the hinterlands, the palaeodrainage network, longshore currents, neotectonic activity, and (local) controls of geomorphology, topography and the configuration of the nearshore and onshore settings, as well as groundwater geochemical process. For instance, a series of 'J'-shaped segments along the Ooldea and Barton Barriers is inferred to have resulted from longshore-drift wave refraction around headland promontories are favourable sites for beach placer. Redox sites along the palaeovalley margin (overbank) are associated with uranium accumulation, related to groundwater geochemical process at redox interfaces within channel sediments. Palaeovalley and palaeoshoreline mapping combined with the study of sea-level events and palynological and zircon dating of onshore sediments to reconstruct these Palaeovalley and palaeoshoreline evolution and to provide a context for known placer and uranium occurrences, together with predictive models for sites of placer and uranium concentration. Mineral exploration has located several high-grade beach placer and uranium deposits/prospects and established the Eucla Basin as a new heavy mineral and uranium province in southern Australia. Weathering, erosion, palaeoriver activity, sea level change, tectonic movement and groundwater process over 40 million years have influenced the concentration of placers and uranium along the palaeoshorelines and in the palaeovalleys.

Sediment provenance studies based on placers from the onshore basin, indicate that the sampled zircons and were derived mainly from the Musgrave Province and possibly the Albany–Fraser Orogen, with minor contribution from the eastern Gawler Craton. The source areas reflect prevailing palaeoclimatic conditions and neotectonic effects. The beach placers are of multicyclic origin. While the provenance is principally the Musgrave Province, there is a strong possibility the HMs have been recycled through Neoproterozoic and Palaeozoic sandstones of the Officer Basin and Permian fluvio-glacial deposits. These are widely distributed in the area of palaeodrainage between the Musgrave Province and Eucla Basin. The term 'palaeochannel-related' uranium deposits probably encompass three of 15 major uranium categories including sandstone, surficial and lignite-related deposits. Large areas of uranium mineralisation known in Cenozoic palaeochannel sediments of Australia fit some or all of these criteria. Palaeochannel-uranium mineralisation in SA is mostly in Cenozoic basinal palaeovalleys developed on or proximal to Precambrian cratons. The controlling factors on palaeochannel uranium ore include sedimentary facies and its association with reducing agents as well as late diagenesis and alteration of the channel sediments. Discovery of economic uranium resources in various palaeodrainage networks make South Australia highly prospective for palaeochannel-hosted uranium deposit: in particular, sandstone (roll-front) styles but also surficial deposits, which to date have attracted little attention as an exploration target.

The present high level of interest in (beach) placer and uranium exploration, targeting Cenozoic sediments in SA, reflects the largely untested potential of these sediments to host placer and uranium.

Techniques have been developed to define shoreline and channel morphology even where buried by over a hundred metres of exotic cover sediment. While the eastern margin of the Eucla Basin has been the focus of mineral exploration and placer and uranium discoveries, the northern and western margins are also prospective. The potential for similarly rich deposits along the western margin is yet to be established, but all areas of the basin margin are currently attracting exploration interest, for both placers and uranium. Further work on modelling the evolution of the placer and uranium deposits is needed in these areas to assist with testing new exploration targets.

SESSION 04EA (ENVIRONMENT)

Keep-up, catch-up or give-up: implications of shallow transect coring, Heron Reef, Great Barrier Reef, Australia

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There is much concern over the fate of modern coral reefs in the face of climate change, with high temperatures, ocean acidification and sea level rise indicated as major potential stresses to be added to overfishing and eutrophication resulting from land use change. Understanding the rate at which Holocene sea level reached its current level and how coral reef ecosystems behaved during this period is fundamental in assessing the consequences for reefs of potential future sea level rise. The best accretion rate data for coral reefs are derived from dated cores. However, relatively few cores have been recovered from modern coral reefs. Previous work on the Great Barrier Reef has produced records of vertical reef accretion in several reefs, but most sites represent one or a few isolated cores that do not allow measurement of both vertical (aggradation) and lateral (progradation) accretion of the reefs. We recovered shallow (~1–13 m) cores from Heron Reef, Great Barrier Reef, including one suite of five cores spaced at five metre intervals along a transect perpendicular to the leeward reef margin. Cores were recovered from the reef flat using a hand-operated hydraulic diamond coring unit and dating was done on coral skeletons that were well preserved and deemed to have been in growth position using both radiocarbon and U-series methods.

Cores from the western leeward margin transect near, but east of, Heron Island ranged in depth from 5 to 10 m, and none penetrated the Pleistocene. Dates obtained from the cores ranged between 4.2 and 7.3 ka with the reef flat having reached its current elevation by 5.4 ka at the inner-most position and 4.2 ka 20 m towards the margin. Hence, reef growth at the most inboard core reached current sea level ~1 ka earlier than it did only 20 m farther towards the margin. Vertical accretion rates calculated from the five cores varied systematically between 2.9 and 4.7 m/ka from outer to inner positions. The differences between the cores represent progradation wherein the reef surface reached present sea level progressively from inner to outer sites. A single core recovered from the leeward margin far to the east yielded a date of 3.12 ka at 9.6 m depth. No samples recovered from the transect cores yielded such a young date suggesting that there was significantly more progradation on the leeward margin to the east than towards the western end of the reef. A single ~1 m core recovered 25 m in from the windward margin of the reef near Heron Island yielded dates of 1.9 ka at 0.1 m and 3.0 ka at 0.7 m depths, again suggesting significant progradation on the windward margin at the channel between Heron and Wistari Reefs.

Our limited core data show that Heron Reef reached current sea level at different times at different places, reflecting significant spatial differences in progradation rates, not only between windward and leeward sites, but even among different leeward sites. Although progradation was expected to be significant on the leeward margin, previous studies have suggested less progradation on windward margins, yet that is not what we found. Although our core data allow a minimum sea level curve to be constructed, none of our cores penetrated the reef where it first reached current sea level and apparent vertical accretion rates vary widely, even in closely spaced cores. Hence, we cannot construct a meaningful sea level curve or evaluate the degree to which the reef kept up or caught up with Holocene sea level rise. All of our cores represent only a portion of a prograding reef margin.

Sequence stratigraphic concepts have revolutionised our understanding of the way in which depositional systems, such as reefs, interact with changing sea level. Apparent vertical accretion rates that cannot account for progradation may not accurately reflect the growth dynamics of a given reef, and thus may not inform us of a reef's true behaviour during sea level rise. As many reefs have been studied on the basis of single cores, it remains to be seen how reliable accretion rates and sea level curves based on those reefs may be.

Marine-terrestrial transitions associated with the world's oldest coral reef fish assemblage (Early Devonian, Wee Jasper, New South Wales)

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Best known for their remarkable fossil fish preservation (Campbell *et al*. 2009; Young 2009), the Murrumbidgee Group limestones (Burrinjuck area, 50 km from Canberra) reach a maximum thickness (1200+ m) in the Goodradigbee valley at Wee Jasper, where the folding seen in the Taemas area is lacking. The upper massive limestones include at least seven reefal structures up to 1 km long and 80–100 m thick, some exceptionally exposed, being washed completely clean by the waters of Burrinjuck Dam. The associated fossil fish assemblage (60+ genera) is the world's most diverse known Devonian vertebrate fauna, dominated by armoured placoderm fishes (Young 2010) that filled numerous niches with comparable diversity to teleost fishes in modern environments like the Great Barrier Reef.

Some 2 km beneath the limestones, a black shale (Kirawin Formation), probably deposited in a deep volcanic lake, has produced Gondwana's oldest (Lochkovian-Pragian) terrestrial arthropods (millipede-like myriapods; Edgecombe 1998), associated with unstudied plants and recently discovered shark remains. Apart from isolated teeth and scales this is the oldest known fossil preservation of chondrichthyans (cartilaginous fishes).

Conformably overlying the limestones is a transition to fluviatile and renewed lacustrine conditions in the Hatchery Creek Group, first studied by Edgell (1949), in which soil horizons with deep roots traces, plant fossils (lycopods, stems, primitive leaves), and numerous fossil fish localities have been discovered (Hunt 2005). Estimated sedimentation rates for a humid fan environment indicate that the 1800+ m sequence could have been deposited in about 5.4 Ma, and mostly or entirely within the Emsian (Early Devonian) using recent Devonian timescale calibrations (Kaufman 2006).

Several recent papers discuss interactions between the first diverse terrestrial vegetation, chemical weathering of vegetated soils, leaf evolution, and dramatic changes in atmospheric CO_2 and O_2 during the Devonian Period. Shallow root penetration of soils (Algeo & Scheckler 1998) and small leaves (Beerling *et al*. 2001) have been correlated with very high CO_2 levels (~4000 ppmv) during the Early-Middle Devonian. Deep root penetration, and large (megaphyll) leaves, only became viable with the spread of archaeopterid trees when atmospheric CO_2 fell to approach modern levels in the Late Devonian (Osborne *et al*. 2004). These ideas depend almost entirely on Northern Hemisphere data, whereas poorly studied sequences in Gondwana (the largest landmass of the time) have already produced the world's oldest lycopods (Rickards 2000) and forest environments (Retallack 1997). The new discoveries in the Hatchery Creek sequence at Wee Jasper will require drastic revision of these ideas.

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SESSION 04SA (SOCIETAL: HERITAGE)

Monitoring of the Burrup Peninsula Aboriginal petroglyphs

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The Burrup Peninsula is a thin finger of land approximately 27 km long and about 5 km wide located on the Pilbara coast of Western Australia. The peninsula is of unique cultural and archaeological significance as it contains the Australia's largest and most important collection of indigenous petroglyphs. Alongside the petroglyphs, the Burrup Peninsula has several large industrial complexes including iron ore, liquefied natural gas production, salt production and fertilisers with Australia's largest tonnage port. Since some of the petroglyphs adjoin industrial areas there has been very public concern expressed that the petroglyphs could be damaged by airborne emissions from the industry. In 2002, The Western Australian government established the independent Burrup Rock Art Monitoring Management Committee (BRAMMC) to review the available expertise and oversee the studies that were conducted to establish whether industrial emissions are likely to affect the petroglyphs.

In 2003 the BRAMMC commissioned a number of studies to monitor the petroglyphs. They included air dispersion modelling studies, air quality and microclimate; colour change, dust deposition and accelerated weathering study and mineral spectroscopy. The studies were based on the monitoring of seven sites with two control sites located on the northern Burrup area and the other five located further south on the lower Burrup Peninsula, closer to the industrial areas

For the last 6 years (2004 to 2009), petroglyphs at seven specially selected sites (chosen under the guidance of indigenous elders) in the Burrup Peninsula were measured using reflectance spectroscopy and colour measurements. Three spots on each engraving and three spots on each background rock were measured *in situ* using a portable spectrophotometer for colour measurement and a reflectance spectrometer for visible and near infrared spectral analysis. The 2004 spectral study is the baseline dataset that has been used to monitor potential variation during the last 5 years

Dust deposition studies were undertaken to evaluate the nature and composition of dust settling on rock surfaces in the areas close to industry and away from industry. The settled dust had a similar phase composition to the naturally weathering rock surfaces so a novel approach was to devise artificially textured, extreme-weather resistant surfaces that would allow the differentiation of settled material.

Fumigation studies were undertaken to simulate changes to rock surfaces on the Burrup in the long term, using the technique of accelerated weathering in a fumigation chamber in the laboratory environment. Fumigation chamber studies used samples of rock representative of engraved and background rock types, at current pollutant concentration levels and at 5–10 times the future pollutant concentration estimates. The pollutant dose was a mixture of the main industrial emissions: nitrogen dioxide, sulphur dioxide, benzene, toluene, xylene, ammonia and iron ore dust. A novel experimental protocol was established whereby the rock surfaces were exposed to the pollutant doses at the same time as being cycled through heating and cooling regimes designed to induce condensation that would occur in the natural environment. The combination of the number of heating and cooling cycles and elevated pollutant concentrations was designed to replicate an estimated 40 years of weathering and exposure to air pollution in the natural environment.

During April 2004 9 sites, including the 7 described above, were selected to measure a range of gas and particulate species which were used to construct acid deposition fluxes which deposit to the petroglyphs on the Burrup Peninsula. Studies were carried out at these sites during two annual periods, from July 2004 until September 2006, and from May 2007 until July 2008. During those periods, the measured fluxes of nitrogen and sulphur, the major acidic species, were used to compare with critical loads, which have been published in separate studies of the region. To construct deposition fluxes rainwater samples were collected to measure pH and ionic composition, a range of gaseous species were measured using passive samplers. They comprised NO_2, SO_2, HNO_3, NH_3 and BTEX gases, including benzene. In addition, the chemical composition of total suspended particulate samples was measured by ion chromatography, and mass concentration was determined gravimetrically on filter samples collected at the sites.

Weathering history of rock surfaces associated with Aboriginal rock art, Burrup Peninsula, Western Australia

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The heritage listed Burrup Peninsula and surrounding Dampier Archipelago, near Karratha, Western Australia, contain the world's largest known gallery of rock art engravings (petroglyphs), estimated to number up to 1 million images (Mulvaney 2009). The peninsula is also the site of major industrial development associated with the port of Dampier, including the Woodside Liquefied Natural Gas (LNG) plant, the Rio Tinto iron ore terminal and the Dampier salt mine. The preservation of a unique Aboriginal cultural heritage, in face of massive industrial development, is therefore a significant issue. In particular, there are concerns that industrial emissions from the gas plant may adversely affect the stability and longevity of the rock art.

The rocks on Burrup Peninsula are dominantly mapped as Gidley Granophyre, a composite sill of Archean age, consisting of an upper unit of granophyre and a lower unit of gabbro. A striking feature of the peninsula is the bouldery outcrop of the Gidley Granophyre on hills and slopes, caused by weathering along closely spaced joints—almost as if giant dump trucks have tipped a jumble of boulders across the entire landscape. The ubiquitous rocky outcrops form the canvas for the petroglyphs, which were formed by pecking, scratching, rubbing and pounding using a variety of tools (Vinnicombe 2002).

On Burrup Peninsula, rock surfaces are coated by a thin (less than 1 mm thick), dark coloured, discontinuous veneer (often referred to as rock varnish), principally composed of oxides of iron, manganese, silica, aluminium and phosphorus. The dark coloured rock varnish contrasts with the generally paler colour of the weathered rock exposed in the petroglyphs themselves, enhancing the visual impact of the rock art. Field observations suggest that the rock varnish may no longer be forming. Indeed, it predates most of the petroglyphs and is only rarely seen to have formed on the petroglyphs themselves. Preliminary LA-ICPMS analyses of the varnish reveal chemical microlamination similar to that reported for rock varnish in USA (Liu & Broecker 2008), which may provide a way of dating the varnish.

We are investigating the processes and rates of weathering and erosion, including the effects of fire, that affect the stability of rock surfaces and hence the longevity of the rock art, using cosmogenic nuclide measurements. In a pilot study, we have measured the concentration of ^{10}Be in quartz mineral separates from five samples yielding erosion rates of ~0.2 mm/1000 years on horizontal rock surfaces and ~1 mm/1000 years on vertical rock faces. The former, largely caused by mm-scale surface flaking, are amongst the lowest erosion rates measured by cosmogenic nuclides anywhere in the world. The latter are inferred to represent a combination of mm-scale flaking and very rare centimetre- to metre-scale block falls. The results of an ongoing, more comprehensive project will provide important information to assist in the long-term management and conservation of the rock art sites, as well as providing the first direct evidence of the age(s) of the rock art.

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SESSION 04DA (DYNAMIC EARTH: GEODYNAMICS AND MINERALS)

Minerals and energy resources: outcomes of lithosphere–mantle geodynamic coupling

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The architecture of the Sub-Continental Lithospheric Mantle (SCLM), its history and geodynamic engagement with plate tectonics and the convecting mantle, can profoundly influence the location, type and preservation potential of Mineral and Energy Resources.

Mapping of the architecture, composition and tectonothermal history of the crust and upper SCLM, utilising geophysical, geological, geochemical, geochronological and isotopic data, suggests that at least 70% of SCLM may have an Archean parentage. This infers that most preserved Proterozoic crust, and a significant amount of Phanerozoic crust, overlies Archean SCLM that has been variably refertilised and metasomatised by mantle melts associated with convergent margin, post-collisional, and mantle plume processes. The preserved Archean SCLM owes its durability to a compositionally depleted (Fe-poor) nature and low water content. This results in a relatively high seismic velocity, positive buoyancy consistent with the elevation of Archean cratons, and a strong rheology consistent with the rigidity of continental sheilds. In contrast juvenile, fertile, dense SCLM typical of island arcs is easily destroyed by delamination during accretionary and collisional events. The accompanying crust is highly susceptible to uplift and erosion. The fate of ancient crust (much of which is lost or hidden) is determined by processes such as crust-mantle decoupling during rifting, crustal imbrication and erosion during collision, and digestion by juvenile mantle melts.

A coupled lithosphere-geodynamic framework facilitates an understanding of the secular and spatial controls on ore development, and the preservation potential of deposits in different settings. Many ore deposit types source metals either directly or indirectly from mantle melts. The metallogenic affiliation of these melts is determined by such factors as the degree and depth or melting, the composition and temperature of the melt source, and interaction with crust. Magmatic and hydrothermal ore deposits, including porphyry copper (and related Cu-Au, Cu-Mo, Sn-W sytems), orogenic gold, Iron Oxide Copper-Gold, sediment-hosted base metal (e.g. Ag-Pb-Zn), and magmatic Cu-Ni-PGE sulphide, show a strong spatial coincidence with structural boundaries between lithospheric mantle domains and with other trans-lithospheric fractures. These zones focus strain and the passage of mantle melts. The source of some of these metals (e.g. Cu, Au) may be medium- to low-degree partial melts of metasomatised mantle (either asthensopheric or lithospheric). Such metasomatism is linked to the history and polarity of subduction. The Ni-Cu-PGE sulphide systems require high degrees of mantle melting, and arise when the 3-dimensional geometry of the SCLM guides mantle plumes to areas of thinner lithosphere where melting is enhanced. Intracratonic basins, host to many giant ore deposits may form in response to changing density of the SCLM or tectonic reactivation of SCLM boundaries.

Petroleum source rocks generally deposit in deepening (particularly rift/sag) basins, and given favourable P-T conditions, generate oil and gas. Migration and trapping of petroleum is affected by tectonic events, with cap rocks and structural traps facilitating long term storage. A view that encompasses a compositionally and structurally heterogenous SCLM and a weak lower crust, can be used to understand lithospheric response to tectonic events, plus the sedimentological and thermal history and structure of prospective basins. This approach could resolve some of the controversies and uncertainties surrounding existing models of basin evolution, and make a major contribution towards the development of a more robust predictive model.

Carbonate melts released from subducted sediments at sub-arc depth

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The recycling of elements and volatiles in subduction zones is a key for the understanding of the chemical evolution of Earth. The comparison of primitive arc lavas to MORB shows that significant amounts of water, large ion lithophile elements (LILE) and also CO_2 are recycled through subduction zones. Sediments and altered oceanic crust are main hosts for LILE and CO_2 in the subducted slab, whereas serpentinites and hydrated mafic rocks are the main hosts for water. Dehydration of hydrous phases, mainly serpentine and lawsonite, in deeper parts of the slab provides the main source of water at sub arc depth. There is increasing evidence that the interaction of such water rich fluids with sediments produces partial melts that play a fundamental role in the recycling of LILE (Hermann and Spandler, 2008). On the other hand, the recycling of CO_2 is still enigmatic. Geochemical studies have shown that significant amounts of CO_2 are present in arc lavas and that most of it derives from the subducted slab (Marty and Tolstikhin, 1998). On the other hand experimental studies (Molina and Poli, 2001; Thomsen and Schmidt, 2008) as well as calculated phase diagrams (Kerrick and Connolly, 2000) suggest that carbonates are refractory and no significant CO_2 is released from subducted sediments at sub arc depth.

We conducted an experimental study to constrain the phase and melting relations in carbonate bearing sediments from 700–1050°C, 2.5–5 GPa, i.e. under conditions relevant for subducted slabs at sub arc depth. 10% of a dolomite-calcite mix was added to a pelite mix containing 2–7 wt% H_2O. The elevated water content induced fluid fluxed melting in experiments at temperatures of 700–800°C. At 3.5 GPa, 800–1000°C a volatile-rich granitic melt is present. At 4.5 GPa a fundamental change in the melt compositions has been observed. Within the silicate melt, there are globules of Fe-Ca-rich carbonate-quench indicating that at 850–1050°C immiscible silicate and carbonate melts coexists. These carbonate melts contain SiO_2, Al_2O_3 and surprisingly P_2O_5 and TiO_2 at a wt.% level and high amounts of U and Th. Laser ablation ICP-MS analyses of mixed silicate and carbonate melts suggest that the LREE and HFSE are also enriched in carbonate melts compared to hydrous silicate melts.

In a previous experimental study, immiscible carbonate and silicate melts in subducted sediments have been found only at high temperatures of ~1100°C (Thomsen and Schmidt, 2008), which is clearly too hot for any reasonable subduction geotherm. Therefore, the possibility of carbonate melts as agent for CO_2 and trace element transfer had been discarded. In contrast, our experimental study shows that immiscible carbonate and silicate melts can form in subducted sediments at temperatures ≥ 850°C and pressures of 4.5 GPa, corresponding to a slab depth of 120–130 km. This is in agreement with observations from natural rocks suggesting that immiscible carbonate and silicate melts might be present in subducted crust at T=950°C and P=5 GPa (Korsakov and Hermann, 2006). Recent studies have proposed that top slab temperatures are likely 850–900°C at 4.5 GPa (Hermann and Rubatto, 2009; Plank et al., 2009). According to our new experiments carbonate melts are therefore expected in subducted sediments. These carbonate melts are able to extract significant amount of CO_2 from the subducted sediments and this process could represent one solution to the CO_2 enigma in subduction zones. Also such carbonate melts are very important carriers for trace elements, especially Th and U. In order to fully understand the importance of carbonate melts in the trace element and volatile recycling in subduction zones, it has to be evaluated in future studies how such carbonate melts react with the mantle wedge peridotites.

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Geochemistry and geochronology of sinter deposits as an exploration tool for geothermal systems

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Siliceous and calcareous sinters are unique surface deposits representing typical expression of continental geothermal systems. Their occurrences imply sub-surface geothermal water temperatures and provide an important guide to the exploration of concealed geothermal energy sources where surface thermal activity has declined or ceased. Recognition of sinter is not straightforward and distinguishing between them and other siliceous and calcareous lithologies is ambiguous. We investigate trace element systematics of ancient silica sinters from the Paleozoic Drummond Basin and travertine deposits from modern geothermal fields in Turkey to develop geochemical criteria for exploration of geothermal energy sources. Compared to quartz from various geological environments worldwide, the silica sinter from the Drummond Basin has remarkably high rare earth element (REE) contents. The sinter is also enriched in incompatible trace elements such as Be, W, U, Th, and particularly fluid-mobile alkali elements (e.g., Cs, Li and Rb) compared to quartz. The enrichment of these elements at surface or in near-surface rocks can indicate the presence of highly evolved alkaline magmatic systems, which can be used as a geochemical tool not only for identifying modern geothermal/magmatic systems but also for locating concealed ancient heat-producing granite or alkaline rocks providing a potential for Engineered Geothermal Systems (EGS). Unlike the siliceous sinter, calcareous sinters (travertine) from the modern environments are significantly depleted in REE, with an unique stable isotope (O and C) composition being characteristic of precipitation as thermogene deposits from rapidly ascending CO_2-rich hydrothermal fluids. Furthermore, U-series dating of hydrothermal siliceous and calcareous sinters is a useful technique to locate active geothermal areas. Geochemistry of siliceous and carbonate deposits in conjunction with geochronology offers an opportunity of identifying modern geothermal sites or heat sources for Hot Sedimentary Aquifers in Australia associated with recent/very young intra-continental hotspot magmatism.

SESSION 04TA (TOPICAL: EARTH SCIENCE HISTORY)

The past is the key to the present: Australian geological mapping, 1830s to WW2

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The earliest Australian geological maps had some economic purpose. Mapping by Lhotsky, Strzelecki, Mitchell and Dana from the 1830s directed attention to areas likely to contain coal, limestone or metalliferous deposits, potential dam sites and show the variability of soils.

Establishment of the various colonial geological surveys from the early 1850s were the result of mineral discoveries or the hope of locating more. However most political/bureaucratic support had flawed ideas about geology, expecting, in some sense, only trained prospectors, and believing that once a basic geological map was produced the need for further geology ceased.

Disagreement about how geological surveys should be carried out saw most work concentrated on known or potential mineralised zones, with little chance for geologists to build up a consistent regional story based on stratigraphic principles, such as was needed to understand the distribution of underground (particularly artesian) water.

Against considerable opposition Alfred Selwyn made the beginning of systematic geological mapping by the Geological Survey of Victoria, following successful British practice, although his men had to undertake topographic mapping at the same time. Nevertheless a series of detailed geological maps was produced which received world-wide acclaim.

Some consistency with colour schemes and symbols began, following the first International Geological Congress held in 1873, and various summary maps of each colony, and attempted whole of continent maps appeared from the 1860s, through to WW1, the pinnacle being in 1932 with the work of T.W. Edgeworth David

While the mapping of Australia at 1:250,000 scale from the late 1940s (described in detail by other speakers) marked the beginning of real understanding of Australian Geology, it was built on the observations and recording of the several earlier generations of geologists who covered vast distances under difficult physical conditions and limited basic information. These workers included HYL Brown, C. Gould, CS Wilkinson, J.E. Carne, RL Jack, whose work still commands respect.

The science and mapping of the Victorian exploring expedition of Burke and Wills, and of the related relief expeditions of 1860–1862

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The Burke and Wills Expedition, officially the Victorian Exploring Expedition (VEE), left Royal Park in Melbourne on the 20 August 1860, under the sponsorship of the recently established Royal Society of Victoria (RSV), with specific instructions to record scientific information along the route ('Instructions furnished to scientific observers attached to the Victorian Exploring Expedition—Surveyor, Astronomer, Meteorologist, Geologist, Mineralogist, Zoologist and Botanist' in *Transactions of The Royal Society of Victoria, Vol. 5*, 1860).

John Macadam, as Honorary Secretary of the Exploration Committee, in a communication to expedition members, advised them that 'You will cause full reports to be furnished … on any subject of interest, and forward them to Melbourne as often as may be practicable without retarding the progress of the Expedition'. There was, however, an important caveat under the heading of 'General instructions for scientific observers' namely, 'Scientific observations or work that would cause hindrance, or otherwise interfere with the progress or necessary work of the expedition, never to be undertaken if contrary to the instructions to the Leader'. From the point of view of the scientific success of the expedition this latter instruction proved to be a major impediment. Robert O'Hara Burke actively and unapologetically discouraged anything standing in the way of his progress to the Gulf of Carpentaria, including collecting scientific artefacts.

William Wills was appointed as expedition surveyor and map maker, Ludwig Becker as artist and geologist, and Hermann Beckler as medical officer and botanist. For many years it has been commonly alleged that the VEE was an utter failure as a scientific expedition (see for example Murgatroyd 2002). No scientific reports of the expedition were ever published. It could be said that the 'political' took precedence over the 'scientific' agenda. Yet upon examination of the records and artefacts it can be argued that some useful pioneering science was done. Major surveying and exploration data was recorded, as well as botany, geomorphology, meteorology and astronomy, hydrology and zoology, and records also made about anthropology and archaeology. Four major relief expeditions were soon to follow similar routes to that of the VEE, and they also recorded much information of value. A review of the work of the VEE and the associated relief expeditions shows a wealth of scientific data and mapping which has not yet been widely recognised.

For some years Frank Leahey, a surveyor in the Department of Geomatics at the University of Melbourne, has been working in the field and revising the expedition's route, relocating campsites and recovering artefacts. He has reassessed favourably the surveying and scientific work of Wills during the expedition. Unpublished documents, scientific collections and a wealth of field sketches and paintings by Becker and others provide further scientific records, including observations of weather, astronomy, geology and geomorphology, rivers, lakes and soils. Some 2000 plant specimens, so far little studied, are in the collections of the Melbourne Herbarium. A search has begun in the Museum of Victoria for forgotten or overlooked geological and zoological specimens, with some recent success. A team of scientists has been assembled to examine and report on this material.

SESSION 04WA (3D MINERAL SPECTROSCOPY OF THE EARTH'S SKIN—1ST NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM)

Abstracts for this session available on the Convention website www.aesc2010.gsa.org.au

U-series isotopic characterisation of an arid region sedimentary-hosted uranium mineralised system

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Sedimentary uranium deposits are an economically significant source of uranium worldwide, with Australia host to the some of largest known recoverable resources of uranium. Hydrologic processes are fundamental in the formation of such deposits, and the use of U-series isotopes in groundwater provides a powerful tool in understanding such systems.

The Beverley uranium mine, (South Australia) operated by Heathgate Resources, is the largest and most advanced in-situ recovery (ISR) mine in the world. The almost completely confined hydrology of the Beverley host aquifer allows for uranium to be mined using advanced acidic ISR technology (Armstrong and Jeuken, 2009). This mineralised system possesses extensive drilling and historical groundwater records, as well as data from ongoing regional monitoring wells that facilitate the monitoring of ISR mining. Hence, the well-characterised Beverley mineralised system offers a unique natural laboratory to investigate the behaviour of U-series isotopes in an arid region mineralised system. These records include detailed geologic and hydrologic data, in addition to time integrated well monitoring data.

Mineralisations occur in the permeable sands of the saline Beverley aquifer, hosted within Tertiary aged Namba sequences (Armstrong and Jeuken, 2009), which consists of interfingering sands, silts, clays and carbonaceous mudstones. The units overlie Precambrian crystalline granitic basement, which outcrops as the Mt. Painter and Mt. Babbage inliers. These basement rocks have unusually high U concentrations and are considered a potential source of the uranium (Callen et al., 1995).

Groundwater samples have been collected along the groundwater flow path upstream, within and surrounding mineralised ore deposits. Preliminary analyses for ($^{234}U/^{238}U$), ($^{230}Th/^{234}U$) and ($^{230}Th/^{232}Th$) measured by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) are presented. Additionally, preliminary U-series data from diamond drill core samples collected through the oxidised zone, ore horizon and into the reduced zone will be presented.

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Uranium-copper systems in Westmoreland region, northern Australia: fluid inclusion studies and geochemical modelling of basinal fluids

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The Paleoproterozoic Westmoreland region, which is located 1250 km south-east of Darwin, is flanked on the south-east by the Paleoproterozoic Mt Isa Inlier and the Neoproterozoic South Nicholson Basin and in the north-west it is onlapped by Mesoproterozoic sediments of the McArthur Basin. The northern McArthur Basin is well known for its association with unconformity-related uranium mineralisation but the potential for unconformity-related uranium deposits in the southern McArthur Basin and adjacent Westmoreland region has not been fully recognised. The oldest rocks in the Westmoreland region are quartzites and carbonaceous-sediments of the Murphy Metamorphics which are unconformably overlain by the felsic Cliffdale Volcanics and intruded by the comagmatic Nicholson Granite. The McArthur Basin sequence unconformably overlies these units with the oldest formation being the relatively oxidised Westmoreland Conglomerate which is conformably overlain by the mafic Seigal Volcanics. Uranium±copper mineralisation occurs close to the upper

contact of the Westmoreland Conglomerate with the Seigal Volcanics, as well as within the overlying volcanic rocks, and in dyke-filled fault zones.

Fluid inclusion studies have been carried out on quartz veining from Jackson's Pit and Eva uranium mines and the Dianne and St Barb copper prospects in the Westmoreland region. Four types of inclusions have been observed. Type A, vapour-rich inclusions, contain 30–100 vol.% vapour with varying amounts of $CO_2 \pm N_2 \pm CH_4$. Type B, liquid-rich inclusions, contain up to 30 vol.% vapour. Type C inclusions are liquid-only. Type D, three-phase (vapour + liquid + solid) liquid-rich inclusions, contain a small daughter crystal. Type A, vapour-rich inclusions and some Type B, liquid-rich inclusions homogenised over the range 171 to 385°C. Other Type B and Type D inclusions typically homogenised between 100 and 240°C with a mode around 120°C, while the presence of liquid-only inclusions suggests trapping at temperatures below 50°C. Low eutectic melting temperatures suggest the presence of $CaCl_2$ in the fluids but final melting temperatures show the presence of both high and low salinity brines. This suggests mixing between saline basinal fluids and low salinity meteoric fluids that continued down to temperatures below 50°C.

We have applied chemical modelling to the Westmoreland region, using the fluid inclusion data and the geology to constrain the composition of the rocks and fluids in the models. The results show that these fluids are capable of transporting significant quantities of both uranium and copper species. Both these metals will precipitate by interaction of the fluid with the originally Fe^{2+}-rich matrix of the Westmoreland Conglomerate. The interaction of the Westmoreland Conglomerate with the oxidised fluids has resulted in the more oxidised assemblage that currently exists. The modelling also indicates that subsequent fluid flow after uranium and copper precipitation would remobilise the minerals once again. Therefore, preservation of uranium mineralisation in the Westmoreland Conglomerate will only occur if there is a cessation of fluid flow after mineralisation.

Furthermore, fluids that penetrated deeper into the basin and also interacted with the Nicholson Granite were more likely to form copper-rich deposits when they initially interact with the overlying Seigal Volcanics but uranium-rich deposits could form at temperatures above 150°C, if fluid flow continued, causing re-dissolution of the copper that precipitated earlier. Therefore, this modelling has demonstrated that higher temperature basinal fluids (up to 200°C), such as those associated with unconformity-related systems, may form high-grade uranium mineralisation near the contact with or within mafic volcanics.

The modelling has demonstrated that both uranium and copper mineralisation may be associated with unconformity-related systems. It has also demonstrated that fluids in the Westmoreland region were capable of simultaneously transporting uranium and copper and that mineralisation was most likely to occur at or above one of the unconformities in this region or when oxidised basinal fluids interacted with reduced mafic dykes or mafic volcanics. In these models, the formation of uranium-rich or copper-rich deposits depends on the degree of fluid-rock interaction which, in turn, controls the oxidation state of the fluid. The modelling also shows that these deposits are readily remobilised by later interaction with oxidised fluids. Therefore, this suggests there is potential for similar styles of mineralisation in the vicinity of carbonaceous sediments and mafic volcanic units of the overlying McArthur Basin.

Geochemical alteration and associated REE mobility at the Ranger 1 No 3 Mine, Northern Territory, Australia

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The Ranger 1 No 3 deposit is an unconformity related uranium mineral system, one of the largest in the Alligator River Uranium Field. The deposit is hosted by the Proterozoic Cahill Schist which is divided into several units within the mine; Lower Mine Sequence (LMS)—dolomitic carbonates; Upper Mine Sequence (UMS)—Chlorite-rich schists; Hanging Wall Sequence (HWS)—Muscovite and biotite-bearing schists. The Archean Nanambu granitoid-gneiss complex forms the footwall.

A large geochemical database exists for the deposit with a 13 element suite sampled at every metre within mineralisation and every 10th metre of drill core outside the mineralised zone. Visualising the geochemical data set in 3D shows a clear zonation of alteration around the deposit. The distal HWS and upper parts of the UMS are K- and Ba-rich. The lower part of the UMS becomes progressively depleted in K and enriched in Mg, moving into zones of massive chlorite which host the uranium ore. In thin-section the uraninite is found to be

hosted by Mg-rich chlorite which is cross-cut by a later generation of more Fe-rich chlorite that is unmineralised. This chemical zonation indicates that the distinction between UMS and HWS is primarily based on alteration rather than lithology.

Complete whole rock analyses were collected for niche samples from three drillholes that intersect the Ranger Deeps Mineralisation. All samples were analysed for the full suite of REE's (by ICP-MS at NTEL). This data was normalised to PAAS (Post-Archean Average Australian Shale) as derived from regional Cahill Schists. This was used as an initial normalisation scheme because of the ability to identify anomalies relative to the regional Cahill or Proterozoic schists. Within the zonation of alteration around Ranger there is a shift from LREE-enriched patterns, normalised to PAAS, in the outer K-Ba alteration zone through to flattened trends for the Chlorite transitional zone and a strongly HREE-enriched trend, centred on Dysprosium (Dy), in the most altered Mg-Chlorite zone. The data was also normalised to Chondrite and shows the distal schists and the carbonates to have the same broad REE pattern, but with bulk depletion in the carbonates. The samples from the edge of the chlorite zone show a broadly similar pattern with minor depletion of LREE and enrichment of HREE. The mean response of the ore-bearing chlorite samples shows a dramatic change in the REE pattern with depletion of LREE and strong enrichment of the HREE symmetric around Dy.

Downhole plots of REE data show that the dominant spatial relationship is one where the LREE's are strongly depleted at the transition from K-rich to Mg-rich rocks. The HREE's show a general decrease from the Hanging Wall Schist to Upper Mine Sequence but are strongly enriched in the zones with ore grade Uranium. This general decrease is associated with a decrease in Al and Ti and probably reflects chemical dilution within a zone of increasing damage and volume increase. Based on this evidence the LREE and HREE's are behaving very differently with whole-scale depletion of LREE in the alteration zone, and preservation of HREE where there is strong enrichment associated with the U.

These broad trends are similar to those recorded by in the regional Cahill schist rocks, although the Ranger rocks show extreme enrichment and depletion, and those associated with U anomalism elsewhere both in the Alligator Rivers Uranium Field and the Athabasca (McLellan and Taylor, 1979; Fryer and Taylor, 1987; Fayek and Kyser, 1997), although the peak around Dy in the samples presented here differs slightly from the Terbium (Tb) peak observed in previous studies. The strongly HREE-enriched trend is similar to those found in the basement hosted, 'simple', deposits in the Athabasca (Fayek and Kyser, 1997). Both fluoride and carbonate complexes can transport HREE and U and F-apatites are preserved in the ore-bearing rocks.

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Are there any sandstone-hosted uranium systems in the Eromanga Basin?

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As part of Geoscience Australia's Onshore Energy Security Program the authors have investigated whether there is any evidence that a sandstone hosted uranium system has operated in the Eromanga Basin and assessed the basin's potential to host significant uranium mineralisation.

The Eromanga Basin is a Mesozoic, intracratonic, sag basin that covers an area of ~1,000,000 km^2 of central-eastern Australia and it onlaps several surrounding Proterozoic provinces that have elevated uranium contents. The Eromanga Basin has been subdivided into three major stratigraphic sequences: a lower non-marine sequence, a middle marine sequence and an upper non-marine sequence. Each sequence is characterised by basal sands that fine upwards into shales and silts, suggesting a gradual change from high- to low-energy sedimentary environments. The overall structural trend of the basin is oriented north-east, with a series of north-east striking troughs and ridges that locally controlled sediment deposition. Subsequent folding has produced broad, regional domes.

To assess the uranium potential in the Eromanga Basin the ***pmd****CRC* five-questions framework was adopted. This framework attempts to understand the whole mineralising system by addressing (1) the geodynamic and pressure-temperature histories; (2) the architecture of the system; (3) the fluid reservoirs; (4) the fluid flow drivers and pathways; and (5) the metal transport and deposition mechanisms.

To answer these five questions, the following studies were made:

- a literature review of the geodynamic setting for the Eromanga Basin and that of existing sandstone hosted uranium provinces. Data have been summarised in a series of space-time plots
- construction of a 3D map from publicly available datasets to better understand the basin architecture and fluid flow pathways
- compilation of water chemistry to map potential fluid reservoirs and transport mechanisms
- whole-rock and multi-element geochemistry together with detailed petrology, to understand uranium deposition mechanisms.

A review of the geodynamic setting suggests that there are potentially three discrete mineralising events in the western portion the Eromanga Basin, which correspond to periods of known uplift and erosion (Skirrow, 2009). In the east there is potential for a single, long-period, uranium mineralising event associated with the uplift of the Eastern Highlands. The 3D map of basin architecture shows that there are large, permeable sandstone packages that are bounded above and below by impermeable shales and that the sandstones are also exposed at the surface along the margins of the basin. This juxtaposition of lithologies is the most favourable architecture and fluid pathway for the formation of sandstone-hosted uranium deposits, because fluids can enter the sandstone through outcropping aquifers and be contained above and below by aquitards. Groundwater hydrochemistry datasets show regional redox and pH fronts along the margins of the Eromanga Basin related to the movement of oxidised, acidic meteoric waters through porous sandstone layers. Uranium is commonly precipitated at redox gradients, particularly in areas close to a uranium source (i.e. sandstones with elevated background concentrations of uranium and/or uranium rich Proterozoic rocks exposed at the surface as in the case of Mt Isa and Mt Painter Inliers).

The potential for sandstone-hosted uranium systems within the Eromanga Basin has been confirmed by recognition of uranium mineralisation at the Four Mile deposit hosted by Mesozoic and Cenozoic sedimentary rocks of the Eromanga Basin (per comm., Heathgate Resources, 2009).

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SESSION 04EB (ENVIRONMENT)

Organic geochemistry and chronology of the Macquarie Marshes, NSW

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The Macquarie Marshes are an internationally important wetland noted for its high biodiversity and role as a refuge for colonial breeding waterbirds. However this wetland system has been declining in the past 50 years due to the river regulation as well as grazing, clearing, fire and agricultural impact.

In this study, 12 surface (0-5 cm) samples and 59 core sections from 5 cores collected during fieldtrips from 2007 to 2009 were investigated. The aim is to reconstruct a chronological and geochemical history of the Macquarie Marshes, particularly focusing on the past 500 years, and to search for anthropogenic impact. Analysis consists of organic biomarkers by GC-FID (Gas Chromatography coupled with Flame Ionisation Detector), bulk organic carbon and nitrogen (TOC, TN, C/N ratio) as well as carbon isotopes ($\delta_{13}C$) by EAIRMS

(Elemental Analysis coupled with Isotopic Ratio Mass Spectrometry), and particle size distribution by laser Mastersizer. The sediment chronology is established by optically stimulated luminescence (OSL) using the single quartz grain method.

The single grain OSL data show that the sediments of the Macquarie Marshes are made up of quartz grains with complex deposition histories. The variation of OSL ages among the quartz grains from the same core section suggests that not all of the quartz grains were fully bleached before their burial in this fluvial system. With the application of the minimum age model, the groups of well-bleached quartz grains that provide the most reliable luminescence ages for these heterogeneously bleached fluvial sediments can be distinguished for age calculation. The OSL single grain dating technique has proven quite successful in dating fluvial sediments as young as 29 ± 5 years old. Age results also show that the upper 50 cm in Loudons Lagoon (northern Macquarie Marshes) and 70 cm in Bora Channel (northern Macquarie Marshes) are younger than 1000 years. Sedimentation rates estimated by the OSL ages are not uniform within given cores, reflecting irregular flood regimes. The sedimentation rate of the Bora Channel core accelerated from about 0.6 mm/yr to 8-16 mm/yr after European settlement. The reversed chronology found in some of the core sections may be explained by bioturbation by plant roots in the marshes where the roots of the reeds can grow to about 2-3 m deep. The dominant (>50%) particle size for most of the samples is fine organic-rich silt, commonly dark grey to black in colour. TOC values in surface samples range between 2 to 5% and commonly decrease down core to 0.05% at the deepest (more than 160 cm). Except for the surface and near-surface samples, TN values for the other samples are below detection. The surface samples display bulk $\delta_{13}C$ values of -23‰ to -26‰ and C/N ratios of 10 to 25, suggesting that the organic matter is mainly derived from terrestrial C_3 plants. The input of aquatic plants is shown by shifts to higher $\delta_{13}C$ values and lower C/N values in some of the core sections. This change of vegetation type is also supported by the aliphatic hydrocarbon biomarkers. In one of the cores from Bora Channel, the temporal variation of $(n\text{-}C_{27}+C_{29})/n\text{-}C_{31}$ indicates that vegetation displays an obvious change at 40 cm, ~ 180 years ago, with dominant grasses before 180 years ago and trees afterwards. Organochlorine pesticides such as DDT, DDD and endosulphan are being sought in some of the surface sediment samples, reflecting the introduction of pesticides by water flow to sediments mainly by cotton farming usage in the surrounding areas. The existence of polycyclic aromatic hydrocarbons such as chrysene and retene in some core sections suggests fire might have occurred either naturally during the drought period or anthropogenically due to land clearing campaigns for grazing or farming purposes. Therefore we infer that human activities have significantly impacted the Macquarie Marshes wetland ecosystems.

Using Mg/Ca as a tracer for 'ocean acidification' in recent marine sediments from the Great Barrier Reef

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The in atmospheric CO_2 over the past 50 years has mixed efficiently with the surface ocean. The result has been a global drop in the surface ocean pH of about 0.1. This process has been called 'Ocean acidification' or 'the other CO_2 problem'. Previous studies by this group have shown that high magnesium calcite (HMC) will rapidly re-equilibrate to a lower Mg content at a lower ambient pH. We found that samples taken by Maxwell and his students in the mid-1960s from the Great Barrier Reef were still available for study. This group analyzed hundreds of sediment samples from around the Capricorn Bunker group reefs and the adjacent Lagoon. This surface sampling was partially repeated by Geoscience Australia several years ago.

The original sediments were analyzed by x-ray diffraction (XRD) in the late 1960s we repeated the measurements using the same technique and discovered a uniformly lower Mg/Ca in the modern sediments when compared to the measurements made by the studies 40 years earlier. Many of the samples were taken from inter-reef areas where sedimentation rates are low and it is obvious we are measuring the same material that was previously analysed. We found drops in Mg/Ca in every environment, in a range from 0.9 to 1.4 mole per cent magnesium. This drop in magnesium concentration is consistent with a surface ocean that is slowly dropping in pH due to progressively higher partial pressure of CO_2 in the atmosphere.

Coral calcification in the central Great Barrier Reef: assessing the combined impacts of terrestrial runoff, global warming and ocean acidification

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Rising atmospheric CO_2 levels is decreasing the pH of surface waters, and thus a decrease in the saturation state of the oceans with respect to $CaCO_3$, in a process known as ocean acidification. This is believed to have a negative impact on marine calcifying organisms. Recent studies of scleractinian corals, have suggested this is maybe a possible cause for the decrease in coral calcification documented in the Great Barrier Reef (GBR) (De'ath *et al*., 2009). Much of the GBR, especially the inner parts of the central region is also subject to terrestrial runoff, which has increased significantly since European settlement (McCulloch et al., 2003). Furthermore coral bleaching events from abnormally high sea surface temperatures has also had a major effect on the reef. To provide a better picture of the most recent status of corals reefs in the GBR, and to understand the combined effects of ocean acidification, global warming and terrestrial runoff on coral growth, here we present geochemical and skeletal information from recent intensive sampling of massive colonies of the coral species *Porites* sp. Coral cores from these coral colonies were collected in mid 2009 from inshore, mid-shelf and outer reef localities of the central GBR, and represent a transition from a sheltered, more turbid, and terrestrial-influenced environment (inshore) to more exposed, less turbid, oceanic waters at the edge of the continental shelf (offshore). These continuous records cover mainly the last ~50 years, incorporating the period when the effects increased CO_2 due to anthropogenic activities should be most significant. We have determined annual calcification rates obtained from linear extension and density measurements on the coral skeletons, and employed positive-ion TIMS analysis of $\delta^{11}B$ composition of coral samples used as proxy for seawater pH. This information is complemented with LA-ICP-MS analyses of the geochemical proxies Sr/Ca, Mg/Ca, U/Ca, Ba/Ca and B/Ca.

Linear extension rates determined from inshore corals provide further evidence of recent decline in calcification. This decline seems to be strongly influenced by two particular events, a peak in extension rates during the 1960s and a marked decline associated with the bleaching event of 1998. This bleaching event has affected the majority of the colonies in the inshore region where a dramatic decrease in linear extension occurs over a period of at least 2 years following the bleaching. Preliminary $\delta^{11}B$ data results from one inshore coral shows and overall decrease with time that suggest a slow change towards more acidic conditions. The record also shows strong interannual variability that appears to correlate with discharge from the Burdekin River and suggest that the more acidic waters from their signal in the coral skeleton. We are currently analysing additional cores to ascertain if there is a relationship between decreasing in $\delta^{11}B$ and in linear extension rate. Our data suggest that episodic events like the 1998 El-Niño, where temperatures exceed a thermal threshold for corals, severally affect coral growth. If temperatures continue to increase these events could become more frequent and/or severe, that in combination with other stressors, like ocean acidification and terrestrial runoff could have devastating effects on the GBR and coral reefs generally.

Predicting the impact of ocean acidification on carbonate mineral stability in eastern Joseph Bonaparte Gulf

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The global ocean absorbs 30% of anthropogenic CO_2 emissions each year, which changes the seawater chemistry. The absorbed CO_2 lowers the pH of seawater and thus causes ocean acidification. The pH of the global ocean has decreased by 0.1 pH units since the Industrial Revolution, decreasing the concentration of carbonate ions. This has been shown to reduce the rate of biological carbonate production and to increase the solubility of carbonate minerals. As more CO_2 is emitted and absorbed by the oceans, it is expected that there will be continuing reduction in carbonate production coupled with dissolution of carbonate sediments.

This study was undertaken as part of a program to collect baseline data from the seabed environments over the Van Diemen Rise, which comprises a series of carbonate platforms and banks in the eastern Joseph Bonaparte Gulf, north-west of Darwin. Water and sediment sampling and preliminary sample analysis were carried out during a survey on board the RV *Solander* in August and September 2009. The objectives of this study were to: (a) characterise the distribution of surface water properties (temperature, salinity, pH,

dissolved inorganic carbon, total alkalinity) and surface sediment mineral composition, and (b) determine the thermodynamic stability of carbonate minerals as referred to the state of saturation.

At the time of the survey, surface water temperature and salinity varied between 27.0 to 31.1º C and 33.7 to 35.2 PSU, respectively, with higher temperatures and salinity in near proximity to the coast and lower temperatures and salinity further off-shore suggesting a longer water residence time on the inner shelf. The pH, total alkalinity and the dissolved inorganic carbon concentrations were measured using methods from Dickson and others (2007, PICES Special Publication vol. 3, 191pp). These properties varied little, with an average pH of 8.143, an average total alkalinity of 2221.5 µmol kg^{-1}, and an average dissolved inorganic carbon concentration of 2011.7 µmol kg^{-1} across all sampling sites.

Surface sediment minerals were identified by XRD and quantified using the SIROQUANT software. The magnesium content in high-magnesium calcite was determined from the d-space of high-magnesium calcite relative to the peak position of the artificially added calcium fluorite. The sediments are composed of quartz and carbonate minerals with a quartz abundance ranging between 5 and 80% reflecting the variable influence of detrital sediment. The carbonate mineral composition is relatively constant with approximately 30% calcite, 30% high-magnesium calcite and 40% aragonite. The mol% $MgCO_3$ in high-magnesium calcite varied from 10.5 to 16.6 mol% with an average of 13 mol% $MgCO_3$, which is close to the global average of 13 to 15 mol% $MgCO_3$ in high-magnesium calcite in tropical and subtropical regions.

The state of saturation for the different carbonate minerals (aragonite, calcite, high-magnesium calcite) was calculated for each sampling site from the ratio of the ion activity product and the solubility product. The carbonate ion concentration used for the ion activity product was calculated from total alkalinity and pH. The solubility products of the carbonate minerals were derived from literature data, e.g. the solubility for high-magnesium calcite as a function of the mol% $MgCO_3$ was based on experimental results by Plummer and Mackenzie (1974, American Journal of Science vol. 274, p. 61–83). The calculated average state of saturation was 1.4 (range: 0.8–1.9) for high-magnesium calcite, 4.2 (range: 3.4–4.6) for aragonite, and 6.4 (range: 5.1–6.8) for calcite. Values close to 1 suggest the mineral is in thermodynamic equilibrium with ambient water, which is the case for high-magnesium calcite. In contrast, aragonite and calcite are distinctively supersaturated. Given the near-equilibrium state of high-magnesium calcite, this mineral phase will likely be lost over a time scale of decades as ocean acidification progresses. This ongoing process will alter the sediment composition significantly given the high abundance of high-magnesium calcite. This study supports the concept of using high-magnesium calcite as an indicator for the progression of ocean acidification where surface sediments have been sampled and preserved over time.

SESSION 04SB (SOCIETAL: SALINITY)

Geomorphological influences on regolith distribution and salt store in the Moruya area, south-east NSW

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North and east of Moruya township, on the coastal plain east of the Great Escarpment in south-east NSW, the Moruya granite has weathered to form a sub circular depression approximately 10km across. This depression has subsequently been infilled with Quaternary to recent sediments of the Moruya River. The 'negative' relief caused by the differential weathering in this area is emphasised by the resistance of bordering granite and hornfels hills surrounding the lowland. There are four factors that may have contributed to the formation of a depression in this area, when elsewhere this granite has 'positive' relief. They are: the concentration of more readily weathered mafic minerals in this phase of the intrusion; the close spacing of structural features (e.g. joints); the preferential weathering and erosion in this geographical area because of the headward retreat of the palaeo-Moruya River and lateral erosion when this River encountered the more resistant hornfels; and the presence of salt in the river water which may have caused physical weathering due to the formation of crystals in void spaces in the weathering granite.

Today the Moruya River enters the depression from the west, through a valley in the surrounding hills and low hills and flows around the southern side of the topographic lowland and eastward out to sea. These resistant

hills are partially formed from hornfels associated with the contact metamorphic aureole around the granite, and partly with granite associated with regional structures in the west, and carved into by the Moruya River in the south. This configuration of weathering protolith together with the deposition of alluvial sediments from the river means that the regolith distribution, especially near the hills, is more complex than it first appears. The lowland area preserves terrace sequences and alluvial plains of the Moruya River.

The shallow 'cup-like' landscape depression also forms a significant hydrogeological feature in this landscape and influences the groundwater pathways. There is a net flux of groundwater from the escarpment, and localised flow associated with hill and low hill areas around the depression. There is also a tidal influence on the lower Moruya River, and lateral flux between the river and the alluvial sediments adjacent to the river. It is assumed that this influence has taken place throughout the period of deposition of alluvial sediments in the depression.

Understanding how salt is distributed and stored in this landscape is challenging. Further, the species of salt present in scalds and surface waters differ in different parts of the landscape. Careful mapping of the geomorphological features, and the inferred distribution of regolith materials in this landscape, helps constrain potential salt storage and distribution. This spatial data, coupled with proposed hydrogeological pathway information has enabled development of a conceptual model for salt storage and transport in the Moruya landscape. This understanding allows more strategic targeting of on-ground agricultural and urban salinity hazard management activities around Moruya.

Using the hydrogeological landscapes approach to identify and profile salt manifestation in the Boro Road area, near Braidwood NSW

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The town of Braidwood is located in the south-east of NSW, Australia. A biophysical approach to landscape classification, using the Hydrogeological Landscapes (HGL) method, was undertaken across the Braidwood 1:100,000 map sheet. This was used to identify areas where salt was manifesting in the landscape, or where there was high export or concentration of salts in-stream. The HGL approach to landscape classification identified the Boro Road area as having a high occurrence of land salinity, in conjunction with moderate salt load and concentration in stream.

Boro Road is located approximately 40 kilometres north east of Braidwood. In a regional geological context, it falls within the Palaeozoic Lachlan Fold Belt, while the local lithology is dominated by a felsic Silurian unit, known as the Long Flat Volcanics. Previous mapping conducted by the NSW Department of Environment and Climate Change has identified this region as an area with known salt outbreaks. Anecdotal evidence also suggests that it as an area where salinity and sodicity have been limiting factors with respect to agricultural production.

The biophysical classification of Boro Road indicated that the salt outbreaks were typically associated with one of the HGL units, known as Duckfield. Stream sampling and detailed regolith analysis was undertaken, on the Duckfield unit, to assist with the development of a conceptual landscape model, further define the fluid movement pathways within the landscape, understand where salt was manifesting in the landscape and inform land management practices in this area.

Mineralogical and geochemical analyses were undertaken on the regolith materials to better understand the processes present in this landscape. Soil 1:5 extracts were conducted to determine the electrical conductivity of the profile across the landscape. In addition, the 1:5 extracts were analysed to determine the major cations, anions and chemistry of the samples. Logging of the regolith materials and soil profiling has also assisted in the understanding of the distribution and nature of the materials in the Duckfield HGL. The information gathered from these analyses was used to determine where salts were present at the landscape scale, where they were present within a profile and the types of salts that were contributing to the salinisation of the landscape.

The understanding of these processes has been used to better inform the conceptual model for this landscape, including a better understanding of fluid movement and solute transport within the landscape, in addition to the nature and distribution of regolith materials and their physical and chemical properties. All this information has assisted in understanding water movement and solute transport mechanisms through the

landscape, in particular where and what types of salts are manifesting in the Duckfield HGL. This has assisted in developing a series of recommendation outlining appropriate land management practices for the Duckfield HGL and the parts of the landscape with specific management needs. These practices will assist in minimising the impact of salinity on soil and surface water health.

Impact of ephemeral streams on salinisation of soils and groundwater in western Victoria

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In many areas of south-eastern Australia subject to problems of dryland salinity there is a strong relationship between recharge and soil/groundwater salinity; areas of high recharge have relatively fresh soils and groundwater, due to flushing of salt through the system. This relationship was tested at a small-scale study site at Willaura in south-western Victoria. Here flat undulating plains (240–260 mAHD), consisting of unconsolidated Quaternary colluvial/fluvial deposits overlying fractured Palaeozoic metasediments, are intensively farmed. A single 35 ha paddock, crossed by a drainage line with 0.5–2 m of local relief, was surveyed for electrical conductivity and instrumented with recording piezometers.

The considerable spatial variability in EM31 conductivity across the paddock accurately reflected the soil and groundwater salinity, which were very high beneath the drainage line (2 mS/cm as $EC_{1:5}$ and 20 mS/cm respectively). This is the lowest elevation part of the paddock with the shallowest watertable, so this area is subject to greater evaporation and transpiration than other areas of the paddock with deeper watertables, concentrating salt in the soil profile. The salt is leached downwards by infiltration events and dissolves in the groundwater when the watertable rises.

The recording piezometers showed that the drainage line is the part of the paddock that receives the most recharge. After small rainfall events, water flows along the drainage line and recharges the underlying groundwater, so the watertable here rises relative to the rest of the paddock. MIKE-SHE modelling shows that overland flow from the sides of the drainage line is enough to create the localised raised watertable.

Only after major rainfall events is groundwater recharge relatively uniform across the whole of the paddock, and the drainage line changes from a recharge to discharge site as the watertable underlying the more elevated parts of the paddock rises.

Thus minor variations (a few metres) in surface relief across a low relief paddock affect the groundwater dynamics and cause significant variations in the salinity of the soil and groundwater. In particular, the area of highest salinity within the paddock is characterised by high recharge, in contrast to many other regions affected by dryland salinity in south-eastern Australia, where the more saline areas are zones of low recharge.

This has important ramifications for developing practical salinity management systems at the farm scale. Ephemeral, low relief streams may be the main areas of recharge and salinisation across much of the farmland of south-eastern Australia; replanting riparian vegetation along them will be important in reducing recharge and mitigating salinisation. Higher elevation parts of paddocks are leached of salt and present no agronomic problems, but feed surface water, groundwater and salt to topographic lows. Therefore management systems that decrease recharge would reduce salinity in the lower areas, e.g. agro-forestry, long-duration deep-rooting perennial pasture rotations and/or continuous cropping with stubble retention and minimum tillage in the off crop period, most usefully as mosaics across the landscape.

The ongoing controversies concerning dryland salinity in Australia: causes, assumptions, management and suspect science

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Dryland salinity in southern Australia has become a controversial issue, particularly during the past decade. This derives from a basic lack of understanding of the causes and processes involved, exacerbated by numerous incorrect assumptions and misinterpretations, which consequently affects management decisions and activities. There are basically two predominant models used to explain secondary dryland salinity in the literature, the rising groundwater model (RGM; also termed groundwater associated salinity—GAS) and the

surface water model (SWM; also termed transient salinity and non-groundwater salinity—NAS). Both models infer different processes and causes, which thence demand different management strategies. The RGM invokes excess water in the landscape, so much so that it has caused local and/or regional groundwater systems to rise to levels close to the surface. This groundwater, which is inherently saline, sometimes referred to as salt 'bulges', has apparently been lying dormant for millennia. The logic behind this model ascribes excessive vegetation (trees) clearing, generally from the hills, which thence apparently allows too much water to infiltrate the soil surface and percolate down to the groundwater (recharging it), causing the water levels down gradient, usually on the flats or at the break of slope, to 'rise' to the surface (termed discharge zones). This simplistic consensus model infers that hydrological processes are solely responsible for the problem whilst many other important synergistic factors such as processes occurring at the surface in the immediate area where the salinisation is expressed, are ignored. Conversely, the SWM (or NAS), has nothing to do with deep groundwater, relying upon lateral surface water accessions, or interflow, which generally occurs above semi-impermeable B horizons common in the natural duplex soils of southern Australia. Despite a plethora of evidence confirming that the SWM is the predominant salinity model occurring on the uplands of southern Australia, including the Murray Darling Basin, it is rarely mentioned in government reports and some academic circles. Indeed, the Australian Academy of Science and the CSIRO, Australia's two most respected scientific entities, promote the RGM but ignore the SWM. Inane statements bordering supernatural fanaticism can be found on these websites blatantly used to reinforce the RGM paradigm, such as '*The awakening monster from the deep*' and '*The great white beast that lurks below*'. In addition, although dryland salinity and associated sodic and saline soils are a natural phenomena across southern Australia, the majority of identified salinity expressions are referred to as secondary, rather than the occasional primary (naturally occurring) feature. This too has considerable obvious implications for sustainable management. An objective of this research was to holistically investigate the processes driving (secondary) dryland salinity on the uplands of south-eastern Australia. This was achieved by using geophysical, pedological, hydrological and biological attributes. No evidence was found linking increased soil salinity to a rising groundwater problem, rather, evidence indicates that the SWM provides the most appropriate explanation regarding the processes occurring in these landscapes. Secondary soil salinisation is a symptom of soil and vegetation degradation, not the cause. Many other associated symptoms are identified and discussed. As salinity is a natural phenomenon in these landscapes, and it is a degradation symptom exacerbated by poor management practices, especially intensive domestic stock grazing, it cannot be a 'threatening process'. It is not a process at all. The initial management activities must thence address the causes of the problem (subsequent to correctly identifying the problem), which is ongoing and/or unchecked (cumulative) degradation, followed by *in-situ* soil and vegetation remediation. Reducing recharge off-site as presently prescribed is usually considered irrelevant. Just when it appeared that rationality was prevailing and the SWM was being accepted as an alternative scenario, a number of reports were released in 2009 promoting the RGM for dryland salinity occurrences in New South Wales, whilst ignoring the SWM outright. Implications of this recent research will be discussed.

SESSION 04DB (DYNAMIC EARTH: GEODYNAMICS AND MINERALS)

Understanding the processes of mineral systems with synchrotron x-ray fluorescence mapping

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In order to understand the processes that operate within mineral systems it is important to consider micro-scale observations and processes and link these to the macro-scale. One technique to facilitate this is the use of multi-element chemistry, but it is critical to understand the residence and context of the anomalous elements. Another important use of the micro-scale, forensic approach is in better understanding metal sourcing and deposition processes in natural systems. This requires better spatial resolution and detection limits of the mappable components (i.e. trace Au) but also the ability to map larger areas (thin section scale) in order to understand the textural context at the site of deposition. Synchrotron x-ray fluorescence mapping (SXFM) allows us to rapidly map large areas for a full x-ray energy spectrum and use this data to develop maps of element concentrations at 2–5 µm with larger-scale textural context. One important application of SXFM is in coupling this mapping ability to techniques like XANES such that we can generate maps of multivalent elements (e.g. Eu; Brugger et al., 2006).

The x-ray fluorescence beamline at the Australian Synchrotron was used in conjunction with the CSIRO/Brookhaven MAIA detector (Kirkham et al., 2009). The MAIA detector is a large area SDD with 96 (and more recently 384) individual detectors in an array. This allows us to map at high velocity and hence collect large area element maps (whole thin section) in ~3–7 hours depending on the trade off between counting statistics and dwell time.

Examples from gold ore samples from the Archean Eastern Yilgarn (Western Australia) were used to with large area SXRF mapping in order to understand better chemical processes at the site of gold deposition. Samples were analysed at the Australian Synchtrotron XFM beamline (Paterson et al., 2007) in July 2009. Post-processing of the data is completed with the *GeoPIXE* software (Ryan et al., 1999). Data is collected using a raster beam where the beam dwell time and size dictates the length of time to collect the maps.

Average or sub-sampled spectral data is modelled to generate a dynamic analysis matrix (DAM, ref) which is used to model the full datasest to generate element images. The process of modelling data to generate a DA is critical in that selections of elements (and their contributing energy lines) can be turned on or off. The DA method allows the user to deconvolve complexly interfering spectral lines (such as W and Au), while deciding which elements to model based on the response from the raw data. This allows data to be collected without a-priori knowledge of all the important elements. However it should be noted that the SXRF technique relies on excitation by the incoming source energy and the user needs to tune the beamline energy to give the best overall result for the material of interest. In order to semi-quantify the data it is important to correct the energy flux coming from the sample which is a function of sample thickness, density and take-off angles. This data is also corrected using *GeoPIXE* and incorporated as a correction in the DA, however care needs to be given to complex geological samples that contain many matrix types. Typical gold samples used in this study contain sulphides, carbonates, and silicates, and so it is important to make a correction relative to the area of interest and may in some cases require the user to generate multiple versions of the images using different matrix corrections in order to get the best data. Where the samples are biological or single phase experiments this problem is typically negated. *GeoPIXE* applies the DA to the full dataset and generates product images for the elements chosen. These images can be large, upwards of 100 MPi with resolutions of 2 microns over cm-scales.

The key benefits of this technique are the ability to measure a full spectral response so that element signals can be derived through post-processing even without knowing about them before analysis, and the spatial context over larger areas. This presentation will discuss a typical workflow, the future of this technique and some advantages and pitfalls, as well as discussing results from Archean gold samples.

Shallow-dipping subduction beneath New Guinea and the geologic setting of the Grasberg, Ok Tedi, Frieda River and Porgera mineral deposits

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Late Cenozoic igneous activity in the central cordillera of the island of New Guinea at 137–144 E is associated with significant copper-gold and gold deposits at Grasberg, Ok Tedi, Frieda River and Porgera. The activity may have been triggered by uplift of the earth's surface and elevation and de-pressuring of the upper mantle as suggested by Douglas Mason in the 1960s, or by slab break-off and upwelling of asthenosphere as suggested by Mark Cloos and co-workers in the 2000s. Alternatively the activity may be related to southward shallow-dipping subduction of oceanic lithosphere from a plate boundary at the New Guinea Trench. Such a slab was interpreted from seismic tomographic profiles by Tregoning and Gorbatov (GRL 2004). Southward progress of such a slab beneath the island would explain the southward migration of igneous activity through the Late Cenozoic, at a rate of about 6 mm/yr, and the transfer of stress from the plate boundary north of the island to the southern front of the Papuan Fold Belt, a distance of 300–400 km. Any associated Wadati-Benioff seismic zone is not apparent in available earthquake data.

Cobar Superbasin architecture—control on the mineralisation

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The Cobar Superbasin is the most highly mineralised sedimentary basin in the Lachlan Orogen. It has an estimated pre-mining resource of 200 t of gold, 4.500 t silver, 2.2Mt copper, 4.7 Mt zinc and 2.8 Mt lead metal, mainly derived from the northern part, which hosts several operating mines: CSA, Endeavor (Elura) and Peak Gold. Major other deposits include Nymagee, Nymage-Hera, May Day, in the southern Cobar Superbasin and Wagga Tank and Mt Hope mine in the Mt Hope Trough.

The Cobar Superbasin is located in the Central Subprovince of the Lachlan Orogen in the central part of New South Wales, about 700km north-west of Sydney. The term Cobar Superbasin is introduced to refer to a series of deepwater troughs/basins, inferred to have formed as half graben and shallow water shelves occupied by the Late Silurian – Early Devonian Cobar Supergroup. The southern part, Mt Hope and Rast troughs comprise sediments, volcaniclastics, volcanic rocks, granites and minor limestone. The northern part of the Cobar Superbasin Basin comprises dominantly siliciclastic sedimentary sequences (up to 9km thick) with minor limestone and felsic volcanic rocks. During the Early Devonian, a carbonate platform, which subsequently broke-down during the advanced rifting forming patchy carbonate rifts, existed along the eastern basin margin. Basin sequences were inverted by combined *thick*- and *thin-skinned* tectonics in the Late Early Devonian and Middle Carboniferous Kanimblan Orogen. On the margins of the deep-water troughs, Silurian granites behaved as tectonic buttresses that controlled basin opening and basin inversion. The basin formed by NE-SW transtension and closed by NW transpression. The overall structural style of the Cobar Basin is NW-SE folding overprinted by NE-SW trending and NNW-trending eastwards oblique left-lateral reverse faulting.

The Cobar Style mineralisation, tectonically transposed and metamorphosed VMS mineralisation, turbidite and carbonate hosted Pb-Zn mineralisation (Sedex/Irish Style) and epithermal gold mineralisation are hosted in the syn-rift basin sequences controlled by favourable structural sites such as deflection zones of reactivated growth faults and intersection zones of marginal growth faults transfer/transform faults. MVT style deposits (Wonawinta) formed in the carbonate sequence of the tectonically stable Winduck Shelf.

The position of the reactivated growth faults on the basin margins and/or their intersection with transfer/transform faults controls formation of major mineral deposits such as Elura, CSA deposit and Cobar Goldfields deposits. In relation to the Cobar Superbasin basement architecture, the mineral deposits can be formed on the following locations:

- in proximity to major basin marginal faults (growth faults) with the maximum block down-throw (the intermediate size Au-rich (Cu) deposits: Cobar Goldfields, Peak, Queen Bee)
- in proximity to the intersection of growth faults with transform/transfer faults (the largest base metal deposits (±Au); CSA, Elura in the siliciclastics and small polymetallic deposits; Nymagee-Hera and Wagga Tank in the volcaniclastic and volcanics)
- in proximity of major transform/transfer faults associated with volcanic rocks (small size polymetallic deposits: McKinnons Tank, Mt Hope and May Day).

During basin evolution and diagenetic processes, the metal bearing fluids were focused by growth faults and associated transform/transfer faults into tectonic (blind faults, overlapping and deflected strike-slip faults) and stratigraphic traps (carbonates and sediments enriched in carbonaceous component) forming mineral deposits which underwent tectonic transposition and weak metamorphism during the inversion phase.

Manganese deposition associated with oblique extension during Mesoproterozoic basin development, Woodie Woodie Mine, East Pilbara

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Woodie Woodie manganese mine is located about 400 km east of Port Hedland in the East Pilbara, Western Australia. Manganese has been mined at Woodie Woodie since the mid-1950s and the mine produces a high-grade manganese product with an average grade of Mn 48%, Fe 5%. The dominant manganese minerals are

pyrolusite, cryptomelane and braunite and the orebodies range in size from 0.2 to 5.5 Mt, and are 50–100m wide and 100–600m in length. The manganese was considered for many years to have a supergene origin with an Oligocene age obtained by Ar^{40}-Ar^{39} dating (Dammer et al., 1994). However, subsequent work has shown that the manganese deposits are much older as they are commonly truncated by a Mesoproterozoic sandstone unit and are more likely to have a hydrothermal origin.

Mapping in the mine corridor by J. Drake-Brockman and the author has shown that the manganese orebodies at Woodie Woodie are generally irregular steeply dipping sheet-like to plug-like bodies (fault-hosted manganese) overlain by stacked bedding-parallel lenses (stratabound manganese). The deposits are generally located close to the unconformity between Archean Carawine Dolomite (including a thick carapace of deeply weathered dolomite; Pinjian Chert Breccia) and the overlying Mesoproterozoic Manganese Subgroup (part of the c. 1400–1070 Ma Collier Group of the Bangemall Supergroup, Martin and Thorne, 2004). The manganese at Woodie Woodie is closely associated with major growth faults that down-throw the Pinjian Chert Breccia into extensional basins which have then been infilled with basal Manganese Subgroup sedimentary breccias, sandstone and siltstone. Pb-Pb isotope ages obtained from Pb-rich manganese at Woodie Woodie range from 837 to 1150 Ma and suggest a possible range of fluid sources and/or mineralisation over a prolonged period (McNaughton, 2009), and are consistent with coeval manganese deposition and Mesoproterozoic sedimentation and basin formation.

A detailed structural model of the Woodie Woodie mine corridor shows that manganese is predominantly located on 2nd and 3rd order NE- to ENE-striking faults adjacent to major NNW- and NE-striking growth faults. The growth faults most likely acted as fluid conduits during the mineralising event. Fault orientations and kinematics at Woodie Woodie indicate that the mine corridor developed in a dextral transpressive regime adjacent to a series of major NW-oriented transfer faults. At a broader basin-scale, NW-SE extension is indicated by the dominance of NE-oriented extensional basins and NW-oriented transfer structures. Regional mapping shows that the Manganese Subgroup sequence thickens markedly to the south-east, suggesting the development of a basin-scale half-graben deepening to the south-east.

The fault pattern at Woodie Woodie represents the reactivation of a pre-existing structural framework established during rifting and deposition of the Fortescue and Hamersley Groups. Subsequent deformation events throughout this region have resulted in multiple reactivation and inversion of many early normal faults. A deformation history is now established for the Woodie Woodie region and includes:

- D_1 — extension associated with rifting and deposition of the Fortescue and Hamersley Groups;
- D_2 — NW-SE extension and development of local Manganese Subgroup basins (associated with manganese deposition);
- D_3 — NE-SW compression produced tight to open WNW- to NNW-oriented upright folds in Archean units and the overlying Manganese Subgroup (this folding is truncated by the flat-lying c. 850 ma Googenhama Conglomerate, basal Officer Basin (Grey et al., 2005) and may be related to the 1030–950 Ma Edmundian Orogeny, Sheppard et al., 2007);
- D_4 — E-W extension with formation of late NE- and NW-oriented grabens throughout the Woodie Woodie region;
- D_5 — N-S compression produces open E- to ENE-oriented folds and warps.

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SESSION 04LB (DYNAMIC EARTH: EARTH STRUCTURE)

Australian basins in 3D

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Determining the 3D architecture of sedimentary basins is vital for understanding many mineral and energy systems. With the continuing focus on energy security at Geoscience Australia, the 3D team within the Onshore Energy and Mineral Division has constructed an initial basin map for Australia in 3D.

To build the Australia-wide 3D basin map, input datasets were chosen for their national coverage, appropriate scale and consistency. To this end, OZ SeeBase™ (both the Phanerozoic and Proterozoic Basins datasets), 9 second digital elevation model (GEODATA 9 Second DEM version 3) and 250m Bathymetry (AusBath 09 version 4) were used as input datasets. When additional basin datasets become available, the Australian Basin 3D map will be able to be updated easily.

The following workflow was used to construct the 3D map:

1 For the four input datasets, ASCII X, Y, Z point sets were extracted from the original 2D ER Mapper™ grids and imported into gOcad™.

2 The point sets were converted into an optimised triangulated surface mesh. Surface optimisation adds triangles to the mesh, where more detail is required for a better fit to the original dataset, and removes them where they are not required. This significantly decreases the size and complexity of the final surface. Using the point sets as a constraint, Discrete Smooth Interpolation (DSI) was run between optimisation steps to mould the mesh to the point set. For the four datasets, overlapping surfaces were intersected, cut and removed to produce a watertight 3D basin map.

3 Sediment thickness was calculated and mapped onto the basin surface as an additional property.

4 The watertight surfaces were converted into a 3D geological block model (gOcad™ voxet) with a cell size of 5 km x 5 km x 100 m (X x Y x Z). As a result, various properties (for example, temperature, maturation, porosity, density, uranium concentration) can be assigned to the basin model in 3D.

An Australia-wide 3D basin map has several significant applications:

- As a constraint in any 3D potential field inversion. Unconstrained 3D potential field inversions are becoming increasingly common, as they produce a 3D magnetic susceptibility and density distribution model. By adding constraints, such as the 3D basin map and petrophysical properties, to an inversion, the results can be improved significantly.

- Assessing geothermal potential. Sedimentary basins are generally more thermally resistive, compared to crystalline basement, and therefore are good insulators, trapping heat within the crust, and hence increasing its geothermal gradient. By combining the Australian 3D basin map with thermal conductivity data, downhole temperature measurements and estimates of heat production, an assessment of geothermal prospectivity can be made for the continent.

- Assessing uranium potential. Several key uranium systems (for example, unconformity- and sandstone-related systems) are found in, or related to, sedimentary basins. By adding additional properties (for example, water chemistry, radiometrics, downhole natural gamma logs), and additional geological criteria, an assessment of uranium prospectivity can be made in 3D.

- As an input into a national scale 'whole Earth' 3D model. When additional national scale datasets (for example, depth to magnetic basement, gravity and magnetic inversions, depth to Moho, tomography, Sm-Nd isotope geochemistry, and earthquake data) become available, they can be integrated with the 3D basin map. By integrating disparate datasets together in 3D, new and more rigorous scientific insights can be made, which will lead to a better understanding of the evolution of the Earth and its resources.

The age of deposition and metamorphism of the Jack Hills metasedimentary belt from in situ U-Th–Pb geochronology of monazite and xenotime

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Metasedimentary rocks from the Jack Hills belt contain the oldest fragments of the Earth's crust—detrital zircon grains that formed up to 4.4 Gyr ago. Chemical and isotopic analyses of these ancient zircons have been used to make inferences about the nature of the early Earth, but despite the importance of the Hadean zircons, the age of the Jack Hills belt and its post-depositional history are poorly known. In this work, authigenic monazite and xenotime have been dated to constrain the depositional age and tectonothermal history of the Jack Hills belt, and thereby elucidate processes that have affected the host-rocks of the Earth's oldest crustal remnants.

The Jack Hills belt is located near the southern margin of the Narryer Terrane, an Archaean orthogneiss belt that forms the north-west corner of the Yilgarn Craton. The Jack Hills belt is a narrow, curvilinear, NE-SW trending belt ~70 km long and <10 km wide. It contains a variety of sedimentary rocks including quartzite, pebble conglomerate, banded iron formation, chert, quartz-mica schist and andalusite schist, and rare mafic/ultramafic rocks interpreted to be of volcanic origin. The metasedimentary rocks have been extensively deformed: the dominant structural feature is the Cargarah Shear Zone, an east-trending structure responsible for the sigmoidal shape of the belt. $^{40}Ar/^{39}Ar$ dating suggests that the shear zone was active during the 1.83–1.78 Ga Capricorn Orogeny. Grunerite in banded iron formation, and hornblende and calcic plagioclase in mafic schist, indicate peak metamorphism reached amphibolite facies but most of the siliciclastic rocks lack diagnostic metamorphic assemblages. The depositional age of the sedimentary rocks is not well constrained but until recently was thought to be Archaean based on Pb/Pb zircon ages of 2.65 Ga obtained from post-tectonic monzogranites in the region. However, some doubt remains as the contact between the intrusive and metasedimentary rocks has been tectonised, and more recent studies of detrital zircons have produced some unexpectedly young dates, 1.6–1.8 Ga, in some samples. Based on these younger zircon crystals, it has been proposed that some, or even all, of the belt may have been deposited in the Proterozoic, and that a post-1.8 Ga tectonothermal event affected the entire belt.

At Jack Hills, quartz-pebble conglomerate and quartzite contain detrital monazite and xenotime grains in heavy mineral layers. In situ SHRIMP geochronology of these grains, and also monazite and xenotime inclusions in detrital quartz grains, gives ages between 3.3 and 3.1 Ga. Conglomerate from Eranondoo Hill, which hosts abundant Hadean zircon grains, contains monazite intergrown with matrix muscovite that yields a weighted mean $^{207}Pb/^{206}Pb$ age of 2653 ± 5 Ma. This date is interpreted to be the time of metamorphic muscovite growth and provides a minimum age for sediment deposition. The conglomerate also contains authigenic xenotime that gives a $^{207}Pb/^{206}Pb$ age of 800 ± 25 Ma, which suggests that at least part of the succession was affected by a previously unrecognised Neoproterozoic event. Authigenic xenotime in conglomerate immediately east of Eranondoo Hill gives a $^{207}Pb/^{206}Pb$ age of 2660 ± 10 Ma, confirming late Archaean metamorphism. Metamorphic monazite in garnet-bearing quartz-mica schist from near Yarrameedie Hill in the middle of the belt records a $^{207}Pb/^{206}Pb$ age of 1858 ± 6 Ma, which likely reflects a tectonothermal episode related to the Cargarah Shear Zone. Several monazite grains from the schist indicate that the centre of the belt also experienced metamorphism at ~2.65 Ga. Massive magnetite-hematite ore in banded iron formation in the north-east part of the belt contains authigenic xenotime that yields a $^{207}Pb/^{206}Pb$ age of 3080 ± 20 Ma, indicating that at least part of the belt was deposited before 3.1 Ga. A second population of xenotime has a $^{207}Pb/^{206}Pb$ age of 1820 ± 25 Ma, reflecting a later episode of heating and fluid flow, possibly related to the Capricorn Orogeny.

The sedimentary rocks dated in this study were therefore deposited before 2.65 Ga, and in some cases, before 3.08 Ga, indicating that much of the Jack Hills belt is Neoarchean or older. The metasedimentary rocks, and the

Hadean zircons they preserve, have experienced at least four episodes of deformation and metamorphic mineral growth spanning more than two billion years (3080–800 Ma).

Late Jurassic–Early Cretaceous volcanism on the North West Shelf: onset of flood basalt volcanism? Evidence from high resolution seismic reflection data and outcrop analogues

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The NWS shelf suffered significant volcanism at the time of breakup in the Late Jurassic and Early Cretaceous. Most of the knowledge concerning this break-up comes from magnetic data, ODP legs and vintage seismic reflection data. Hydrocarbon exploration has progressed ever closer to the continent ocean boundary in recent years and in pursue of hydrocarbons, more high resolution 2D and 3D reflection seismic datasets have been acquired. Subsequently several new hydrocarbon wells were drilled. Together this new data offers significant insight into the volcanic evolution of the NWS margin and possibly the early phases of flood basalt volcanism. Most flood basalt provinces preserve little record of the early phases of flood basalt volcanism, either because they are currently too deeply buried, or obscured by younger flows. The NWS might be an exception mainly because the intensity of igneous and volcanic activity seems to be limited compared with other flood basalt provinces and therefore crucial in our understanding of volcanic margins. Examples are given from the Exmouth and Browse basins, offering insight in varied topics such as: sill propagation in structured basins, relationship between sills and volcanoes, volcanic geomorphology, timing and duration of volcanic events and the generation of volcaniclastics/hyaloclastites. Combined with outcrop analogues a more detailed picture is emerging. These results have important implications for diverse subjects such as geodynamics, volcanology, structural geology and global climate change studies. Knowledge will develop and increase with time as new hydrocarbons are being discovered in the frontier basins of the NW shelf.

$^{40}Ar/^{39}Ar$ geochronology of the West Kimberley Province lamproites: constraints on Australian plate geodynamics

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Although volumetrically insignificant and relatively obscure, lamproites and related rocks have attracted considerable attention due to their unusual mineralogy, geochemistry, depth of origin and the association (in some cases) with diamonds. Lamproites are also important for studying the evolution of the mantle, diatreme emplacement mechanisms and the origins of diamonds. Approximately twenty separate lamproite provinces are known worldwide, with most located along the margins of Archean cratons.

The Miocene West Kimberley lamproite Province (WKP) in north-western Australia incorporates four distinct (olivine and leucite) lamproite regions, termed the Ellendale, Calwynyardah, Noonkanbah and Eastern Lennard Shelf fields (Jaques et al., 1984a,b). The first three fields form a (~150 km) north-south lineament from the south-west margin of the Proterozoic King Leopold Mobile Zone into the Phanerozoic Fitzroy Trough. It has been suggested that this north-south distribution may reflect movement of the Australian plate over a (stationary?) mantle plume (e.g. Jaques et al., 1984a,b).

The objective of the current project was to investigate the above premise further, using high precision $^{40}Ar/^{39}Ar$ ages obtained from fresh magmatic lamproite samples (Gesocience Australia collection) collected across the WKP. Samples were selected from 21 WKP lamproites from all four fields. Mineral separates of euhedral phlogopite grains (but also wadeite and jeppeite) were prepared from this material. $^{40}Ar/^{39}Ar$ laser probe step-heating analyses of phlogopite and other mineral grains were carried out in the Noble Gas Geochronology and Geochemistry Laboratory at the University of Melbourne.

With some exceptions, the measured $^{40}Ar/^{39}Ar$ are broadly consistent with previous K-Ar ages reported by Jaques et al. (1984b) and Wellman (1973). Lamproites from the northern Ellendale Field yielded ages ranging from 21.00 ± 0.29 to 22.16 ± 0.12 Ma (errors are ±2σ). Samples from lamproites in the southern Noonkanbah Field yielded more variable ages, attributed to alteration, with the more consistent results indicating an age range from 20.13 ± 0.14 to 20.70 ± 0.65 Ma. One lamproite from the central Calwynayardah Field recorded an age of 20.83 ± 0.22 Ma, while the isolated Rice Hill lamproite from the Fitzroy Valley yielded an age of 19.12 ±

0.22 Ma. Only one lamproite was analysed from the Eastern Lennard Shelf Field giving an age of 20.26 ± 0.38 Ma. The unusual Walgidee Hills lamproite was dated at 17.45 ± 0.05 Ma.

The new $^{40}Ar/^{39}Ar$ results improve upon the precision of the existing K-Ar ages and provide new ages to previously undated lamproites. The data also confirm the north-south progression of lamproite ages in the WKP. Correlation of these new ages with their geographic location and the structural architecture of the area provide constraints on the geodynamic controls on the emplacement of the WKP lamproites. Possible models for emplacement of the WKP include: (i) emplacement of lamproites in response to plume magmatism, with the age progression related to northward migration of the Australian continent during the Miocene; and (ii) emplacement of lamproites along trans-lithospheric structures associated with the Proterozoic King Leoplold Mobile Zone and the Paleozoic Fitzroy Trough, with age progression related to sequential dilation along these structures.

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SESSION 04TB (TOPICAL: EARTH SCIENCE HISTORY)

Imaging the Australian continental crust and its margins—a chronicle of deep seismic profiling, 1946–2006

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This paper chronicles the history of the upsurge in the application of controlled source seismology during the second half of the 20th century and early 21st century that has enabled spectacular 3-D imaging of geological structures across the Australian continent down to the crust-mantle boundary and even deeper.

During the 1950s, Australian seismologists were very much aware of experimental deep seismic reflection work being done in North America and Europe. They made wide-angle seismic recordings from the Moho during atomic bomb tests in the South Australia and the data provided the first published studies of Australian crustal structure based on wide-angle seismic methods. The 1950s also saw the start of wide-angle recording of quarry blasts, experimental deep reflection recording, and onshore-offshore-onshore recording of marine shots around south-western Australia.

After the 1960 meeting of the International Union of Geodesy and Geophysics (IUGG) in Helsinki, the Australian Academy of Science became involved in the international Upper Mantle Project (UMP). This initiative coincided with a program by the Australian Government to conduct systematic geological and geophysical mapping across the whole of continental Australia and its margins as a strategic necessity.

During the 1960s there were a number of wide-angle seismic projects undertaken as a contribution to the Upper Mantle Project—BUMP, CRUMP, WRAMP, and FRUMP. In PNG there were two large seismic investigations around New Britain and New Ireland to investigate volcanic activity centres. There were some spectacularly successful experiments in deep seismic reflection imaging of the Earth's crust down to the Moho near Mildura, in the Ngalia Basin and in Western Australia.

The 1970s saw the introduction of long-endurance portable seismic tape-recording systems for wide-angle seismic profiling in the Australian region. Also, in 1976 BMR commissioned a 48 channel DFS-IV digital acquisition system for near-vertical seismic profiling. Technological improvements enabled more ambitious projects imaging of the Earth's crust. Huge Ord Dam construction blasts and the TASS project enabled wide-angle recording across the whole continent. Detailed wide-angle profiling was conducted in the Lachlan

Orogen, Bowen Basin, Pilbara region, MacArthur Basin, and in the Tennant Creek-Mount Isa region. In PNG a wide-angle seismic project was undertaken across the Papuan Peninsula. Near-vertical deep seismic experimentation continued in conjunction sedimentary basin investigations across the country.

The 1980s decade saw the start of systematic deep seismic profiling along transects that were many 100s of kilometres in length. Onshore, over 1000 km of deep seismic profiling was acquired across the basins of southern Queensland during 1980–86, and there were associated wide-angle seismic projects. There was deep seismic reflection profiling and wide-angle profiling across the hugh gravity features in central Australia. There was a profusion of seismic projects across Australia from the Yilgarn Craton to the New England Orogen. The mid-1980s saw the introduction into Australian waters of the research vessel 'Rig Seismic' capable of conducting deep seismic profiling of the Earth's crust across the Australian continental margins. Marine seismic profiling was conducted from the Lord Howe Rise to the Great Australian Bight to the Exmouth Plateau.

During the 1990s a huge effort was put into examining the marine continental shelf areas to the north of Australia, including ocean bottom seismograph surveys. Onshore, deep seismic profiling focused on 'hard rock' areas including the Yilgarn Craton, Mt Isa region, western Victoria, Broken Hill Block, and Tasmania. In 1997 the Australian National Seismic Imaging Resource (ANSIR) was established and took delivery of an improved data acquisition system and vibrator seismic source vehicles. During 1993–98 passive seismic recording became significant with the SKIPPY and KIMBA imaging of large scale crustal and upper mantle features

During 2000–2004 Australia conducted marine surveys aimed at establishing claims under international Law of the Sea legislation. Seismic profiling was conducted in ten offshore areas, including the offshore areas of Antarctica. Onshore, many seismic reflection programs were conducted in areas such as the Yilgarn Block, Curnamona Province, MacArthur Basin, Mount Isa Block, western Victoria, Lachlan-Thomson Orogen. Tanami Goldfields area and the Gawler Craton – Olympic Dam region.

Thus, in the sixty year period 1946 to 2006 our knowledge of the crustal architecture across the Australian continent and its margins has mushroomed from very crude ideas to very detailed knowledge in many areas. In future, equipment and computing advances will continue this trend towards enhancing our detailed knowledge of Australia's endowment of resource-rich provinces using seismic imaging techniques.

The evolution of naming and defining rock units in Australia: a story of cooperation for good communication

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Codes, guidelines, and standard practices for naming and describing Australian stratigraphic units have been discussed for more than 60 years since the Australian and New Zealand Association for the Advancement of Science (ANZAAS) set up a Research Committee on Stratigraphic Nomenclature in 1946. Like today's Australian Stratigraphy Commission, its aims were 'to encourage the orderly use of names and definitions for stratigraphic units'.

Australia was a pioneer in stratigraphic classification. The first Australian Code of Stratigraphic Nomenclature, published in 1950, was only predated by those of USA and Canada. Four editions of the Australian Stratigraphic Code were published: 1950, 1956, 1959 and 1964. The 4th edition was reprinted with minor alterations in 1973.

Geological investigations across the continent were expanding rapidly in this post-war period and rock, fossil and time terms were often used interchangeably. The Stratigraphic Code developed from a set of definitions and recommendations into a tried and proven guide that demanded adherence by geologists, and improved communication and understanding of Australian geology.

The development of an Australian Code of Stratigraphic Nomenclature went hand-in-hand with documenting the names already in use. The Central Register of Stratigraphic Names (or Stratigraphic Index) was started in 1949 and has continued ever since. The Register initially assisted with the publication of the Australian volumes of the International Stratigraphic Lexicon, containing the names, definitions and key references to the existing Australian geological units at the time. These volumes were compiled and published between 1951

and 1966, through co-operation between the State Surveys, the Universities and the Bureau of Mineral Resources (BMR). An index volume was published in 1975 and an international Antarctic volume was finally published in 1983.

In the meantime, in 1966 the Stratigraphic Nomenclature Committee, now under the auspices of the Geological Society of Australia, was invited to become the Australian organisational member of the International Subcommission on Stratigraphic Classification. This gave us the opportunity to contribute to international standards and guidelines. In 1976 the International Stratigraphic Guide was published and Australia adopted it in 1978. The Stratigraphic Nomenclature Committee continued to review and offer advice on Australian geological units and in 1985 published the 'Field geologist's guide to lithostratigraphic nomenclature in Australia', which discusses aspects of the International Stratigraphic Guide most relevant to Australia, explains special cases and describes Australian administrative procedures.

In conjunction with the work of the Stratigraphic Nomenclature Committee, co-operative efforts, especially between the State and Territory Surveys and BMR, continued and the Central Register was maintained as card files held in BMR, and updated as new publications were released. As early as 1974 the possibility of computerisation of the Register was discussed and in 1979 input to GEODX (the Geological Index database) commenced. Hardware and software has changed over the years, and in July 1995 the database was the first in the Australian Geological Survey Organisation (now Geoscience Australia) to become searchable from their website.

Since the 1980s the Stratigraphic Names Committee (now the Australian Stratigraphy Commission) has discussed and made recommendations on igneous rock nomenclature and sequence stratigraphy in particular. The committee has also eased restrictions on using similar names for different units, and allowed the re-use of some abandoned names.

Over the last decade, a regular column has been established in TAG (The Australian Geologist) for discussion of stratigraphic matters, including the description of sub-surface units on the basis of geophysical character. Access to both the current stratigraphic guidelines and the Australian Stratigraphic Units Database is now through a Geoscience Australia website (http://www.ga.gov.au/oracle/stratnames/index.jsp).

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A national scientific and economic masterstroke: the quarter-million geological mapping of Australia

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The geological mapping of the whole of the onshore continent was possibly the greatest scientific program that has been attempted in Australia. It occurred between 1948 and 1978 and was completely successful. The program is largely unknown to the public, or fellow scientists, or general historians (except Geoffrey Blayney

and a few others). It was followed by a huge growth in prosperity, and that prosperity continues and perhaps increases.

So, what happened to start it?

Well, for over a hundred years there had been hard work, and then more hard work, to try to understand the geology of whole States. These efforts culminated in attempts at a national understanding by people like Griffith Taylor who prepared books for the public. For professionals there was a top-level synthesis by T.W.E. David in 3 volumes with the title *Geology of the Commonwealth of Australia*.

The public at large continued to think of Australia in as a place too big to comprehend, peopled thinly by tough adventurous people who could ride horses, handle cattle, and get rich by opening small mines if they came across some mineralised rock.

A change happened because vertical aerial photographs were invented and were used in the study of known mining districts by AGGSNA (the Aerial Geological and Geophysical Survey of Northern Australia). That survey had found its feet by the time good information was needed for defence in World War II but adequate maps were often not available, and so in the Battle of the Coral Sea the plane crews were given pages torn from school atlases in Townsville, and carried geologists as guides.

After the war young and very energetic geologists, such as Reg. Sprigg in South Australia, could see that their States could and should be mapped in manageable time. They started to do it, with permission and without it. That adventure started at the grassroots level.

Sir Harold Raggatt recognised what was happening and used his World War II experience to swing into action with high-level State colleagues. The maps became a national program and were made by hundreds of people in hundreds of four-wheel-drive vehicles. There were over 500 large maps to be done, starting usually by using air photos to make base maps showing topographic features. The air photos, base maps and geological maps were each really a national program. The combined results were draughted and published in colour by large groups of superbly capable people, along with Explanatory Notes, Reports and Bulletins.The intellectual result was the first really good picture of onshore Australia. The economic result followed because the picture was used by mining entrepreneurs. (The history of offshore Australia was different and is not discussed here.)

1:250,000 geological mapping in Queensland—from black and white aerial photographs and Landrovers to integrated digital datasets

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Systematic 1:250,000 geological mapping of Queensland commenced in Queensland in 1950 as a joint initiative between the Geological Survey of Queensland (GSQ) and the Bureau of Mineral Resources (BMR). Mapping commenced in the north-west in the Mount Isa Inlier and Georgina Basin. Over the next 25 years, the rest of Queensland, totalling 119 sheets, was mapped, mostly with the support of the BMR, except in the south-east where seven sheets were mapped by GSQ alone. At least one GSQ geologist was generally included in each team, and in some cases GSQ geologists were the majority and even the project leader. The last area covered by BMR-GSQ first pass mapping was in the Carpentaria and Karumba Basins between 1968 and 1973 when field work for the Red River sheet was completed. At the same time, GSQ completed mapping of the Gympie Sheet north of Brisbane.

Most coloured First Edition maps were drawn at BMR, but a few were produced by the Department of Mines Drafting Branch. All were accompanied by explanatory notes. It was not until 1993 that the last coloured First Edition map, Maryborough, in the south-east was published by GSQ, and several other sheets in the south-east, Bundaberg, Gympie, Ipswich and Brisbane, have never been published in colour, although they are covered by coloured 1:100,000-scale and 1:500,000-scale maps.

As the first pass mapping was being completed, a new initiative to revise the geology of the mineralised parts of Queensland in more detail commenced, again with the support of the BMR. Two projects through the 1970s focused on Mount Isa and Georgetown. The output from these was mainly 1:100,000 scale maps, along with commentaries, but second edition 1:250,000 maps were subsequently produced for Mount Isa and two

1:250,000 special maps for Georgetown. GSQ continued to fund 1:100,000 mapping close to Brisbane and other cities as part of its Urban and Environmental Geology program.

With the withdrawal of BMR from systematic geological mapping in the early 1980s, GSQ secured funding to carry on the work in more remote areas, and set up mapping teams in the Hodgkinson and Broken River Provinces and later the Townsville hinterland centred on Charters Towers, where a field base was set up, and the Anakie Province in central Queensland. Resulting from this work was a combination of 1:100,000 and 1:250,000-scale maps. BMR geologists contributed to aspects that fitted with their more mission-oriented program.

In 1990, BMR underwent another review becoming the Australian Geological Survey Organisation, and with the National Geoscience Mapping Accord, returned to regional mapping. The North Queensland Project was initiated to revise the geology of Cape York Peninsula, which at the time was the focus of the multi-governmental, multi-disciplinary Cape York Peninsula Land Use Study. Four 1:250,000 sheets, Ebagoola, Hann River, Walsh and Red River were mapped, and for the first time, the data was compiled digitally. Regolith mapping also accompanied the more traditional mapping.

In the mid to late-1990s, GSQ undertook a program of 1:100,000 mapping in the New England Fold Belt, supported by airborne geophysics. From 2001, third pass mapping was started with reinterpretation of the geology of the Townville and Cairns hinterland using newly acquired geophysics that was not available in the 1980s. This was extended to the Mount Isa area in 2005, where a program of integrating all of the various datasets with new fieldwork has recently been completed. Areas beyond the outcrop area of the Mount Isa Province have been reinterpreted, both the surface geology using Landsat and radiometric data, and also the subsurface using magnetic and gravity data.

None of this recent work has resulted in publication of standard 1:250,000 maps. With digital compilation and print-on-demand techniques, GSQ has concentrated on producing seamless GIS, where scale is irrelevant, and publishing maps at 1:100,000-scale, accompanied by regional reports rather than individual map commentaries or explanatory notes.

Each stage has utilised new technology—black-and-white aerial photographs and the Landrover were the new technologies of the 1950s, followed by coloured aerial photographs in the second-pass stage. We now have a vast array of datasets and tools to assist us, but these cannot entirely replace boots on the ground.

SESSION 04WB (3D MINERAL SPECTROSCOPY OF THE EARTH'S SKIN—1ST NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM)

Abstracts for this session available on the Convention website www.aesc2010.gsa.org.au

SESSION 04RC (RESOURCES)

Coal seam gas in Australia

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Coal Seam Gas (CSG) in Australia, particularly Queensland, has grown in a few years from a glint in the eye for some far-sighted entrepreneurs to a huge industry, with several LNG trains currently being planned for Gladstone. This paper will trace some of the early pioneers and their history, outline the growth in both production and reserves, and discuss some of the issues which confront this new industry.

Coal seam gas (CSG) exploration commenced in Queensland in the 1980s. It was mostly led by visionaries of various hues including people like Bob Bell, Dick Groves, Ron Prefontaine, Steve Scott and Jim Butler Senior. The first four were associated with companies which in years to come grew into behemoths such as QGC and Arrow, while Jim's company discovered the Fairfield/Spring Gully complex. Some larger companies saw the possibilities early on the piece, such as Santos and Origin, while a number of even larger companies popped their toes in the water only to lose heart and exit the chase too early to make money. There were a number of

smaller companies who saw the opportunity in recent years to get into the game as it was taking off during the past five years. There have also been quite a few who found that, serendipitously, they held acreage which was highly prized as a CSG asset, but which had been actually picked up years before chasing an entirely different conventional play. Fortune favours the nimble of foot in this situation. There have been many winners and losers in the scramble over CSG in the past 20 years.

Production from CSG started around a dozen years ago. At that time, conventional wisdom was that:

- only the Permian coals would ever produce at economic rates (the few fields which were producing)
- the volumes would never be big enough to concern the conventional resource producers
- Jurassic coals were too thin, with too much associated water to ever be economic
- overall, CSG would always have to sell into the market at a discount due to the uncertainties of production
- long term gas supplies for the East coast markets would need to come from either the North West Shelf or PNG.

Slowly, over the late nineties and into the early years of this century, CSG gradually increased its market share and built reserves as Scotia/Peat and Fairfield/Durham Ranch (now Fairfield/Spring Gully) started to produce significant volumes and exploration and appraisal continued apace in both the Bowen and Surat Basins. By the middle of this decade, it had become readily apparent to those working close to the industry that both the Bowen and Surat Basins were probably going to work and work well.

The issues faced by the industry included:

- saturation of the domestic market
- the perception that CSG would always be risky, in terms of bankable reserves and production rates
- overlapping tenures, with coal, geothermal, Underground Coal Gasification and CO_2 storage tenures
- water disposal
- drilling, logistics and personnel
- capital expenditure and expertise in LNG
- acquiring and/or proving up sufficient gas for the planned projects.

Some of these issues are well on the way to being solved. For other issues, the solutions are still over the horizon and will require significant effort by the companies, various state government departments and the landholders and their representatives working in unison to solve. This presentation will discuss these issues in detail and outline the approaches being taken by the stakeholders to resolve them.

What of the next couple of decades? It is thought that by 2030, there could be up to 10 LNG trains on the eastern Queensland coast, most probably at Gladstone, but possibly trains in Townsville and Newcastle as well. This will, by then, be a vibrant long term industry in Queensland (Bowen, Surat and possibly Galilee Basins) and NSW (Sydney and Gunnedah Basins).

Development of an atlas of CO_2 geosequestration potential for NSW

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The process of regional characterisation is used to establish the carbon dioxide (CO_2) geological storage potential of an area before an actual site is selected. The purpose of an atlas is to facilitate the regional characterisation process at the country/state-scale screening stage. Geological storage of CO_2 involves the capture and separation of CO_2 from a source (such as a coal-fired power station or high-CO_2 natural gas field) then transportation (usually by pipeline) and injection into the geological subsurface for long-term storage. Certain geological conditions are required for subsurface storage of CO_2, such as a porous and permeable reservoir rock to allow injection and storage of the CO_2, overlain by an impermeable seal rock to retain the injected CO_2. Geological storage options for CO_2 include: saline aquifers, depleted oil and gas reservoirs

possibly with enhanced recovery, and enhanced coal seam methane (ECSM) recovery in unmineable coal seams. For the first two options, the CO_2 is preferentially injected as a supercritical fluid to minimise the required volume and the minimum depth to achieve supercritical conditions is about 800 m. In the latter case, CO_2 will be preferentially injected as a gas because gaseous CO_2 adsorbs onto the surface of the coal and is ideal between 300 and 800 m depth.

In NSW the data coverage at suitable depths (i.e. deeper than 800 m) is highly variable and is concentrated over the Bowen, Gunnedah, Sydney, and Clarence-Moreton Basins. Therefore, the storage potential of these basins can be evaluated with some degree of confidence. Data are sparse over the other sedimentary basins and therefore, their storage potential is very speculative.

Regional mapping is essential for determining the suitability of sections of basins for geological storage of CO_2. The NSW Atlas prepared by CO2CRC provides maps to assist in interpreting the key geologic, physiographic, and anthropogenic factors affecting CO_2 storage opportunities in NSW. The key layers mapped include: sediment thickness, coal depth and rank, anthropogenic CO_2 sources, natural geological CO_2 accumulations, existing energy and groundwater resources, geothermal conditions, hydrogeology, and civil infrastructure. A series of maps were also created to make a high level, qualitative, and illustrative attempt to identify those areas where there are social and environmental sensitivities that may affect the approvals process for carbon storage projects.

Sediment thickness and coal depth are important factors because the depth of injection dictates the volume of CO_2 that can be injected. Coal rank determines the capacity of the coal to adsorb CO_2 because lignite has poor storage potential compared to bituminous coal. To decrease the cost of a CCS project, a storage site needs to be proximal to the anthropogenic CO_2 sources that will be captured. Some coal seams and conventional natural gas reservoirs in NSW contain elevated levels of CO_2 that has remained in place for thousands to millions of years with no evidence of leakage. The presence of naturally occurring CO_2 in the sedimentary basins of NSW demonstrates the ability for long-term storage of CO_2 but also indicates a decrease in the total pore volume, because some pores are already occupied by CO_2. Existing energy and groundwater resource extraction activities were included because these could provide synergies or conflicts for a geosequestration project. Geothermal conditions were considered because temperature effects CO_2 density and hence storage capacity. Finally, a good understanding of hydrogeology is vital to a saline aquifer storage project.

Each sedimentary basin was evaluated with respect to the basin size, depth, porosity/permeability, existence of reservoir-seal pairs, tectonic stability, abundance of geological structures, geothermal conditions, hydrocarbon potential, hydrocarbon industry maturity, coal depth and rank and level of infrastructure and accessibility. Each criterion was assigned a weighting and the basins were then ranked according to their suitability for geosequestration of CO_2. The Atlas indicates that CO_2 storage opportunities in NSW still require more detailed consideration and more geological data. The complex geology of the state, coupled with the age and low porosity-permeability of many of the reservoir rocks will limit storage prospectivity in some areas but it is too early to 'write-off' the storage potential of NSW. The Atlas will help in prioritising areas for further study.

Igneous intrusions in the sedimentary basins of eastern Australia: implications for hydrocarbon generation and CO_2 storage potential

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This presentation investigates some implications for hydrocarbon exploration and CO2 storage potential assessment in a sedimentary basin affected by igneous intrusions. Several sedimentary basins of Eastern Australia including the Gunnedah-Bowen and the Surat Basin system (GBSB) have experienced significant igneous activity. Igneous intrusion emplacement in such basins represents a strong thermal and petrophysical perturbation on the petroleum system. The high temperatures associated with volcanic and magmatic activity may result in permanent changes in the surrounding rocks, either directly, or through circulating high temperature fluids affecting reservoir properties of both coal seams and sediments.

Numerous sills, dykes and plugs of alkali-olivine basalt and teschenite have intruded the Permian and Triassic sediments of the Gunnedah-Bowen Basin in New South Wales (NSW). Coals of these successions, heat-affected by the magma, have been varyingly altered, and thermal aureoles have been developed around individual

intrusions. The alteration occurred on many levels, from contact metamorphism of the organic and inorganic components of the sedimentary sequences to alteration of fluid and gas content and quantity, leading to widespread mineralisation and alteration of minerals such as carbonates and clays in coal cleats and pores in sediments. Given the limited seismic coverage in the region, and ambiguities in identifying intrusions, predicting areas of such localised thermal aureoles is, however, difficult. Uplift, faulting, and differential compaction due to igneous sills may generate structural hydrocarbon traps and add to the complexities in interpreting seismic data. Doming caused by igneous intrusions is probably a more significant trapping mechanism in the Gunnedah Basin and southernmost Bowen Basin than previously recognised, and is reported from several exploration sites. For example, the Lantern-1 well, drilled in the NSW portion of the Bowen Basin, tested the hydrocarbon potential of the Permo-Triassic section on an anticline formed by a Late Triassic gabbroic intrusion.

The economic implications of igneous intrusions can be very considerable. If an igneous intrusion takes the form of a sill following a major coal seam, coal may be lost (cindered) over a wide area. Alteration to a higher rank directly affects the coal's productive potential. While localised rank increases can occur as a direct and indirect result of these intrusions, the associated mineralisation or destruction of cleat surfaces can adversely affect coal seam gas quality and permeability. In coalbed methane (CBM) exploration igneous intrusions are commonly regarded as unwelcome phenomena, tending either to totally dispel seam gases, or to selectively replace methane with carbon dioxide. However, in contrast to the generally accepted negative view, igneous intrusions in the form of sills can have a beneficial effect on coalbed methane potential by providing additional gas generation and acting as impermeable seals.

High mole fractions of CO2 in natural gases pose a significant issue for hydrocarbon exploration and production in many areas around the world, particularly in sedimentary basins that have been subjected to some igneous or volcanic activity, such as the GBSB. The CO2 concentrations are highly variable, with seam gases in the GBSB ranging from pure methane to pure CO2 over short distances. Intrusions, especially sills and dykes, can result in the introduction of large volumes of CO2 into coal seams. The CO2 flushes out the methane, sometimes almost completely and is the carbon source for some carbonate minerals. The heat of the intrusions and accompanying CO2 changed the gas content and quantities of the coal systems in these basins, resulting in up to 98% CO2 content in some coal seam gases.

Many sedimentary basins containing extensive magmatic complexes are targets of hydrocarbon exploration and/or CO2 geological storage. Igneous intrusions into coal-bearing sequences occur in various forms and, if present, need to be considered in coalbed methane exploration and CO2 storage potential evaluation. On a basin-wide scale, igneous intrusion emplacement in the GBSB may be important due to the volume of coal and surrounding sediments they may affect. Igneous intrusions generate a hydrothermal system with important consequences for hydrocarbon maturation and migration, including chemical reactions and mass transport on the surrounding rocks (reservoir properties). Thus the sedimentary basins in which there has been widespread igneous activity require careful assessment for both hydrocarbon exploration and CO2 storage potential, as the intrusions potentially impact on both containment security and CO2 storage capacity.

Indian Gondwana coal and greenhouse gas control technologies

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Early to Late Permian coal of India associated with Gondwana Supergroup sequence is referred as Gondwana Coal, named after indigenous 'Gond' tribe of Jharkhand State in eastern India. The coal represents 99% of thermal and coking coal for India, with an estimated 22 billion tonnes of resource for the population of 1.1 billion people. Coal is the primary source of energy for power production for second highest growing global economy. Coal provides in excess of 60% of power for industrialisation, and current annual production of 350 million tonnes is expected to more than double with in ten years, Clarke et al, (1997). Majority of the Permian coal bearing basins of India are elongate, half graben structure, with one side marked by an unconformable contact between the coal bearing sequences and the basement rocks, and the other by syn-depositional boundary fault, Casshyap and Tewari,(1984) The basins occur, namely as the Damodar Valley Basin of east India, the Son-Mahanadi Valley Basin of east central India, the Pench-Kanhan Valley of central India and the Pranhita-Godavari Valley Basin of south central India, Raja Rao, (1983). In petrological characterisation coal has subdued lustre due to the presence of fine laminations (lithotypes) and association of finely dispersed mineral matter within dull and bright lithotypes. The dominant macerals are of vitrinite and inertinite groups with

minor macerals of exinite group. The inorganic components of coal include discrete minerals and trace elements associated with m the macerals and minerals, Singh, (2001). Future utilisation of coal in the developing economy appears to be conditional upon the development of effective technologies and uses in an environmentally acceptable way so as to favour reduction in green house gases. In order to meet the above India is one of the participant members of International Energy Agency (IEA). and the recently established Australian Global Carbon Capture and Storage Institute. Within India, a Coal Bed Methane Division has been established at the Central Mine Planning and Development Institute, Ranchi, and continuing pioneer work of Coal India and the Central Fuel Research Institute will enhance environmentally acceptable use of coal in India. Low Greenhouse Gas Technologies or Clean Coal Technologies include Integrated Gasification Combined Cycle, Coal Seam Gas, Underground Coal Gasification, Carbon Capture and Storage and the Fluidised Bed Combustion.

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SESSION 04EC (ENVIRONMENT)

Aminostratigraphy of Late Quaternary Gulf St Vincent, South Australia: amino acid racemisation dating of single foraminifera, *Elphidium*

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Gulf St Vincent is a semi-enclosed basin within the southern Australian margin. It is isolated from the Southern Ocean by the presence of Kangaroo Island, whose northern coast provides the southernmost margin to this basin. The Late Quaternary sediments from Gulf St Vincent have been the subject of several studies investigating changes in sea level primarily attributed to eustatic oscillations over Last Interglacial (MIS 5e, 125 ka) to Holocene time-scales (Cann *et al.,* 1988; Murray-Wallace *et al*., 1993). A significant discrepancy exists between estimated palaeo-water depths for the Gulf during MIS 3 (-22 to -30 m; Cann *et al*.,1988; Murray-Wallace *et al*., 1993) and that of the coral record at Huon Peninsula (-37 to -53 m; Chappell *et al*., 1996; Murray-Wallace, 2002; Waelbroek *et al*., 2002).

The aims of this study were to derive an amino acid racemisation based chronology for Gulf St Vincent using single *Elphidium* tests (foraminifers), and to estimate sea-level within the Gulf during MIS3.

Reverse-Phase High Performance Liquid Chromatography (RP-HPLC; Kaufman and Manley, 1998) was undertaken on samples consisting of single *Elphidium* and *Marginopora* (foraminifers) and multiple *Elphidium* tests, on single bivalve shells and on whole-rock samples. Accelerator Mass Spectrometric ^{14}C dating was undertaken on four bulk samples consisting of multiple *Elphidium* tests at ANSTO, the results of which were used for calibration of amino acid D/L ratios to obtain numeric ages. Uranium-series dating was undertaken at the University of Queensland on a single coral specimen, *Goniopora lobata*, recovered during this work from coastal outcrop at Kingscote, Kangaroo Island.

The utility of single *Elphidium* tests as subject material for AAR studies was examined using a visual preservation index and D/L ratios. After screening AAR results for covariance of racemisation among amino acids in each test, and for contamination, the results from 492 tests were utilised (63 rejected) from core SV#5, (394 of which were from the core section 0.53–3.85 m).

Our results indicate the foraminifer *Elphidium* can be considered robust for this type of study, and as a result an additional 177 individual *Elphidium* were analysed from 22 further sediment samples from core (n = 16) and outcrops (n = 6) in Gulf St Vincent.

Core SV#5 was differentiated into two units, Holocene and Marine Isotopic Stage 3, based on D/L ratios in single *Elphidium* tests, with the boundary at 52–53 cm. The mean calibrated age using all tests (mean glutamic acid D/L = 0.256 ± 0.022, n = 394 *Elphidium* tests) for the pre-Holocene section of SV#5 was 47,800 ± 8,100 a. Using only the best preserved tests (mean glutamic acid D/L = 0.260 ± 0.024, n = 256 *Elphidium* tests) this age was 49,300 ± 9,000 a.

Despite the differences in AAR methods between RP-HPLC (this study) and gas chromatography (e.g. Murray-Wallace *et al*. 1993), and the different sample types (principally foraminifer tests here, molluscs in previous studies) the conclusions are similar. Single foraminfer tests of Last Interstadial age are present in sediments in water depths of > 30 m, and suggest a palaeo-sealevel for Gulf St Vincent during MIS 3 of -20 to -30 m. This is higher than global estimates for this isotopic stage, yet consistent with previous estimates for this location. The presence of Last Interglacial age coral, *Goniopora lobata* at Kingscote, whose southern-most habitat at present is in Shark Bay, W. Australia, and Elizabeth Reef, eastern Australia, indicates a strengthened Leeuwin Current in Southern Australian waters during the Last Interglacial, and sea-surface temperatures 2–3° higher than at present.

Re-evaluation of microbial deposits from Shark Bay and their geologic significance

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Microbial activity in the Shark Bay World Heritage precinct represents the product of changing environmental characteristics due to abnormal water salinity and stressing conditions. The distribution and characterisation of microbial deposits and their sedimentary record are being re-evaluated using high resolution image interpretation and sediment data from field campaigns of sampling and coring at three distinct embayments inside the World Heritage area.

Microbial mats from tidal flats in Shark Bay are composed of different microbial communities that reveal distinct colors, texture, growing morphology and distribution. Despite the very gentle morphologic gradient, the bacterial communities live in very specific positions showing definite zonation related to different water depth conditions in the tidal environment. Parameters like salinity, water depth, turbulence, luminosity and accommodation space, associated with shore morphology, waves, wind direction and sediment influx are responsible for the occurrence and distribution of the microbial communities and their resultant organo-sedimentary deposits. Substrate morphology in Hamelin Pool displays an important role in controlling the presence of microbial structures like domical and club shaped heads in places with steep gradient contrasting with the mats on gentle gradient domains.

The interaction between microbial films, carbonate particles and organic-mineralisation produce distinct carbonate fabrics, characteristic of some microbial deposits. Fenestral fabrics produced during desiccation and oxidation of organic matter are responsible for the fenestral porosity that in many cases is still preserved in the geologic record and will be a distinctive characteristic of the resultant rock.

The embayment deposits recorded during the Holocene are composed on top of thin layers of microbial carbonate as upper part of a shallowing sedimentary cycle. Cores of the researched sites reveal that carbonate sediments represent a veneer (max. 0.50cm) over a sandy substrate and started growing after a maximum flooding of the sea level, gradually changing to a microbial carbonate system, during the actual high stand system tract (HSST).

The embayment areas are characterised by low and smooth gradients, restricted tidal influx and well defined tidal zonation. Seven different microbial communities were identified and their principal development and occurrence concentrate in the intertidal zone where strong insolation high salinity and daily chemical variability select and protect bacteria from predators. In the case of the dominant Pustular Mat the intertidal zone offers the best conditions to grow, responding to optimum insolation, coarse sediment supply and not excessive fine grain carbonate particles.

Bacteria take advantage of daily waves and tidal currents that slowly cover the very flat area, supplying sediment to the thin microbial veneer that is progressively adapting and expanding. However after the summer hot season severe erosion occur creating important deposits of dead microbial mat along the shoreline, composed mainly of Pustular Mat.

In the lower intertidal and near subtidal zone the high rate of fine carbonate sediment particles in suspension and being deposited prejudice Pustular Mat that is still small in size (less than 1cm high) and sparse because the pustules rapidly become filled by sediment that reduces insolation limiting growth. In these places different filamentous bacteria produce Smooth Mat composed of fine filaments that are able to permeate and trap sediments producing laminar fabrics in places with high sediment rate.

At Nilemah embayment the subtidal microbial community is responsible for the widest microbial deposits (600m average) producing extensive pavements, ridges and heads of microbial carbonate, mainly by Colloform globular morphologic deposits.

Organo-sedimentary deposits of stromatolites and microbial laminites are important markers in geological history whilst also being an important petroleum reservoir system. Microbial boundstone deposits with framework and vugular porosity are responsible for oil and gas reservoirs in NeoProterozoic to Mesozoic basins. Facies and fabrics of recent microbial deposits provide useful analogues for the understanding of ancient carbonate systems.

Preserved biomarkers in ephemeral saline lake sediments as constraints on inland regional evaporative regimes

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Australia today is widely regarded as a hot, dry place; a continent composed mostly of desert, fringed with trees. It was not always so: faunal and sedimentary evidence indicate that during the Tertiary, Australia's climate was humid-subtropical [1]. Decreased sea surface temperatures in the late Tertiary lowered the temperature and humidity of air masses penetrating the Australian continent, and Australia began to dry out. However, these changes did not affect all parts of the continent equally; moreover, they were accelerated by the onset of glaciation during the Pleistocene. In order to reconstruct the nature and extent of the changes that occurred with the onset of aridity on the Australian continent, we require multiple lines of evidence from diverse locations. Since Australia is an erosional continent, well-preserved continental sedimentary successions covering the last 200,000 years are sparse. As a new approach, we study lipid biomarkers preserved in sediments of playa lakes and use them as proxies to reconstruct regional climatic variation in south-eastern Australia through the mid- to late-Pleistocene. This period of time includes arguably 'the greatest environmental transformation of the last 20 million years'. [2]

Lipid biomarkers are chemical fossils that are diagnostic of the organisms that produced them and that are stable in rocks and sediments over geologic timescales. As such, they are indicative of the presence and, to an extent, the relative abundance of organisms within a paleo-community. By extrapolation, environmental parameters required for these organisms' survival in the present day can be used to reconstruct the conditions at the time when the biomarkers were deposited. Thus, biomarker data can be integrated with palynological, sedimentological and isotopic studies to refine climate reconstructions on a regional level, and also to provide information about the types of organisms that inhabited the region through time. However, as with macrofossils, the presence of indigenous biomarkers is dependent on the conditions encountered during deposition and diagenesis. Dry, oxic conditions are not conducive to biomarker preservation; unfortunately, playa lakes are intermittently dry, and desiccation cracks in the lakebed promote oxidation of sediments to depth. Therefore, it was necessary to test whether these environments would contain extractable quantities of indigenous biomarkers in deeply buried sediments.

We have extracted lipid biomarkers from a 13 m core taken at the north end of Lake Tyrrell, an ephemeral salt lake in north-western Victoria, where conditions through the mid-Pleistocene are less well characterised [3]. Despite variable oxidising and reducing conditions through the core and an average TOC content <0.2%, extractable biomarkers occur in clay-rich sediments deposited when the lake was fresh more than 500,000 years ago, and in evaporite-rich sediments deposited during the last 120,000 years. We have correlated biomarker suites to mineral assemblages for multiple subsamples throughout the core, and have confirmed biomarker syngeneity and the viability of paleoenvironmental reconstruction at the site. Sterol, isoprenoid and triterpenoid biomarker lipids have yielded the most specific information, indicating the existence and variability of populations of bacterivorous ciliates, gymnodinoid dinoflagellates, halophilic archaea and green

algae within the lake throughout its more saline period. We present quantitative analyses of the correlation between biomarker suites and mineral assemblages through the core; the ultimate goal is to construct a record of the effects of changing salinity and aridity on communities of organisms living within and around the lake.

Further work includes the use of stable carbon isotopic signatures of n-alkanes to determine the relative dominance of C3 to C4 plants in the area through time, possible use of long chain alkenones for paleotemperature reconstructions and compound specific radiocarbon dating of indigenous lipids combined with optically stimulated luminescence dating of quartz sands from the core to constrain the timing of environmental change at Lake Tyrrell from the Pleistocene through to the present.

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Radiocarbon dating of Archaeal lipids in microbial mats from an Australian salt lake

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Australian salt lakes are one of the only terrestrial records of climate change in Australia. However, salt lakes are notoriously difficult to date due to highly fluctuating sediment deposition rates and long periods of erosion creating considerable disconformities. Here we present a new strategy for dating salt lake sediments based on the isolation and radiocarbon dating of membrane lipids of halophilic Archaea. Lake Tyrrell, north-west Victoria, is a primarily groundwater fed hypersaline lake (salinity ~200 ppt), exclusively inhabited by planktonic and benthic halophilic Archaea and bacteria, and Dunaliella, a halophilic alga.

Conventional bulk radiocarbon dating of salt lake sediments is susceptible to contamination from multiple inputs (e.g. aeolian deposited carbon). Salt lakes also have particularly low organic carbon contents which can lead to errors in measurements when performing conventional radiocarbon analyses. To avoid these problems this study has focused on carbon sourced from the halophilic Archaea present in the water column of the lake. These organisms are deposited contemporaneously with sediments and the lipids of these organisms are preserved. These lipids can be extracted from the sediments and lipids specific to halophilic Archaea can be isolated and concentrated

Shallow (~15 cm) cores have been collected from the lake deposits which include microbial mats beneath a 1–2 cm salt crust. The cores have been sectioned into centimetre thick sections and extracted. Biomarkers of Archaea have been analysed by gas chromatography—mass spectrometry and radiocarbon dated by Accelerator Mass Spectrometry. These analyses require only micrograms of carbon and are therefore suitable for dating the low quantities of carbon in these extracts.

Microbiological and geochemical characterisation of the saline playa Lake Gnarpurt, western Victoria

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Lake Gnarpurt is located in the volcanic Western District Plains of Victoria, approximately 70km from the Southern Ocean and 130km west of Melbourne. At the present time, Lake Gnarpurt is dry. However, in the recent past, it was filled with saline water and surrounded by farmland. Since its drying, Lake Gnarpurt has been a significant source of airborne dust which has adversely affected local farmland by advecting halite over grassland and crops. Three sampling expeditions were undertaken—two summer trips in March 2008 and February 2009 and a winter trip in August 2008. Samples were taken from the dry surface of the lake as well as at heights of up to 150m above the ground using meteorological balloons and large kites.

The nature of the blown sediment ranged in size from clay to coarse sand, and originated from the lake floor that consists mostly of weathered basalt. We will present data on nutrient analyses of the windblown sediment which also yields blue green algal remains. Inorganic and organic geochemical characteristics of the lake floor, and how these relate to algal blooms that occurred in the lake when it was full, will also be reported.

Microbiological analysis showed variations in bacteria present between the summer and winter samples. There were greater numbers of bacteria found in the summer months, yielding a variety of taxa, with *Bacillus* being the dominant genus. The quantity of bacteria present in the winter sample was lower, but the diversity was found to be greater and evenly distributed across three different phyla—Firmicutes, Actinobacteria and Proteobacteria. Analysis of samples taken at differing heights showed that the microflora varied, but were a subset of those found on the surface of the lake.

SESSION 04SC (SOCIETAL: GROUNDWATER)

Regional mapping of palaeovalley groundwater resources in arid Australia

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The structural and stratigraphic remnants of geologically ancient rivers, many dating to at least the Eocene, are widespread across the arid interior of Australia. Changing climatic conditions throughout the Cenozoic have dried the continent to such an extent that surface water now rarely flows in these palaeovalley systems. However, the fluvial sediments which were deposited as valley-fill sands and gravels may function as high quality aquifers which are capable of storing and transmitting significant quantities of groundwater. In many of Australia's outback deserts such palaeovalley aquifers commonly provide the only reliable source of potable water available for remote aboriginal communities, pastoral stations and mining enterprises.

Geoscience Australia is playing a lead role in an innovative research project aimed at better understanding the characteristics and behaviour of groundwater resources in the arid zone. 'Water for Australia's Arid Zone—Identifying and Assessing Palaeovalley Groundwater Resources' is a four year research project which began in April 2008. Funding of $4.935 million is provided through the Raising National Water Standards program (RNWS), administered by the National Water Commission. The Australian Government's $200 million RNWS supports the National Water Initiative by funding projects that improve the national capacity to measure, monitor and manage Australia's precious groundwater resources. Geoscience Australia is working closely with state and territory government partners from Western Australia, South Australia and the Northern Territory to ensure the success of this investigation across multiple field localities.

Our preliminary research efforts have built upon the existing state-wide hydrogeologic and palaeovalley maps of Western Australia (Commander, 1989), South Australia (Hou et al., 2007), and the Northern Territory (Tickell, 2008). Initial work has focused on improving the regional definition and understanding of palaeovalleys across seven arid zone regions, namely the: 1. Paterson Province—Canning Basin (Western Australia); 2. Murchison Province (WA); 3. Tanami region (Northern Territory); 4. Ti Tree Basin (NT); 5. Lake Mackay district (NT); 6. eastern Eucla Basin—western Gawler Craton (South Australia); and 7. Musgrave Province (NT–WA–SA). We have applied innovative analysis to multiple national-scale GIS, remote sensing and geophysical datasets to enhance the mapped detail across these vast regions. Results thus far indicate that such methods are highly effective in generating new insights of the spatial patterning and distribution of palaeovalley systems, thereby increasing the resolution and accuracy of regional maps. The analytical datasets and methods which we have mainly utilised are:

- the latest processed version of the 1-arc second digital elevation model derived from Shuttle Radar Topographic Mission (SRTM) data (~30 metres resolution); this data can be used, for example, to generate long-profile (elevation) sections along palaeovalley reaches

- application of the Multi-resolution Valley Bottom Flatness (MrVBF) algorithm to the new DEM data, to demarcate the landscape and highlight the location of relatively flat and low-lying areas (typical of palaeovalley signatures) in contrast to steeper hilly areas

- analysis of thermal conductivity anomalies in near-surface rocks and sediments using pre-dawn imagery from the NOAA–AVHRR satellite sensor

- use of newly released national-scale geophysical coverages such as airborne magnetics and radiometrics data

- synthetic flow analysis using ArcHydro software tools, allowing reconstruction of possible drainage patterns and enforcement of preferred flow directions across the DEM surface.

Ground-truthing of selected areas will seek to validate the new palaeovalley maps derived from integrated remotely sensed and geophysical datasets. Fieldwork activities were initiated at several project sites in 2009, including the Lake Mackay and Ti Tree areas of central Australia and the Murchison district in WA. These operations have involved ground-based geophysical surveys (gravity and electromagnetics) to more accurately define the on-ground location of the palaeovalley thalweg, which represents the preferred drilling target for constructing water bores. In summary, the combination of innovative regional mapping techniques and targeted field investigations is proving to be a highly effective strategy for improving our knowledge and understanding of Australia's arid zone palaeovalley systems.

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Groundwater interactions in the Lower Murrumbidgee catchment, New South Wales

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The Lower Murrumbidgee catchment is in the eastern side of the Murray basin, and its hydrogeology is influenced mainly by the Shepparton, Calivil and Renmark aquifers. The area is semi-arid and groundwater is being increasingly used to supplement river water for irrigation in some parts of the catchment, to support major agricultural and horticultural industries. In order to use the groundwater sustainably, there is a clear need to understand the groundwater dynamics, including quantifying the amounts and rates of recharge, aquifer connectivity, groundwater-surface water interaction and the impacts of groundwater extraction and irrigation. The aim of the overall study is to develop and use element and isotope hydrogeochemical methods to understand the groundwater dynamics. In this presentation, we show the variation in water compositions across the catchment, in different aquifers and surface water, and infer the physicochemical processes that have impacted water composition.

Groundwater has been sampled from extraction bores and environmental monitoring bores and surface water has been sampled from the Lower Murrumbidgee River and Yanco Creek. To date we have approximately 180 bores and surface water sites between Narandera and Balranald (East-West) and south of Coleambally and Griffith (South-North), in particular in the Colleambally and Murrumbidgee irrigation areas. The extraction bores are typically screened in multiple intervals in the Calivil and Renmark aquifers, whereas the environmental monitoring bores are screened in specific aquifers, including the uppermost Shepparton aquifer. Water samples were analysed in the field for pH, EC, Eh, DO, alkalinity, and temperature, and Fe^{II} and S^{-II} in some cases. Major, minor and trace element concentrations were analysed in the laboratory using a combination of ICP-ES, -MS, IC and ISE. Duplicates, standards and charge balances indicate that uncertainties are typically within ±5%. Deuterium and oxygen isotopic compositions have been measured in approximately 80 samples.

pH_{GW} ranged from 5.39 to 7.46, and surface water (Lower Murrumbidgee and Yanco Ck) was in some places slightly more acidic or alkaline. EC_{GW} was mainly between 150 and 4000 µS/cm, with the exception of some samples that were greater than 11000 µS/cm. Groundwater from the Shepparton aquifer tended to have

higher total dissolved solids (TDS) than the deeper aquifers. Alkalinity$_{GW}$ was between 50 and 580 mg/L HCO_3^-. TDS increase in general from east to west, and from south to north, and the waters change from Na-HCO_3^- type in the east to Na-Cl type in the west. This probably reflects the increased water-rock interaction and residence time resulting from the westerly flow of groundwater. TDS are also higher to the north of the river, possibly reflecting longer-term irrigation activity in the Murrumbidgee Irrigation Area.

Major element concentrations and ratios (e.g., Na, Ca, Mg, HCO_3^- Cl, Na/Cl, Br/Cl,) indicate a combination of evapotranspiration, cation exchange (possibly reverse) and mineral dissolution and precipitation have affected groundwater composition. The groundwater compositions in the western parts of the catchment (west of Hay) show clearer trends in element concentrations and proportions than in the eastern parts, indicating that extraction and irrigation in the east are influencing groundwater compositions and probably enhancing mixing and interaction between aquifers. Deuterium and oxygen isotope ratios are close to the meteoric water lines, but tend to heavier oxygen and lighter deuterium, indicating some evaporation. The signatures from the shallow groundwater (e.g., the Shepparton formation) are similar to or lighter those from surface water (sampled in late summer), indicating summer recharge. Samples from deeper aquifers (e.g., Calivil and Renmark) are lighter in oxygen and deuterium than present day summer surface water, suggesting recharge from different seasons or older waters recharged under climatic conditions different than present day.

Acknowledgments

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Pilbara Coast Groundwater Study

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TEMPEST airborne electromagnetic (AEM) and magnetic data were acquired around the lower parts of the De Grey, Yule, Fortescue and Robe Rivesr in the Pilbara Region of Western Australia. This study expanded the understanding of aquifer geometries and groundwater salinity distribution within the region.

Where available borehole logs were used to assist the interpretation and regional magnetic data and radiometric data, Landsat 7ETM+, SRTM and geological maps were also incorporated into the study.

Basement geology of the De Grey and Yule areas consists of highly deformed volcanics which have been faulted/sheared along north-east and east-north-east trends. Also deformed, but largely to a lesser extent, are the meta-sediments and meta-volcano-sediments. The De Grey area contains highly magnetic ferruginous sediments, possibly representing the banded iron-formation (BIF) of the George Creek Group. Subsequently, everything has been intruded by a series of granitoids which vary in relative age.

Comparison of the basement interpretation against the AEM conductivity data provided little additional geological information, but was able to identify the seawater influence and a number of the controlling structures in the basement. There was moderate correlation with the current drainage within the Yule survey whereas no strong correlation with the current drainage was noticed in the De Grey survey

Basement geology of the Robe and Fortescue areas is a similar lithology with addition of ferruginous sediments and undifferentiated deep intrusives. Structurally, the Robe and Fortescue areas are quite different to the other survey areas to the east. Within this area the structural trends are dominated by north striking faults as well as late north trending dykes and minor east striking dykes. The normal component on the north striking faults has been inferred from the magnetic data and does not reflect the previously mapped geology.

The magnetic response of the ferruginous sediment in the central part of the survey areas shows a sudden change from a high frequency to a lower frequency from east to west suggesting an increase in depth to magnetic sources. In addition to this deepening of the sediments, the unit also appears to be indicating a change in dip from horizontal in the east to more vertical in the west. This is indicated by a magnetic texture change from mottled (flat lying), sub-linear (inclined) and linear (near vertical).

The comparison between the basement interpretation and the AEM data provided similar results as to the Yule and De Grey comparison. The presence of seawater and its possible structural controls were identified. A

minor correlation between the basement geology and AEM data is present indicating some structurally control on deposition of alluvial systems.

The significant contrast in conductivity between the unconsolidated sediments and the bedrock allows for the identification of the upper contact of the weathered bedrock. In addition, the availability of borehole data from holes that penetrated bedrock assisted in constraining the depth of this contact. A limited range of conductivity values generated surfaces that approached a close fit with the interpreted upper weathered bedrock contact. These surfaces were compared with available borehole data to assist in determining the most appropriate conductivity value to represent the top of weathered bedrock.

In the thicker aquifers of the De Grey and Yule Rivers the conductivity values appear to be dominated by clay material resulting in elevated conductivities. It is possible that in a small number of locations the presence of freshwater results in a reduction in the observed conductivities, though a reduction in the clay content could result in a similar effect. As distance from the main river channels increases there is little variation in the observed conductivity values of the alluvium.

In the De Grey area three palaeochannels have been identified in the conductivity data, one of which has been mapped with a high degree of confidence and appears to extend to the basement surface. This feature doesn't appear to correlate with any basement structures and is interpreted to be an erosional channel in the basement which has been infilled with alluvium. The mapped aquifer extents closely match the interpreted deep palaeochannel but are limited in the western extent.

The other palaeochannels have only been inferred and display a moderate to shallow depth extent in the conductivity data.

For each of the areas relative porosity maps were generated by selecting different conductivity bands to represent porosity. Ranges for each of the conductivity bands were determined by examination of the various electromagnetic datasets and comparison with the known and anticipated distribution of different lithologies.

In addition the salt water interface was mapped in 3D.

This information is now being incorporated into a groundwater model.

Northern Australia's water resources: the vitality of groundwater

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The high evaporation rates and long dry seasons of northern Australia mean that very few rivers—indeed, very few river reaches—flow year-round. Hence, all perennial rivers are highly valued, supporting endemic ecosystems, providing tourism and fishing opportunities and all have a high cultural significance for Indigenous and non-Indigenous people alike.

Critically, inland rivers that flow through the dry season are sustained by localised groundwater discharge. Discharge occurs where streams cross outcrops of shallow aquifers, or where deeper artesian waters puncture the landscape, generating springs. These localised points of discharge are few and the risk of impact from development is high. In these environments, ecosystems have adapted to streamflow conditions that are rainfall-dependent in the wet season and groundwater-dependent in the dry season.

Groundwater take in the north is currently very low, estimated at about 275 GL/a across the northern catchments, with extraction concentrated in the shallow carbonate aquifers in the Northern Territory and deeper Great Artesian Aquifers in northern Queensland.

Water tables in the shallow aquifers respond dramatically to seasonal rains, often rising and falling over 10 metres each year. Many shallow aquifers fill to capacity, draining slowly during the dry season. These shallow groundwaters generally have good quality water, with extractable yields determined by their capacity to recover each wet season. The annual natural rise and fall of water levels, however, means these systems generally have lower safe yields than deeper, regional systems and confined aquifers. There is also a risk of extraction reducing any streamflow of local rivers reliant on groundwater input. Where water allocation plans

are being implemented or developed in the Northern Territory, for example, all are resulting in caps to groundwater extraction.

In the east, deep groundwater supplies from the Great Artesian Basin are potential additional sources of water, with existing significant extractions for stock and domestic purposes. Further use requires more monitoring of groundwater dynamics to determine safe extraction levels; artesian springs provide the most important source of dry season flow for Queensland's northern rivers.

Groundwater recharge rates vary across the landscape, depending on soil type, vegetation and topography, as well as rainfall amount and other climate variables and depth to water-table. The complex interplay between these parameters means there is not always a direct correlation between rainfall and groundwater recharge rates. Soil-vegetation-atmosphere transfer modelling indicates that rainfall regime (rain per rain day, number of rain days) is critical, and a reduction in total annual rainfall can still result in higher potential recharge. Pathways for water infiltration to water tables can be complex and may change in importance through the year: Rivers may recharge aquifers during the wet months; discharging groundwater may keep rivers flowing during the dry months.

Groundwater data are very sparse for most aquifers across northern Australia, however, with large uncertainties regarding volumes that might be safely extracted. Increased extraction may have impacts downstream that currently cannot be fully evaluated, and consequences due to climate change can currently only be speculated.

Acknowledgments

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Upland swamps, siltstone aquitards and discrete interval borehole sampling in the Woronora Plateau of the Sydney Basin

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The Woronora Plateau overlies the Southern Coalfields of the Sydney Basin and supports numerous upland swamps in Sydney's water catchment area. Many perennial tributaries originate within these small upland swamps of several hectares size, which exist near the watershed divides in the dissected plateau. The swamps therefore form a critical component in the water quality and supply to the local environment and Sydney's water supply.

One upland swamp (15B) was sampled and characterised for comparison to the local geology and groundwater. The swamp and surrounding hillslopes were sampled from surface water and a series of piezometers. Field measurements, stable and radioisotopes and general chemistry were used to compare surface water to groundwater. The groundwater and geology were accessed via an open diamond core borehole about 500 m away on an adjacent ridge. The detailed geology was compared to previous nearby borehole logs. At the open borehole discrete 5 m intervals were isolated, sampled and measured using ANSTO's zone-of-interest groundwater sampler (ZOIGS). The target intervals selected were based on drill core and geophysical logging results that inferred naturally fractured near-horizontal layers of higher hydraulic conductivity, separated by siltstones or other coherent sandstones. Isolation of the fractured intervals was achieved using inflatable straddle packers, with vibrating wire piezometers measuring pressures above, within and below each isolated zone. Effective isolation by the packers and the siltstone aquitards was able to be confirmed by head differences and independent recovery curves of adjacent zones during purging and sampling. Calculations using Hvorslev's (1951) method were applied to recovery curves to infer the effective hydraulic conductivities for each isolated zone.

Tritium, deuterium, oxygen-18 and other geochemistry show that the lowest portion of the swamp, immediately above the outcropping siltstone lens, had a higher contribution of groundwater. Exposure of the iron-rich groundwater to the atmosphere just above the siltstone outcrop causes the dissolved iron to oxidise and precipitate, forming a localised ferruginous duricrust. It is the duricrust that seems to dictate the location of the basal rock bar of the swamp. Much of the sandstone underlying the swamp has become highly

weathered, probably due to organic acids and reduced conditions allowing silica dissolution and the mobilisation of clays. In comparison, the encrusted terminal or basal rock bars give a defence against nick-point erosion at the outlet of the swamp. This maintains the required low hydraulic gradient, allowing ongoing capture of sediments and organic material and preserving a perched water table within the swamps.

Two significant siltstone layers in the borehole core were found at similar elevations within the swamp and in two previous boreholes in the area, suggesting that they are quite extensive. Elevations of basal and mid-swamp rockbars of over 20 swamps in the local area show that many coincide with the calculated level of these siltstone layers allowing for the slightly dipping strata. The implication is that the aquitard properties of the unfractured, low hydraulic conductivity siltstones may have delineated the extent and be critical for the survival of the swamps.

BHP Billiton Illawarra Coal Pty Ltd supported this and other baseline studies to better understand the upland swamps before undermining proceeds. Longwall coal mining often leads to subsidence and fracturing of strata, and could result in changes to the surface to groundwater and aquifer to aquifer connectivities. Careful mine planning and consideration of the geological controls of upland swamps should avoid damage to these important features of the ecosystem and water supply in the Woronora Plateau.

SESSION 04LC (DYNAMIC EARTH: RESTLESS EARTH)

Oxygen and Hf isotopic constraints on 150 my of subduction-generated magmatism in the South Patagonian Batholith, South America: implications for tracking plate configurations and movements

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The Cordilleran margin of south-western South America has a 150 my record of subduction-related magma genesis in the form of the South Patagonian Batholith (SPB, 47–53ºS). Magmatic and inherited zircon components of the SPB provide a rare opportunity to examine this 150 Ma evolution. They also enable us to track changes in plate configurations and movements. Previous U-Pb zircon dating has shown that the oldest intrusions were emplaced during the late Jurassic (150–157 Ma ago), and in part are coeval with the waning stage of more widespread, mainly silicic, Jurassic volcanism in southern South America. The U-Pb age data also document that magmatic events were not continuous, but episodic through to the Neogene. The late Jurassic to early Cretaceous (~157 to ~137 Ma) and Neogene (~25–15 Ma) are notable periods of voluminous magma generation. Previous whole-rock Sm-Nd data highlighted a general progression through time from more crust-derived magma sources to those that are more juvenile. We have carried out SHRIMP oxygen isotope analyses and LA-MC-ICP-MS Lu-Hf data for previously dated zircon grains. These new isotopic data provide a far greater insight into the evolution of the South Patagonian batholith than was possible from U-Pb and whole-rock Sm-Nd data alone. The $\delta^{18}O$ values in the late Jurassic are high (ranging to +8) indicating crust-derived magma sources. They decline rapidly during the Late Jurassic and early Cretaceous to $\delta^{18}O$ values seen in zircon from mantle-derived sources (from +5.0 to +5.6) and even lower to values typical of hydrothermally-altered sources. This suggests that with the passage of time, the crustal sources were relatively quickly consumed by magma generation in the subduction process. Involvement of crustal melting gave way to primitive, and hydrothermally altered sources for the generation of the middle Cretaceous and younger plutons. The ε_{Hf} data support this model; the Late Jurassic magmas have negative values (ranging to -9), rising to positive values by the early Cretaceous and remaining so through to the Neogene. Significantly the Hf data indicate that whilst sources were primitive from the middle Cretaceous, they had already had a significant crustal residence time. The sympathetic behaviour of zircon $\delta^{18}O$ and ε_{Hf} with time can be linked to larger scale changes in plate configurations and movements, such as the closure of the Rocas Verdes Basin in the early Cretaceous.

Varying lithospheric rigidity during Paleogene/Neogene evolution of the south-west Pacific: evidence from the New Caledonia Trough

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The New Caledonia Trough is a broad (up to 200 km wide) bathymetric depression that extends from New Zealand to New Caledonia. The geometry of the trough is remarkably consistent along its entire length. Water depths are around 3–3.5 km within the trough and about 1 km on its flanks. Available evidence suggests that the crust is thinner under the trough than under its flanks (~15 km versus >20 km). The physiographic New Caledonia Trough is underlain by two distinct sedimentary basins, the New Caledonia Basin in the north and Aotea Basin in the south. These sedimentary basins are thought to have formed in response to aborted Cretaceous rifting related to the modification of the dynamics of the Pacific/Gondwana subduction zone.

There is mounting evidence that the New Caledonia Trough formed independently of and more recently than the Cretaceous sedimentary basins. Seismic reflection data show that the New Caledonia Trough is filled by a thin (~1 km thick) layer of horizontally-stratified post-Eocene sediments that onlap the trough margins. This suggests that deposition within the trough mostly took place after the trough formed. A lack of major basin-bounding faults suggests that the trough is unlikely to be a rift basin formed during Cretaceous extension. Instead, reflectors beneath the onlap surface that parallel the sloping sea-floor on the trough flanks are indicative of a post-Cretaceous sag feature. Deeper sediments representing the New Caledonia and Aotea Basins are affected by horst and graben structures that are more indicative of rifting processes. The thickness of these older sediments is roughly the same beneath the flanks and the axis of the trough, a further indication that the New Caledonia Trough is a distinct physiographic feature un-related to Cretaceous extension.

A positive free-air gravity anomaly of up to 20 mGal extends along almost the entire length of the New Caledonia Trough, but this is not expected over a trough and associated thinned crust of these dimensions. Crustal structures of this scale are formed under local isostatic equilibrium and, away from the trough margins, the corresponding free-air gravity signature would be near-zero. Despite this apparent inconsistency, the positive free-air gravity of the New Caledonia Trough can be explained by sediment deposition onto rigid lithosphere after the trough was formed in weak lithosphere (local isostasy). This apparent variation in lithosphere strength also adds insight into the region's thermal evolution.

Forward flexure and gravity modelling show that the body of trough-fill sediment is sufficient to explain the 20 mGal free-air gravity anomaly, but only if the underlying crust does not fully subside to compensate for the additional load of trough-fill sediments. If little subsidence occurs, then the positive gravity effect of the sediment body is not balanced by a mass deficit at depth. Support of a sediment load and the associated positive free-air gravity anomaly requires strong, rigid lithosphere. In the case of the New Caledonia Trough, modelling suggests that at the time sediments were deposited into the trough (post Eocene) the lithosphere had an effective elastic thickness of at least 30 km (cf. ~0 km at the time the broad and deep trough formed).

The large-scale geometry of the New Caledonia Trough and the positive free-air gravity anomaly related to its sediment fill suggest an increase in lithospheric rigidity after the trough was formed. Given that lithospheric rigidity is dependent on temperature, it can be inferred that the lithosphere was warm at the time the New Caledonia Trough formed, but that it cooled sufficiently to allow the subsequently-deposited sediments to be supported by rigid, strong lithosphere. Knowledge of this thermal evolution provides insight into regional heat-flow variations in the greater Lord Howe Rise region, an otherwise poorly-constrained hydrocarbon exploration frontier. The results also demonstrate the way in which gravity data can contribute to assessing petroleum prospectivity in frontier regions by providing constraints not only on basin geometry, but also on the thermal history of the lithosphere.

The seismic potential and 4D geodynamic evolution of the Vanuatu Arc

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The Islands of Vanuatu and Santa Cruz in the SW Pacific form a linear volcanic arc above what appears to be a relatively simple NNE-trending, east-dipping subduction zone (the northern and southern New Hebredes Trench). This dynamic region of the SW Pacific has been rocked by recent seismicity with several large

magnitude earthquakes (Mw>6.5) occurring approximately 150 kilometers north of the Island of Espiritu Santo. This sequence of high magnitude earthquakes combined with recently developed 3D models of the region, which include the subducted Australian plate and detached slab segments, has led to a more comprehensive understanding of the complex evolution of the Vanuatu Arc. These recent events can be explained by a model involving localised sub-horizontal shortening caused by the arrival of a buoyant section of subducting oceanic crust, the West Torres Plateau at the Solomon Trench. The formation of a vertical tear in the subducting Australian plate reduces the risk of high magnitude seismicity in the central part of the arc.

The Vanuatu subduction system is divided into two segments (northern and southern) based on the geodynamic characteristics and seismic potential of each zone. The northern section is characterised by the West Torres Plateau, a bathymetric high located within the leading edge of the Australian Plate. East-directed subduction of the composite Australian plate has led to the collision of the plateau with the northern New Hebredes Trench. Consequently, this section of the arc is almost completely locked.

Immediately south of the West Torres Plateau lies the d'Encrecasteaux Ridge. Approximately 45–50 Ma ago the ridge formed a strike-slip shear boundary along the northern margin of the now extinct New Caledonia Arc. This major plate boundary is subducting beneath the Vanuatu Arc. We suggest that the down-dip extension of the fossil plate boundary has developed into a sub-vertical slab tear. This tear has facilitated decoupling between the northern and southern parts of the subducted Australian plate.

South of the d'Encrecasteaux ridge, the subducting oceanic crust is relatively smooth so subduction is unimpeded. Instantaneous GPS plate motion data (Wallace et al., 2005) show that the southern Vanuatu Arc, which is located above relatively smooth oceanic crust, is moving to the WSW at up to 100 mm/yr. To the north of the ridge, however, upper plate velocities are reduced to almost 0. Differences in upper plate motion support a model involving independent subduction dynamics between the northern and southern parts of the subduction zone and therefore different seismic potentials.

Decoupling of the subducting Australian plate along the d'Encrecasteau ridge is manifest on the upper plate (the Fiji Basin) as two major active, but perpendicular, spreading centers referred to as the Hazel-Holme extensional Zone (HHEZ) and the Central Spreading Ridge. The point where the HHFZ terminates against the active New Hebredes Trench lies directly opposite the d'Encrecasteaux ridge. We suggest that this triple plate junction is critical for the evolution of the entire subduction zone. The south-western part of the South Fiji Basin is moving freely to west driven by ongoing and unimpeded subduction and hinge rollback. The northern part of the arc and North Fiji Basin remains relatively stationary and in a state of temporary lockup. We also suggest that the pole of subduction hinge rotation lies at the point of intersection between the spreading center, the West Torres Plateau and the Vanuatu Subduction trench.

The separation of the region into several independent plates and slab segments has resulted in irregularly distributed high magnitude seismicity. The potential for large magnitude earthquakes in Vanuatu and surrounding regions is not equal along the arc. Our interpretation suggest that the northern part of the Vanuatu Arc, where the West Torres Plateau enters the subduction zone represents a region of high seismic potential, however, decoupling of the subducting slab into northern and southern sections as well as breakup of the overriding plate into smaller, independent microplates suggests that the central part of the Vanuatu arc will react independently and is unlikely to experience large magnitude earthquakes. The recognition of tears and breaks in subduction has implications for the seismic potential of the entire SW pacific and other subduction systems worldwide.

Reference

Wallace et al., Geology; November 2005; v. 33; no. 11; p. 857–860; DOI: 10.1130/G21834.1

The Australian–Antarctic depth anomaly: interacting tectonic and geodynamic processes

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The Australian-Antarctic Depth Anomaly (AADA) is well-known as an unusually deep, hourglass-shaped section of oceanic crust that stretches from the Southeast Indian Ridge (SEIR) to both the Australian and Antarctic continental margins, with possible onshore extension. We quantify the roughness of each region, and remove

roughness attributable to spreading rate and sediment thickness variations to create a residual roughness grid. We find that the roughness of the AADA is explained by variations in spreading rate and sediment thickness, except where it is coincident with the Australian-Antarctic Discordance (AAD), a well-known anomalous tectonic feature associated with unusual 'chaotic' basement morphologies, which is much rougher than predicted based on spreading rates and sediment thicknesses. To understand the size and shape of the Australian-Antarctic Depth Anomaly (AADA) we compute a residual depth anomaly grid using new seismic data from the Australian and Antarctic margins to better constrain the thickness of sediments overlying oceanic crust. The resulting residual depth anomaly map reveals that the AADA is generally a broad 500 m depth anomaly that is not 'hourglass-shaped' on its western-side, although the eastern boundary is distinctly V-shaped. Within the AADA, it is apparent that very anomalously deep (>1000 m) oceanic crust formed at two tectonic settings. One is coincident with the Australian-Antarctic Discordance (AAD), crust younger than 20 Ma between 120°E and 128°E. The other encompasses the oldest oceanic crust adjacent to the Australian and Antarctic margins.

Many different models have been proposed to explain the anomalous roughness and depth of the AAD, and almost all invoke the presence of cold and/or depleted mantle, which is known to produce oceanic crust that is rougher, thinner and deeper than crust formed under normal mantle conditions. While the presence of cold/depleted mantle explains the formation of anomalously rough and deep oceanic crust since ~20 Ma, it fails to explain the formation, prior to ~20 Ma, of anomalously deep crust that is not also anomalously rough.

Many previous geochemical and residual depth anomaly studies have found that the V-shape of the eastern boundary of the residual depth anomaly is a result of the progressive westward incursion of Pacific-type mantle into Indian-type mantle. We therefore hypothesise that without the Pacific-mantle incursion, the residual depth anomaly would have formed a N-S trending band extending across the width of the Southern Ocean, with relatively linear eastern and western boundaries at approximately 115°E and 140°E. We investigate the possibility that the broad-scale residual depth anomaly is a negative dynamic topography feature resulting from the presence of an ancient subducted slab beneath this region.

The very anomalous depths (>1000 m) of oceanic crust adjacent to both the Australian and Antarctic margins can possibly be explained by the combined effects of ultra-slow spreading rates, which are known to result in thinner and deeper than normal crust, and the negative dynamic topography.

The highly unusual depth anomaly patterns present in the Australian Southern Ocean can be explained by a combination of the presence of a body of cold/depleted upper mantle beneath the SEIR, the incursion of Pacific-type mantle into the Indian-type mantle domain, negative dynamic topography related to an ancient subducted slab, and ultra-slow spreading rates.

The petrogenesis of A-type granite: an end-member of granite formation mechanisms

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Granite magmas are the result of either; 1. crustal anatexis, or 2. A combination of mafic differentiation coupled with crustal assimilation, or 3. closed magma chamber system fractional crystallisation. Although they are creatures of the continental crust, it is clear from Nd- or Hf-isotopes that many granite provinces have substantial mantle input. Our thermal modelling, and others (eg. Annen et al. 2006), conclude that the ability of mafic intrusions to raise crustal temperatures to their solidi is restricted by; prevailing crustal temperatures; the size of the mafic intrusion, and; the *meltability* of the crust. Modeling highlights two end members of the cooling history of magma chambers: 1. where the isotherm representing the solidus of adjacent wall rocks migrates out beyond the margins of the intrusion leading to crustal melting and assimilation. 2. where the intrusion never heats the wall rocks beyond their solidus temperature and cools within its own margins as a closed system. The first scenario predicts a time interval when the crustal anatexis 'front' migrates out into the wall rocks, possibly at a temperature buffered by invariant melting reactions. This thermal front will then retreat. S-type (C-type?) granite is the product of magma extraction from the crustal zone traversed by the migrating anatectic front. I-type (M-type?) granite is the product of assimilation of parts of the front by the primary mantle –derived magma chamber (e.g. Foden et al., 2002). The front will retreat back into the original magma chamber, and therefore the model predicts that the time-span of I-type magmatism will be prolonged beyond that of S-type activity. Magma chambers that do not heat the walls above their solidi will evolve by

fractional crystallisation yielding A-type melt. This will be favored by shallow-level intrusion in cooler crust. As predicted by Turner et al (1992) and then Marsh (2006), this may involve a crystallisation front whereby the siliceous residual liquid is trapped in a crystal network released by front foundering and compaction. The *Fe*-number is a discriminant of granites Frost et al (2001). A-types (Collins et al. 1982) are ferroan in the sense that they are depleted in Mg relative to Fe. This is an obvious indication of the role of fractional crystallisation in A-types compared to its lesser role in the generation of S- and I-types. A-type granites are also equally depleted in other strongly compatible trace elements (e.g., Cr, Ni, V and Sc). They are commensurately enriched in incompatible elements such as K, Rb, the REE, U and Th and are thus also often high heat production granites. The lesser depletion of Mg and other compatible elements in the S- and I-types results from buffering by maintained contact between the magmas and unmelted residual phases (pyroxenes, hornblende and biotite). (cf the 'resitite' of White and Chappell, 1977). Although A-type granites are more mantle-like than S- and I-types, Nd- and Hf isotopes indicate a small but significant crustal component. Modelling (MELTS and Pele) indicates that fractionation to produce A-type granite is optimal when the parental basalt or its mantle source is crustally contaminated at the start. Fractionation is dry, under low P conditions. A-type granites are typically post-tectonic and emplaced during stages of lithospheric extension following orogenic collapse. The events at the terminal stages of the Delamerian – Ross Orogeny provide good evidence in support of a scenario whereby orogenic termination was a result of delamination. and this may explain the origin of the contaminated mantle source of A-types and also a source for abundant eclogite xenoliths transported by Jurassic Kimberlite

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SESSION 04TC (TOPICAL: EARTH SCIENCE HISTORY)

Northern Territory—1st edition 1:250,000 mapping

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The first edition 1:250,000 geological maps for the whole of the Northern Territory were published by the Bureau of Mineral Resources (BMR) between 1961 and 1979.The field work was carried out between 1953 and 1975.

No systematic mapping of the Northern Territory had been carried out before 1953. Hossfeld's 1951 geological map of the Territory more or less summarised the state of knowledge at that time.

It was the discovery of uranium at Rum Jungle and other localities in the Katherine-Darwin area which led to the first systematic mapping at 1-mile to the inch; starting in 1953, by 1955 three parties of four geologists each were operating in the area producing 1-mile sheets.By the end of 1958 the whole of the Katherine-Darwin area had been mapped, mostly at 1-mile scale. Following Harold Raggett's vision of the mapping of the whole continent at 1inch to 4miles, and later 1:250,000, the six sheets covering the Katherine-Darwin area were the 'first cabs off the rank' in the Northern Territory and were published in 1961–62. From then on mapping at 1: 250,000 scale of each geological province and basin was carried out with one or two field parties involved in each. The last major province to be mapped was the Granites-Tanami in 1972–73. Remnants of the Arunta Complex not included in previously mapped areas were 'mopped up' in 1974–75 and the last first edition sheet was published in 1979.Major Bulletins were published on the completion of mapping each province and basin.

The BMR field parties generally consisted of 3 or 4 geologists, cook, mechanic and 2 or 3 field assistants. All parties were based out of Canberra and vehicles and stores were picked in Brisbane or Adelaide and driven up to the field. Food catering was planned ahead and most non-perishables were purchased in bulk from Brisbane or Adelaide. Once in the field a base camp was set up with office tent, cookhouse, mechanic's workshop and all modern conveniences (i.e. bucket showers and 'flaming fury'!). Geological traverses away from base camp lasted anything from a day to 2 weeks and when back in camp a day or so was spent plotting results etc; latterly a draftsman was included in some parties. After 1960 helicopters were used to access the more rugged terrain or scattered outcrops an earlier attempt to use a helicopter was frustrated by the helicopter's lack of power which meant that the geologist and pilot spent many hours clearing a take-off strip! One early problem was the availability of radio transmitters—each party was issued one transmitter for use in base camp and rarely was one available to take on traverse—this almost caused a fatal disaster when a vehicle broke down in an isolated area and the geologist spent a week in hospital suffering heat exhaustion after walking 30 miles over rough limestone country to get help. No OHS rules then!

Apart from the dedication of geologists and staff of the BMR, the success and relatively rapid production of this series of maps was due to the availability of aerial photography and base maps together with their photo-scale compilations.

The outcome was maps showing relatively detailed lithostratigraphy with names approved under the Code of Stratigraphic Nomenclature. Chronostratigraphy was no problem in the Phanerozoic, but in the Precambrian the main determinant was superposition and tectonic style. During the course of the mapping advances were being made in geochronology: samples of igneous rocks, mainly granites, and glauconitic sediments were dated by K/Ar and Rb/Sr techniques. These results combined with the known geology led the BMR to subdivide the Proterozoic into Adelaidean, Carpentarian and Lower Proterozoic (or Nullaginian) Systems. More accurate dating by SHRIMP has now made these subdivisions obsolete.

Some significant results as a by-product of the mapping include the discovery of the Mount Bundey iron and Groote Eylandt manganese deposits, the discovery of the Strangways meteorite crater and the presence of nappe structures on the margins of the Amadeus Basin. More indirectly the mapping led to the discovery of the Frances Creek iron and Alligator Rivers uranium deposits.

History of 1:250,000 geological mapping of Western Australia

Dennis Gee[1], John Blockley[1], Peter Dunn[1]
[1]formerly GSWA gurus

The mission to complete the 250K mapping of Western Australia as part of a national program was a contest of will and endurance. Talbot began systematic mapping of more remote WA regions at a scale of 1 inch:4 miles (1:253,440) in 1911. He (and others) produced all or part of 29 rectangles before he was unfortunately speared by aborigines, not fatally, but of sufficient seriousness for him to abandon the program.

First impetus for systematic mapping came with the creation of BMR in 1946. Its mandate *inter alia* was to 'undertake in cooperation with State mining departments, geological surveys and other work associated with exploration'. BMR began mapping the Canning and Carnarvon Basins in 1948. Such was the swiftness of this 'invasion', that Chief Government Geologist Matt Ellis sent a solitary graduate geologist to keep an eye on the BMR at Exmouth. Jack Sofoulis thereby became the first GSWA collaborator with BMR on a mapping program.

Over the ensuing decade, BMR published eight 1 inch:4 mile sheets. Matt Ellis gave grudging acceptance to BMR mapping in the sedimentary basins, but 'hard rock' provinces were GSWA territory. In 1956, under pressure from BMR, Ellis sent geologists to Marble Bar, Nullagine and Balfour Downs to instigate GSWA's participation. In 1962 the last of the 1 inch:4 mile sheets were produced.

In 1961 incoming Director Joe Lord restructured GSWA into Regional Mapping, Mineral Resources, Sedimentary Basins and Engineering and Hydrogeology Divisions. He then promptly deployed most geologists on regional mapping.

This was the springboard for independent modern-era standard-series geological mapping in GSWA. Excellent work was done in the Hamersleys, where geological teams elucidated the stratigraphy of the iron formations. Mineral resource geologists were scattered to mineral-poor provinces, hydrogeologists were banished to the Kimberley, and regional mappers opened windows in mineral provinces.

The nickel boom caused substantial delays due to staff losses and several waves of recruiting were necessary, the majority coming from British institutions. Following the nickel boom momentum was regained, and with the appointment of a Regional Mapping Supervisor dedicated to the mission, GSWA established integrated multi-member parties, working concurrently on adjacent sheets, tackling individual tectonic units, with frequent field reviews by all involved geologists. This was something GSWA had not done consistently before. There ensued a decade of staff stability, high productivity, team enthusiasm and map consistency.

Our modus operandi was two geologists per map sheet, each with a Land Rover and a field assistant, on weekly fly camps, and generally sharing an office caravan in a central field location. Field stints were either 3 lots of 8 weeks or 2 lots of 12 weeks. As far as we know there was only one default.

Unravelling the mysteries of the Archean shields demonstrated that regional mapping was indeed worthy research. We brought in academics generally with mutual benefits. But some universities derided our work as 'only reconnaissance' and followed us with less memorable results.

One memorable output of this campaign was the production in 1979 of a State 1:2.5M geological map on which the presentational problems of legend structure in the Precambrian were largely solved by integrating traditional litho-stratigraphy with radiometric dating, in a move to a chrono-stratigraphic framework.

The high productivity of the 1970s and early 1980s occurred at a time when BMR was enduring several reviews, the core issue being its role in regional mapping. Specialists in basin analysis were engaged in the Officer Basin, but BMR participation was absent from Precambrian terrains except the Yilgarn Craton, where GSWA 'borrowed' some first-class veteran field mappers in 1979 to help complete the Lord's Mission. Regional mapping was an unfashionable word in Canberra in the 1980s. This changed after the Woods Review and the NGMA of 1990, and BMR resumed Yilgarn mapping, this time at 1:100k scale, in 1993.

Constant prodding by Joe Lord was a major stimulus; he threatened not to retire till the mapping of the State was done. By 1979, fieldwork in the final holes in the Yilgarn was complete, and Joe retired. But the finish gun could not be fired till 1986 when Kellerberrin and Corrigin Maps and Explanatory Notes were released.

On reflection, the quarter million mapping standard was just right to build the regional tectonic framework. One cannot efficiently build up from 1:100k. Similarly one cannot effectively scale down from 1:1M to get the picture. The Chief Government Geologists Conference of 1950 got it right.

Regional geological mapping in South Australia

Robert Dalgarno[1]
[1]self-employed

South Australia has a proud history of post-World War II geological mapping by the Geological Survey or divisions of the various government departments, namely the Department of Mines, then Mines and Energy and Mines and Energy South Australia (MESA) and today's PIRSA. The mapping focused on minerals and energy exploration, firstly for uranium, then for further coal basin discoveries after the initiation of mining at Leigh Creek, and finally as a stimulus to industry search for minerals and petroleum from the late 1950s. This latter phase continues through to the present day with initiatives for second-round 1:250,000 scale mapping of geology and geophysics and accent on increasing detail as digital packages.

1:250,000 scale mapping of South Australia started from 1960. Before this there was a series of 1 mile maps (1:63 360 scale) and 4 miles to the inch (1:253,440 scale) maps and for areas of interest around the State. The larger scale maps focused on the South East and Kangaroo Island, (1951 and 1954). Others like LINCOLN, MAITLAND and INVESTIGATOR followed up to 1961. The Olary Special was a notable contribution arising from mapping by the Mines Department to support uranium development at Radium Hill. Regional mapping was also carried out in the mid to late 1950s in the Mount Painter Inlier. These were mapping parties based on shearer's quarters and supported by a cook and mechanic. Much of the work was done in pairs from a vehicle and fly camp but some geologists traversed alone on foot for several days to a week without a vehicle in rough terrain. This early phase of mapping depended upon availability of aerial photographs and time availability by officers whose main task may have been related to examination of old mines, regional chemical sampling, assessment of regions for iron ore, coal or groundwater and engineering projects, etc. The work also depended on compilation of suitable base maps by National Mapping, the Army Survey Branch, the Department itself, and also the internal limitations of compilation, drafting and scribing of the geological maps for publication.

Thus, although the need for State-wide geological mapping at 1:250,000 scale was recognised by 1960, a number of the maps were assigned to individuals of various Divisions of the Department as long term projects, and were subject only to editing scrutiny by the Senior Geologist of Regional Mapping. One important step in systematising the mapping of the State was the introduction, in the early 1960s, of formal Rock units consistent with the Code of Stratigraphic Nomenclature.

Relationships with the Bureau of Mineral Resources were constrained somewhat by the politics of the time. South Australia was desperate to find energy resources and undertook 1-mile to the inch mapping in the region of Leigh Creek in the 1950s. Much of the subsequent mapping was carried out on Government approval to find similar coal basins in the Flinders Ranges area as feed for the Port Augusta power station. Premier Playford was focused on South Australia's independence from the Federal Government's mapping program and wanted to manage his own priorities. In South Australia, the mapping projects were frequently long term and the responsibility of an individual working for managers with varying objectives. Many final map reports were not completed. In contrast, the BMR was more systematic and sent out annual field parties with a program of designated 1:250,000 map sheet areas to complete in a four to five month field season. There was then a 'write up period' for final compilation of map and detailed Record before the next mapping season. This did not apply in South Australia.

Mapping in the first phase of the 1960s and early 70s was rarely carried out with available regional geophysics and the Department was largely reliant on an agreement with the BMR for airborne magnetic surveys. South Australia had its own seismic survey team for basin appraisal which was run systematically in remote areas. Regional geochemical chip sampling and drilling formed part of the Departmental program as a result of the close affiliation with the Australian Mineral Development Laboratories, which was originally its own Analytical Branch. Isotopic dating, which played an important role in mapping by the late 1960s, was initially done in collaboration with Canberra.

Discussion of the second round 1:250,000 mapping program and the influence of the Chief Government Geologist's Mapping Accord in the 1990s will require a more comprehensive approach. The introduction of digital mapping techniques has introduced great changes to the procedures and presentation of geological maps. There is a debt owed to the pioneers in regional geological mapping of the State. This debt is the scope and scale of mineral and petroleum discovery of the late 20th Century.

History of 1:250,000 geological mapping of NSW and ACT

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Geological mapping has been an important element of activities of the Geological Survey of New South Wales since its establishment in 1875. The Geological Survey's investigations into the mineral resources and geology of the State have provided strong support and an effective framework for coal, mineral and petroleum exploration and development.

The 1950s saw the commencement of the standard series geological mapping program. The program arose from the realisation that a systematic approach to mapping was necessary in order to provide a sound scientific basis for discovery and development of the State's mineral resources. A scale of 4 miles to the inch, subsequently changed to 1:250,000 was chosen as the most appropriate for the purpose.

Between 1952 and 1962 seven map sheets were published at a scale of 1:253 440 (later converted to metric), four by the Bureau of Mineral Resources Geology and Geophysics (BMR) and three by the Geological Survey. In 1962, four geological sheets were compiled at a scale of 1:250,000 for the first time. Field work was also completed on the eastern one-third of the Canberra 1:250,000 sheet to allow publication of a second edition Canberra sheet by the BMR.

The period 1964–1975 was a time of significant achievement. Over 40 full colour geological maps at a scale of 1:250,000 were published. Although largely reconnaissance in nature, they fulfilled the aim of providing almost a statewide geological map coverage. The program included reconnaissance mapping of many areas that had not been previously mapped. This program was initially driven by Len Hall and subsequently by Toby Rose.

A systematic metallogenic mapping program at a scale of 1:250,000 commenced in 1969 and the first map in the series, Bathurst, was published in 1973. This program of metallogenic mapping was completed in 2001,

with coverage of all areas of significant mineral potential in the better exposed parts of the Lachlan and New England fold belts. The metallogenic map series built on the available 1:250,000 geological maps by overlaying mineral deposit information.

In 1990, the National Geoscience Mapping Accord (NGMA) commenced with the aim of integrating aspects of the mapping programs of the Commonwealth's Australian Geological Survey Organisation (AGSO) and the various State Geological Surveys in areas of high priority for minerals and petroleum exploration. Production of a second generation of 1:250,000 scale maps and geoscientific databases commenced with the Bathurst map sheet under the NGMA in 1991. Between 1991 and 2000, three 1:250,000 map sheets were completed in the central west of NSW under the NGMA.

Commencement of the Bathurst 1:250,000 mapping project also marked the start of a new multi-disciplinary approach to geoscience mapping. For the first time, mapping and interpretation were guided and assisted by the detailed digital airborne magnetic and radiometric data, gravity data and other remotely sensed datasets (Landsat TM, Spot). GPS technology was used for the geophysical surveys to aid navigation, and by geologists to accurately locate field observations on high quality base maps.

In 1994, New South Wales received a substantial funding increase through the Discovery 2000 (1994–2000) and Exploration NSW (2000–2006) government exploration initiatives. The second generation 1:250,000 mapping program benefited greatly from the availability of new high resolution airborne geophysical coverages that were acquired through these initiatives.

In 2006, the New South Wales Government approved funding for the New Frontiers initiative to focus on the undercover areas of western NSW. New airborne geophysical data was acquired and a series of 1:250,000 scale geological/geophysical interpretation maps was commenced. Five of the interpretation maps have now been compliled based on enhanced images of geophysical data and satellite data, controlled by outcrop geology and drillhole information. The final products are interpretation maps showing likely basement lithologies and structural elements.

Geoscience mapping at 1:250,000 scale has made a substantial contribution to improving knowledge of the geological framework of New South Wales. Large areas of New South Wales are now covered by second generation mapping in key areas that are prospective for a wide range of mineral deposits. The 1:250,000 geoscience mapping has played an important economic role in attracting and maintaining exploration investment, aiding the discovery rate and informing land use planning decisions.

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History of the quarter-million-scale geological map program in Victoria

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Prior to the 1960s, the most detailed regional maps of Victoria were at 8 miles to the inch. In the mid-1960s, pressure from mining and petroleum exploration companies for regional maps at a better scale resulted in an offer from the BMR to carry out mapping in Victoria. It was felt that this offer should be refused, and John Knight, then Acting Director decided that the Geological Survey of Victoria should do this task. It became the major task of the mapping and drafting sections for the next decade. Initially the main effort was a cartographic one, with both the base needing to be drawn, after which the existing detailed mapping was fitted to it.

Preparing a fully coloured map for printing in those days was a complicated process that took up to 2 years. Production of the full suite of 20 maps would therefore have taken many years, so it was decided to produce a preliminary two-colour 'bring your own Derwents' edition. This greatly speeded up map production, and the full series was printed within two years, including a single fully coloured one covering Melbourne, in 1967.

Preparation of this preliminary edition had an added benefit in that it pinpointed areas with very poor information. As soon as the preliminary edition was printed, attention was focused on producing a fully coloured edition. Many GSV geologists were marshalled into providing field information that was used to modify the preliminary maps. Four sheets with the poorest coverage were remapped by Mapping Section

geologists. With each sheet covering an area of >14,500 km^2, and with poorest coverage coinciding with the most difficult terrain and/or most complex geology, this was a major task, requiring an intensive and sustained field effort. Mapping of the most difficult maps took roughly 1½ years per sheet, and they were the last to be printed.

The first coloured editions were printed between 1971 and 1977. Several novelties were used: a single colour scheme, modified from the international scheme, plus a scheme of symbols that was intended to cover any unit that might crop up in the field. An 'environmental' legend was developed in which marine, subaerial, intrusive and extrusive units were in different columns. This is still used, on larger-scale maps. Each map had cross-sections, some more than one.

The third-generation quarter-million maps were digital, done when all the surveys were shifting from analogue to digital maps. Mapping done since the analogue edition was incorporated in the digital edition. A severe deficiency of the digital maps is that they were drawn on a different base of streams and roads, and while some attempt was made to fit the geology to the new base. It was not successful. As a consequence, the digital maps are less accurate than the old analogue maps of the 1970s. An additional problem was that the digitisation was done using Genamap software, which was not on friendly terms with other, more widely used software.

This problem was addressed in 2002–2004. Data were translated from Genamap to ArcMap by AGSO, and the translated data verified by a GSV cartographer. This also provided the opportunity to update and further develop the legends and geological unit symbols. This fourth edition was used as regional cover on the GSV's GeoVic website geological map. However, problems with the non-matching base persist in this edition.

The problem with geology not matching the base is finally being addressed through the GSV's Seamless Geology Project. A workable base became available in the early 1990s and was used for all detailed mapping, using GIS software to capture linework and geological sites. A great deal of mapping is therefore available in a digital format that matches the detailed base (and is available on the'detailed geology' layer in GeoVic). Much of the older mapping is being redrawn to match the modern base, although the strict time limit for the project means that, for most of Victoria, this can only be done at 1:250,000 scale. Western Victoria, west of the Mount William Fault, has been completed and geological input for much of Central Victoria has been prepared. The project aims to be completed by mid-2012.

SESSION 04WC (3D MINERAL SPECTROSCOPY OF THE EARTH'S SKIN—1ST NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM)

Abstracts for this session available on the Convention website www.aesc2010.gsa.org.au

SESSION 04RD (RESOURCES)

Western Amadeus Basin: revised Neoproterozoic correlations and prospectivity

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The Amadeus Basin, a relic of the former Centralian Superbasin, contains a thick succession of Neoproterozoic to Palaeozoic age in central Australia. In the NT, the well exposed northern part has been well studied, and has been the target of a successful campaign of petroleum exploration. In contrast, the relatively small and remote WA component has been poorly studied beyond first pass reconnaissance mapping in the early 1960s. Previous work recognised that the WA exposures are predominantly of Neoproterozoic age, but perceived facies changes led to a mostly separate stratigraphy being set up in WA, with equivocal correlations to the eastern succession.

Recent fieldwork by GSWA indicates that the western Amadeus Basin shows much closer similarity to the stratigraphy within the NT than previously reported, although the presence of the basal Heavitree Quartzite and Bitter Springs Formation in both areas had been correctly identified. The overlying thick but poorly exposed Boord Formation had previously been interpreted as either a correlative of the glacigene Areyonga

Formation or the Olympic Formation/Pioneer Sandstone in the east. This interval is now recognised to contain several disconformities and two discrete glacial units, as well as significant pre- and post-glacial intervals, closely resembling the entire succession between the Bitter Springs Formation and Arumbera Sandstone in the NE Amadeus Basin; we recognise likely correlatives of the 'Finke beds'[*], Areyonga, Aralka, Olympic, Pertatataka and Julie Formations. Lithostratigraphic similarities are strongly supported by stromatolite biostratigraphy, which can be used to subdivide the Bitter Springs Formations into Gillen and Loves Creek Members, as in the NT, and stromatolite horizons in inferred correlatives of the 'Finke beds'[*], upper Aralka and Julie Formations can be confidently matched to these units in the eastern Amadeus Basin, and correlatives elsewhere in Australia.

There is no compelling evidence of the previously postulated interdigitation of the entire Boord and Carnegie Formations. Instead, the thick immature siliciclastic Carnegie Formation and the overlying Sir Frederick Conglomerate, Ellis Sandstone and Maurice Formation are interpreted as a synorogenic package related to the Petermann Orogeny. They are thus considered correlatives of the Neoproterozoic to Early Cambrian Arumbera Sandstone – Mt Currie Conglomerate package in the NT, and likely extend into the Cambrian. The Carnegie Formation contains common *Arumberia*, a problematic biogenic structure first described from the Arumbera Sandstone. There is a significant angular unconformity at the base of the Carnegie Formation, which removes the Boord Formation in the southern half of the area such that the Carnegie Formation directly overlies the Bitter Springs Formation, a factor contributing to the erroneous interpretation of Carnegie–Boord equivalence.

Fault-bound outliers of Amadeus Basin lie within Arunta Province basement to the north of the main basin. These contain Heavitree Quartzite and Bitter Springs Formation at the base, variously overlain by either glacigenic siliciclastics or Angas Hills Beds. While the former may all be of Permian age, the possibility of Neoproterozoic glacials must also be considered. The sandy and conglomeratic Angas Hills Beds have previously been correlated with either the Devonian Pertnjara Group of the eastern Amadeus Basin (synorogenic to the Alice Springs Orogeny) or considered to be of Permian age. While the age of this unit remains unknown, we note the similarity of clast assemblages and palaeocurrent directions to the Petermann synorogenic package in the south. We plan to constrain the age of these units with detrital zircon dating in the future.

The Neoproterozoic of the eastern Amadeus Basin is associated with demonstrated or possible source rocks and shows at numerous levels (e.g. Bitter Springs, Areyonga, Aralka and Pertatataka Formations and lateral correlatives) and exploration for Neoproterozoic plays is on-going in that area. Although it is not possible to determine actual source potential or maturity from weathered surface outcrops, the recognition in WA of correlatives and similar facies to units with source potential in the NT, raises the potential for petroleum in WA Amadeus Basin. There is also strong evidence for halotectonics, likely related to a salt unit within the upper Gillen Member, and hence a salt seal is expected over the 'Gillen petroleum system' at depth within WA.

Rift evolution in the Capel and Faust basins, offshore eastern Australia, and implications for regional petroleum prospectivity

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The Capel and Faust basins are located on the northern Lord Howe Rise between eastern Australia and New Caledonia in water depths of 1300–2500 m. Under the Australian Government's New Petroleum (2003–2007) and Offshore Energy Security (2007–2011) programs, Geoscience Australia acquired new geological data including high-quality 2D seismic data, high-resolution multibeam bathymetry, gravity and magnetic data, and rock dredge samples. These data have been analysed and synthesised for a geological and petroleum prospectivity assessment of the area. Prior to this phase of data collection, geoscientific data was limited to regional seismic profiles acquired during the 1970s to 1990s, shiptrack potential field and bathymetric data, and one DSDP drill hole.

The interpretation of new data has improved definition of depocentres previously indicated by regional satellite gravity data. The largest depocentres are approximately 150 km long and 40 km wide. Seismic data

[*] Informal unit recognised in Finke 1 and Wallara 1 petroleum wells.

suggest that the basin-fill attains a maximum total thickness of over 6 km and consists of two syn-rift and one sag megasequence packages, overlying a pre-rift basement. The basement includes an older (?Mesozoic) sedimentary succession and a possible rift-precursor volcanic succession. The early syn-rift megasequence (Syn-rift 1) is inferred to be dominated by Early Cretaceous (or older) volcanics and volcaniclastic sediments. It may also include coaly and lacustrine sediments. The late syn-rift megasequence (Syn-rift 2) is likely to be dominated by Late Cretaceous non-marine clastic sediments, with localised volcanics and coal. The upper part of this megasequence was deposited under increasingly marine influence and is likely to include deltaic and shoreline sandstones. The post-rift megasequence is essentially a Late Cretaceous to Recent deepening-upward marine succession that becomes increasingly calcareous and fine grained.

Structural and stratal geometries indicate that the depocentres evolved in two distinct extensional episodes. A period of structuring, involving widespread erosion, local uplift, basin inversion and gentle folding, followed each of these rift phases. The Syn-rift 1 phase is likely to be a part of the Early Cretaceous regional extension and magmatism widely documented from the eastern Gondwana margin, which may represent a precursor to the fragmentation of the margin. Major faults bounding these early-formed depocentres are generally oriented NNE–SSW and cut across the pre-existing NW–SE regional structural grain. The largest depocentres exhibit an en echelon arrangement that suggests an oblique (?ENE–WSW) extensional vector. The Syn-rift 2 phase probably represents a lead up to the opening of the Tasman Sea during the Santonian. The major faults that developed during this phase are generally restricted to the westernmost areas of the Capel Basin and follow the north-westerly regional structural trend. This suggests that these faults did not evolve fully within the study area due to the locus of the extension being located further westward, i.e. along the breakup axis of the Tasman Sea, thus preserving the earlier NNE–SSW-trending rift architecture over much of the study area.

Regional tectonostratigraphic reconstructions suggest that the pre-rift and early syn-rift successions in the Capel and Faust basins may include the equivalents of the Mesozoic Clarence-Moreton or Maryborough basins, eastern Australian basins with known potential petroleum systems. Moreover, seismic character comparisons with offshore New Zealand basins (e.g. Taranaki, Northland) suggest that the pre- and syn-rift megasequences in the Capel and Faust basins are likely to contain coals that may be potential hydrocarbon source rocks. 1D basin modelling indicates that any source rocks present in the pre-rift and the lower syn-rift sections are likely to have attained oil or gas maturity in the deeper depocentres. The occurrence of clinoforms and moundforms in the syn-rift and the lower post-rift megasequences suggests that deltaic and turbiditic sandstones may provide potential reservoir rocks at these stratigraphic levels. A range of fault-related, anticlinal and stratigraphic trapping styles are possible. Moreover, regional satellite gravity data suggest the occurrence of other major depocentres, of similar dimensions to those in the Capel and Faust basins, in the central and southern Lord Howe Rise, indicating the potential of this vast offshore area as a petroleum exploration frontier.

Surface and sub-surface geology of the Capel-Faust Basins, offshore eastern Australia: influence of basement structure

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The Capel and Faust basins are part of the northern Lord Howe Rise, offshore eastern Australia. These frontier basins formed during the initial phases of extension leading to the Cretaceous break-up of the east Gondwana margin. The basins subsided to their present depths of 1300–2500m in the early Cenozoic. Geoscience Australia is investigating the geology and marine environment of this frontier area as part of the Australian Government's New Oil (2003–2007) and Energy Security (2007–2011) programs. High-resolution 2D seismic, gravity, magnetic and multibeam bathymetry data were acquired in 2006–2007 and synthesised to derive 2D and 3D geological information and knowledge of these basins and underlying basement. A clear relationship between surface and sub-surface geology was observed. This has contributed to an improved understanding of basin structure, large-scale basin architecture, tectonic reactivation along the basin margins, and potential fluid migration pathways. An analysis of seafloor features will also contribute to future marine bioregional planning in the study area.

Seafloor features mapped from multibeam bathymetry data, collected in the north-west corner of the study area, were correlated with potential field grids and shallow sub-seafloor features interpreted from seismic data. Pockmarks, furrows, small escarpments and slump scarps, interpreted on the seafloor, are observed

above depocentre edges and are associated with stacked debrites and/or channels, and older pockmarks in the sub-surface. The age of the sub-surface features are from the Late Miocene to Present. Seafloor volcanoes, Eocene–Early Miocene volcanic seamounts and dykes along bounding faults are associated with basement highs, while igneous sills are more widespread within the depocentres. In some places, igneous intrusions cause local forced folds in overlying sediments that continue up to the seafloor. An extensive network of polygonal depressions on the seafloor is present above the major depocentres, where polygonal faults are well developed within the Late Oligocene–Middle Miocene sediments. Some faults extend to the seafloor. The correlation between the undulating seafloor depressions above and the structural lows formed by these faults suggests that movement is ongoing.

The superimposed surface and sub-surface geological features correlate with basin architecture interpreted from seismic and potential field data and are aligned along four major structural trends: NNE-SSW, NE-SW, NW-SE and ENE-WSW. There is a good correlation between gravity and seismic basement topography. The basement highs observed on seismic data correlate with gravity highs and the basement lows correlate with gravity lows. The integration of gravity, magnetic and seismic facies enabled the basement structure to be delineated and characterised. Four different types of basement can be interpreted: plutonic, volcanic, sedimentary and undifferentiated. The dominant structural trends in the study area correlate with the inherited pre-rift trends and this pre-existing fabric has significantly affected the subsequent development of the basins.

The relationships between surface and sub-surface features suggests that active seafloor deformation, sedimentation and erosion are linked to uplift of basement highs and associated local bottom current activity. Tectonic reactivation, along with the volcanic activity, appears to have peaked during the Middle Eocene and continues subsequently through several pulses to Recent. Fluid migration pathways are observed along the reactivated depocentre edges, as well as above the younger syn-rift sequence, and are associated with seafloor pockmarks, pipes, and mud diapirs in the sub-surface.

The spatial correlation between surface and sub-surface geological features observed in this study provide a predictive tool in mapping structural trends, large-scale basin architecture, tectonic reactivation history and potential fluid migration pathways in sedimentary basins with a paucity of seismic data, such as the southern Lord Howe Rise region or other remote frontiers. Fluid migration pathways may provide evidence for the presence of an active petroleum system in the region.

SESSION 04SD (SOCIETAL: GROUNDWATER)

Geochemical and water quality implications of changing dynamics in surface water–groundwater interactions

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It is becoming widely accepted that surface water bodies (such as streams, lakes and estuaries) are connected to the aquifers below them and that these water resources need to be largely managed as one resource. For instance, it is now generally agreed that over-abstraction of groundwater from an aquifer may reduce the baseflow in overlying streams or even change a particular stream reach from naturally gaining water from the aquifer to losing water into the aquifer. Consequently research is being undertaken to understand the physics of surface water groundwater interaction such as: the temporal and spatial dynamics of surface water groundwater interactions in response to changing hydrologic conditions (pumping, river regulation and climate change); the colmation of the streambeds due to changes in flow regimes and sediment loads causing changes in streambed permeability and transfer rates; and the behaviour of systems that become hydraulically disconnected due to decreasing groundwater levels.

However, partly in the light of the recent years of drought conditions and the immediate shortage of water, there is much less focus on how changes in water management practises, or changes in land-use for that matter, may affect the quality of either surface water or groundwater. Such changes, which are often delayed due to slow transport times in the aquifers, may influence the long term suitability of the water for human use

and the environment. This keynote presentation will highlight some of these issues using case studies in Australia and abroad.

Streambed sediments and aquifers in the immediate vicinity to streams are usually very biologically reactive environments (in terms of organic matter reactivity) due to their relative young age and the often high fluxes of dissolved and particulate matter from the surface. This zone, often termed the hyporheic zone, is biologically and chemically very sensitive to changing flow conditions. Natural undisturbed streams often have a spatially alternating pattern of up- and down-welling zones exchanging dissolved solutes (e.g. O_2, NO_3^-, Fe^{2+}, Org-C, etc.) between the stream and the streambed and thus supporting biological processes. Significant lowering of the water table (e.g. by pumping) can disrupt this exchange which in turn affects the fluxes of aforementioned solutes leading to changed condition for microbial and biological processes. In Maules Creek, a tributary to the Namoi River, streambed invertebrate fauna was found to be seriously impacted in terms of biodiversity and abundance by declining groundwater levels. On larger spatial (~1000 m) and temporal (~decades) scales surface water recharge through these reactive sediments appear to cause plumes of reduced water with high concentrations of dissolved reduced iron (Fe^{2+}). High levels of Fe^{2+} are a potential nuisance for groundwater abstraction due to its ability to cause bio-clogging, but more importantly in some environments Fe^{2+} is associated with harmful levels of certain trace elements such as arsenic. To what degree Australian aquifers are at risk is presently poorly known.

The hyporheic zone, and more widely the riparian zone, can also function as a buffer zone preventing contaminants in the groundwater, such as agrochemicals (nutrients and pesticides), from reaching the surface water environment. These buffer mechanisms can either be supported by a finite pool of sedimentary reactants (Org-C, pyrite, iron-oxides, etc.) within the aquifer or by a renewable pool of reactants being replenished by processes on the boundary to the surface water body. In a study of groundwater discharge on a beach in Denmark, sedimentary pyrite (FeS_2) and organic matter was found to remove NO_3^- by denitrification in the aquifer. However, as the sedimentary pool of pyrite and organic matter is not replenished at this site the buffering is not infinite and the NO_3^- could potentially reach the surface water environment with time. Currently very little is known about the longer term chemical and biological effects of changing land-use and water management practises in relation to surface water groundwater interactions. In summary, it is important not only to focus on the physical issues related to changes in surface water groundwater interactions, but also to understand the chemical and biological ramifications of these changes to maintain a good water quality for humans and the environment.

Management of groundwater lenses on small islands in the Pacific

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Water resources in small island countries in the Pacific Ocean are amongst the most vulnerable in the world. Many rely on fresh groundwater lenses underlain by seawater as their principal water supply source. This talk outlines the natural and anthropogenic threats to their groundwaters; and describes management strategies to sustain and conserve these resources. A simple steady-state approximation is used to provide insight into the key climatic, hydrogeological, physiographic and management factors that influence the quantity, quality and salinity of fresh groundwater lenses. Examples of the dynamic nature of freshwater lenses as they respond to these drivers are given and development and management strategies to conserve and protect freshwater lenses are discussed. Six key objectives are proposed to ensure future groundwater sustainability: improve understanding and monitoring of water resources and their use; increase access to safe and reliable water supplies and appropriate sanitation; achieve financially, socially and environmentally sustainable water resource management; increase community participation in water management and conservation; improve governance in the water and sanitation sector; and provide training opportunities for and mentoring of staff in the sector.

Hydrochemical facies and hydrological processes within a subtropical coastal catchment, Fraser Coast, Queensland

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Along shorelines, in addition to discharge from surface drainage systems coastal aquifers also discharge to the sea. This groundwater input to the marine environment is often overlooked yet can be a significant component of the chemical and nutrient budgets of coastal waters. In these settings there are many forms of mixing between ground and surface waterbodies which include rivers, estuaries, bays and oceans, with both confined and unconfined aquifers. There is also hydraulic connection between the different aquifers.

Here we report on part of an integrated project that considers potential landuse impacts in forested coastal catchments and the adjoining coastal strip. This study describes the characterisation of ground and surface waters within the Poona Creek catchment of the subtropical Fraser Coast region, Queensland. A hydrochemical database which includes in-situ physico-chemical measurements, and major ion and nutrient concentrations has been developed for samples collected from surface water sites and a range of groundwater test and supply bores throughout the elevated catchment and along the low-lying coastal zone. Data are interpreted using graphical methods such as scatter plots, Piper and Stiff diagrams in order to, (a) define hydrochemical facies and controls over them, (b) group settings based on hydrochemical facies, and (c) identify areas of potential interaction between surface and subsurface water bodies.

Most of the waters are of Na-Cl chemical character regardless of salinity, which reflects the dominance of on-shore winds and the orographic effect of the nearby ranges. However, the physico-chemical and ionic data reveal there are different hydrochemical facies within these ground and surface waters. Differentiation between subsurface waters is shown to be related to: degree and frequency of saline intrusion, level of confinement, location of recharge areas and hydrogeology. Differentiation between surface waters relates mainly to drainage morphology, flow regime and proximity to the coast (decreasing TDS landwards).

Connectivity between water bodies is identified to occur largely by the following spatially-controlled processes: (a) fresh and marine surface water mixing, (b) shallow unconfined alluvial groundwater and drainage system interaction (seasonal gaining and losing by streams), and (c) saline and fresh groundwater interaction in near-shore zones. The hydrochemical character of many of the surface and shallow groundwaters indicates groundwater baseflow contribution to the drainage systems making this a potentially significant pathway for nutrients from the surrounding plantation areas. Overall, however, nutrient levels in both surface and subsurface waters indicate little to no impact from forestry operations at the time of sampling.

In addition, shallow groundwaters adjacent to the Poona Creek estuary clearly show tidal influence and a zone of mixing between marine and terrestrial waters. There are several small coastal communities that use groundwater from limited freshwater aquifers within Quaternary sediments. The water chemistry in some of the residential bores indicates hydrological connectivity between the aquifers and the marine environment. This connectivity may permit nutrient and/or metal discharge into the adjacent Great Sandy Strait.

SESSION 04DD (DYNAMIC EARTH: EARTH STRUCTURE)

He, Ne and Ar in peridotitic and eclogitic paragenesis diamonds from the Jwaneng Kimberlite, Botswana—constraints on diamond formation

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Research goals in noble gas geochemistry include understanding the structure of the Earth's mantle and the creation of a coherent model of its evolution. In this regard, noble gas compositions in mid-ocean-ridge basalts (MORBs) and ocean island basalts (OIBs) have provided very useful information on the mantle. However, virtually all these data are from samples that are effectively of zero-age, and therefore, they only give information about the present composition of mantle noble gases. If noble gas measurements are made on

mantle-derived samples of different ages, these can allow further refinement of models concerning mass transport in the mantle.

Diamonds have unique characteristics which make them potentially very useful as sources of noble gases from the mantle: (1) most diamonds appear to be derived from 150 km to 200 km depth in the Earth, (2) diamonds cover a wide range of crystallisation ages of between 1.0 and 3.5 billion years, and (3) diamonds have suffered little interaction with crust or atmosphere. Thus, diamonds provide a direct window into the ancient mantle.

We have undertaken helium, neon and argon analyses of eleven polycrystalline diamonds from the Jwaneng Kimberlite pipe, Botswana, with known diamond paragenesis. In contrast to the findings of crustal noble gases in framesites from the same kimberlite pipe (Honda et al., 2004), the Jwaneng polycrystalline diamonds appear to have similar noble gas, particularly neon, isotope compositions as observed in MORBs, regardless of their parageneses. This implies that the Jwaneng polycrystalline diamonds may have formed in recent time, possibly as young as the kimberlite emplacement age of 235Ma. In contrast, Jwaneng framesites could be as old as the diamond inclusion age of 2.9 Ga. Furthermore, neon isotope compositions in the mantle where Jwaneng diamonds formed appear to have temporally changed from crustal Ne (as observed in the framesites) to the MORB-like Ne (as observed in the polycrystalline diamonds).

The apparent difference of neon isotope compositions and formation ages between the Jwaneng polycrystalline diamonds and framesites may imply that primordial noble gases in the upper part of the mantle have significantly been outgassed at early stage of the earth's formation, and that crustal noble gases could have been introduced into the diamond stability field of the sub-continental mantle by subduction-related processes. Subsequently primordial noble gases were continuously supplied from the lower to upper part of the mantle in order to form MORB-like Ne compositions in the upper mantle.

Geological architecture and evolution of the southern Gawler Craton: improved constraints from recent geochronology and reflection seismic imaging

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The Gawler Craton, South Australia, preserves a complex, multi-stage history spanning an age range from Mesoarchean through to Mesoproterozoic. Uncertainties concerning the spatial distribution and tectonic significance of various events in this regional history are reflected in contrasting geodynamic scenarios that place the Gawler Craton in widely differing positions with respect to other Australian cratonic elements throughout the Proterozoic. Here, we present new U-Pb SHRIMP zircon ages collected from a regional-scale transect across northern Eyre Peninsula. These new ages serve both to further define the distribution of previously known rock-forming episodes and tectonothermal reworking events, as well as identify the presence of previously unrecognised events. The new geochronological constraints are incorporated into a geological interpretation of a recently-acquired deep seismic reflection profile that provides an east-west crustal-scale cross section across the northern Eyre Peninsula.

The most significant of the new results is the recognition of exposed Mesoarchean (~3150 Ma) granites and gneisses containing inherited zircon suggesting the presence of underlying crust as old as ~3300 Ma. As the oldest previously-identified rocks in the Gawler Craton have ages of ~2550 Ma, the new results extend the early history of the Craton by over 600 million years. Rocks of ~3150 Ma age have been identified only to the east of the Kalinjala Mylonite Zone (KMZ), near the eastern margin of the Craton. The distribution of this ancient crust provides additional evidence for contrasting geological histories on either side of the KMZ prior to ~1700 Ma. Other evidence includes the distribution of ~1850 Ma Donington Suite granitoids, ~1790 Ma extrusive and intrusive magmatism, and ~1750 Ma volcanism and volcaniclastic sedimentation, all found only east of the KMZ.

Basement gneisses to the west of the KMZ have a variety of protolith ages preserved in inherited zircons, including ~2000 Ma (Miltalie Gneiss) and ~2550–2500 Ma components, as well as a newly-identified age component at ~2800 Ma. The majority of gneissic rocks west of the KMZ are shown to have been extensively deformed, partially melted and intruded by granitoids during the Kimban Orogeny between ~1740 and 1710 Ma. Also infolded with these gneisses to the west of the KMZ are quartzites, carbonates, BIF and pelitic metasedimentary rocks of the Hutchison Group.

High-grade metamorphism of Kimban age has not been recorded east of the KMZ. Geological differences across the KMZ suggest ~Kimban-aged juxtaposition of mid-crustal gneisses and migmatites to the west with upper crustal, relatively unmetamorphosed volcanic and volcaniclastic rocks to the east. Magnetic and seismic data suggest the KMZ is an east-dipping structure, at least in the northern Eyre Peninsula. The presence at the surface of mid-crustal migmatitic rocks in the footwall of this structure suggests significant crustal extension and mid-crustal exhumation on northern Eyre Peninsula during the Kimban Orogeny. Previous structural and metamorphic studies further south on Eyre Peninsula have interpreted the KMZ as the product of large-scale dextral transpression. It is notable that the trend of the KMZ swings to the NNW on northern Eyre Peninsula from a more NE trend to the south, raising the possibility of local contrasts between transpression and transtension along the KMZ during the Kimban Orogeny.

The increasing recognition of distinct geological histories across the KMZ prior to the Kimban Orogeny, from Mesoarchean through to Paleoproterozoic, suggests that Kimban-aged tectonism on this structure may represent reactivation of a long-lived, pre-existing structure.

Magnetotelluric survey along the east–west Southern Flinders Ranges seismic traverse, South Australia

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In a collaborative project by Primary Industry and Resources, South Australia (PIRSA), Geoscience Australia and the University of Adelaide, magnetotelluric (MT) data were acquired in September 2009 along the east-west southern Flinders Ranges seismic traverse in South Australia. The seismic and MT data acquisition are part of the Australian Government's Onshore Energy Security Program and PIRSA's Plan for Accelerating Exploration (PACE) initiative. The MT data form a valuable complementary addition to the seismic data for the investigation of energy potential and crustal architecture of this region.

AuScope (part of the National Collaborative Research Infrastructure Strategy) MT instruments (based at the University of Adelaide) were used (through an ANSIR agreement) to record both broadband data with a frequency range of 200 Hz to 0.008 Hz and long period data with a frequency range of 0.1 Hz to 0.0001 Hz. This enables sensing of Earth electrical conductivity from near-surface in the crust to depths well below the Moho. Two orthogonal components of the magnetic field were measured with induction coils for the broadband acquisition, and three components of the magnetic field were recorded with fluxgate sensors for the long-period data. Two horizontal components of the electric field were measured at each site with orthogonal NS and EW dipoles ~50 m long. Data were recorded at fifteen sites with a nominal spacing of 10 km covering a profile ~150 km in length.

Data were processed to industry standard EDI files prior to the generation of apparent resistivity and phase plots. A suite of plots were created to investigate dimensionality including, skew angle, phase tensor ellipses and Parkinson arrows. Parkinson arrows point to regions of high conductance and away from more resistive blocks. Preliminary analysis of the long period data has revealed that the Parkinson arrows generally point to the east at higher frequencies. At lower frequencies these arrows swing southerly pointing to the south-east.

Dimensionality analysis of the long period data has revealed that stations towards the west of the line are generally 2-dimensional while there are a number of stations towards the eastern end that appear 3-dimensional. Initial 2-dimensional modelling has been undertaken (with the removal of those stations or frequencies that are strongly 3-dimensional) and early models show a conductive layer that widens towards the eastern end of the line, possibly indicating a thickening in Adelaidean sedimentary rocks.

Further modelling of both long period and broadband data is in progress. These models, along with associated products, will be evaluated in conjunction with the deep seismic data to gain a better understanding of the structure and thickness of the Adelaide Geosyncline and the crustal-scale relationship between the Curnamona Province and the Gawler Craton.

Remote sensing of mineral systems in the Gawler-Curnamona—a new HyMap-calibrated ASTER mosaic in South Australia

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More accurate mapping of land surface composition at a continental-scale for improved resource exploration is becoming possible through a new generation of remote sensing technologies. These include the multi-spectral Japanese ASTER sensor onboard the US TERRA satellite which was launched in December 1999 and has now collected an image archive that effectively covers the Earth's land surface three times over. HyMap and ASTER calibration, processing and standardisation approaches have been produced as part of a large multi-agency project to facilitate uptake of these techniques and make them easily integrated with other datasets in a GIS.

Collaborative research, undertaken by Geoscience Australia, the Commonwealth Scientific Research Organisation (CSIRO) and state and industry partners, on the world-class Mt Isa mineral province in Queensland was completed in 2008 as a test-case for these new methods. The project demonstrated that geochemical information about alteration chemistry associated with footprints of mineral systems can be acquired by analysing spectral ground response, particularly in short-wave infra-red. Key materials that can be identified include clays and magnesium/iron/aluminium oxyhydroxides, as well as information on mineral composition, abundance and physicochemistry (including crystallinity) for minerals such as kaolinite, which can be used as a surrogate for identifying transported versus *in situ* regolith material. The identification and classification of regolith materials and thickness indicators is essential to facilitate ongoing exploration in challenging regolith-dominated terrains, like those in South Australia.

High resolution mineral maps, from instruments such as HyMap, allow the recognition of various types of hydrothermal alteration, and can map and distinguish between distinct geochemical and mineralogical alteration halos and fluid pathways. The techniques and applications applied in the Mount Isa program are being extended into a similar study for the eastern Gawler and Curnamona Cratons in South Australia. The expansion of this work into ASTER products at lower spectral and spatial resolutions is to: facilitate low cost regional investigations including bedrock mapping, to identify potential exploration targets, and to enhance understanding of the composition of surface materials in a regional context.

New approaches for ASTER calibration using high-resolution HyMap imagery, and testing for compensation for atmospheric residuals, lichen and other vegetation cover effects have been developed by CSIRO. This software can calibrate and process terabytes of multi-scene imagery, and a standardised suite of ESRI GIS products improve non-specialist user interpretation and comparison with other datasets such as radiometrics, geology, and topography layers in 2D maps. The ASTER products also can be used to validate and groundtruth 3D geological and mineralogical maps and predictions derived from 3D inversion and modelling of potential-field data. If consistent, the combined 2D and 3D mineral maps can allow more predictive inferences about the prospectivity and characteristics of mineral systems in the subsurface, even where prospective host rocks are buried and not directly visible in the spectral maps alone. As an effective surface mapping tool, the spectral data may also provide a valuable constraint for improving the quality of 3D inversion and modelling of potential field data.

ASTER geoscience maps and related products have also now been developed for the Gawler-Curnamona area cover about 180 ASTER scenes. These data provide a ready-to-use tool kit that will aid explorers in identifying and mapping unconsolidated regolith material and underlying bedrock and alteration mineralogy. Bedrock signatures can now be identified in areas previously recorded as 'extensive cover sediments'. This means that, in addition to being able to make mineral classifications that characterise transported materials and may indicate buried resources, it is also possible to find new windows of basement geology in areas previously mapped as cover. This has considerable application for mapping geomorphic processes, understanding and characterising chemical dispersion pathways, and targeting surface sampling for mineral exploration.

Seamount and ocean island record preserved in accretionary complexes

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Subduction of oceanic islands and seamounts is a common process along modern subduction zones, with a present-day subduction rate of ~0.34 seamount km^{-1} Ma^{-1} along the Pacific margin. Subducting oceanic islands and seamounts have a major impact on subduction zones and, notably, affect the seismogenesis (e.g. Bangs et al., 2006), supra-subduction magmatism (e.g. Hoernle et al., 2008) and mechanisms of accretion and subduction erosion (e.g. Buchs et al., 2009). Although some of these effects are clearly of fundamental interest for the evolution of convergent margins, our knowledge of mechanisms that control subduction, accretion and the extent of preservation of seamounts and oceanic islands in subduction zones is limited. In order to understand the role of seamounts and oceanic islands on the evolution of convergent margins, we have studied accretionary complexes in South Central America and Iran. Our approach is based on the integration of field, satellite, and geochemical data, and focuses on the characterisation of accreted oceanic sequences and development of accretionary complexes.

In South Central America, late Cretaceous to Miocene accretionary complexes include slices of an oceanic plateau, seamounts, and oceanic islands that never exceed greenschist facies conditions, indicating accretion at relatively shallow levels. The seamounts and oceanic islands are characterised by a broad range of geochemical compositions indicative of intra-plate and near-ridge settings of formation. Detailed mapping indicates the South Central American accretionary complexes developed through discontinuous accretion and subduction during the entire history of the margin (i.e., since the late Campanian). Although the margin was probably dominated by subduction erosion during much of its development, punctuated accretion of seamounts and oceanic islands was sufficiently effective to add locally several tens of km of exotic material to the accretionary prism. Accretion occurred at shallow level by: (1) superficial peeling of topographic highs on the downgoing oceanic crust; and (2) off-scrapping of larger portions of subducting oceanic islands.

In Iran, a 'Variscan Accretionary Complex' developed along the Paleo-Tethys active margin between the Devonian and Triassic and was exhumed during the closure of the Paleo-Tethys in the Triassic (Bagheri and Stampfli, 2008). Oceanic islands capped by atoll carbonates accreted in the Permian, represented by km-size slices of greenschist, blueschist, and marble embedded in a matrix of meta-greywacke. Our new results show these slices can be mapped based on satellite multispectral data and that the accretionary complex includes slices of distinct oceanic islands. The slices accreted by underplating under greenschist to blueschist facies conditions, conjointly with forearc sediments. Accretion probably occurred as the volcanic edifices were dismembered during their transit to deeper levels of the subduction zone.

Our results from South Central America and Iran indicate accretion of oceanic islands and seamounts can occur over a large range of metamorphic conditions, from very shallow to deeper parts of the subduction zone. The combination of tectono-stratigraphic, petroloic and geochemical data provides evidence for different modes of accretion, allows recognition of different volcanic edifices, and provides an insight into the development of accretionary complexes during ongoing subduction.

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Recycling of oceanic crust into upper mantle magma sources—melting behaviour of upwelling, heterogeneous mantle

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Many primitive mafic volcanics may contain components derived from upper mantle melting of non-peridotitic lithologies, some of which may have been introduced into the magmas' source regions by deep subduction and subsequent entrainment into upwelling mantle. Such lithologies may include high pressure forms of mid-ocean ridge basalt, gabbro and pelagic sediments (eg. pelites or carbonate-rich materials), and a range of residues after partial melt extraction from these lithologies.

In this presentation we will compare the melting behaviours of some of these different lithologies, as determined by high pressure experimentation. We also report experiments at 3.5 GPa designed to explore the nature of partial melting, melt migration and reaction processes that may occur in upwelling, heterogeneous mantle, consisting of ambient peridotite and discrete bodies of eclogite (former oceanic crust).

A layered experimental configuration was used in these reaction experiments, in which an eclogite layer was run in contact with a garnet lherzolite layer. Run products consist of complex layered assemblages in which there is clear evidence of partial melting to produce highly siliceous liquids and refractory eclogite residue and reaction of the evolving melts with peridotite to produce garnet + pyroxene–bearing and olivine-free reaction zones between the eclogite and peridotite.

Olivine-free reaction lithologies similar to the reaction zone material observed in these experiments have been recently proposed as major source materials of some Hawaiian and other intraplate magmas, including flood basalts (Sobolev et al. 2007). The basis of this model is that many primitive intraplate magmas are richer in SiO_2 and Ni than MORBs or experimental partial melts of peridotite, consistent with formation of the natural intraplate lavas by partial melting of orthopyroxene-rich, olivine-free reaction lithologies (in which Ni behaves incompatibly, in contrast to its behaviour during melting of olivine-bearing source materials such as peridotite).

However, we argue on phase petrology grounds, that olivine-free pyroxenite lithologies are unlikely to be the source of Ni-enriched lavas. During upwelling of heterogeneous upper mantle, a complex series of reaction and mixing processes will homogenise the original eclogitic heterogeneity back into the mantle, forming reertilised peridotite. This refertilised peridotite will exhibit mixed isotopic signatures of the original peridotite and eclogite components, but melting will be controlled by peridotitic phase relations (i.e olivine-present partial melting). The observed high Ni contents may derive from other effects related to fractionation or oxygen fugacity etc.

Reference

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Experimental constraints on chlorine behaviour in subducted sediments

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It is widely accepted that a fluid phase released from the subducted slab fluxes partial melting in the overlying mantle wedge, however, the nature of 'subduction fluid agent' remains a matter of debate. The Cl concentration in 'subduction fluid agent' is also poorly constrained, although experimental studies have shown that complexation with chlorine (and possibly other halogens) at high concentration might produce a strong effect on relative HFSE vs. REE/LFSE partitioning.

Detailed chemical analyses of oceanic crustal material have revealed that subducted sediments are the dominant host of LILE in the slab. The significance of such a role is further supported by considering that the

composition of the 'slab fluid agent' which migrates from the subducted slab to the mantle wedge is assumed to be buffered by the subducted sediment residue component located at the slab-mantle interface. Therefore, determining accurate sediment-derived fluid and melt compositions at high P are critical for understanding mass transfer from the slab to mantle wedge.

We have conducted an experimental study on hydrous Cl-bearing synthetic pelite over a pressure and temperature range of 25-45 kbar and 650-850°C, respectively. The starting composition contains 6.65% water and 0.05% chlorine, equivalent to ~1wt.% NaCl solution. Apatite was found to be the major chlorine carrier with Cl concentrations ranging from ~0.1% at 750°C, 45kbar to 1.2% at 800°C, 25kbar. While Cl in apatite shows a consistent trend of increasing concentration with increasing temperature, a decrease in Cl concentration was found to occur with increasing pressure. Chlorine was also detected in several other hydrous mineral phases (e.g., phengite, amphibole, biotite) in variable concentrations (from 200-800ppm). The chlorine content in the coexisting melt or aqueous fluid phase was determined by both analysis and mass balance calculations. From the resultant data we were able to obtain a set of chlorine partition coefficients between apatite and melt/aqueous fluid ($D_{Cl\ ap\text{-}liq}$) and while these values show a general increase with increasing temperature, they are found to decrease with increasing pressure. Chlorine partition coefficients between apatite and melt, $D_{Cl\ ap\text{-}melt}$, are found to vary from ~1.5 (e.g. at 750°C, 35kbar, and 800°C, 45kbar) to ~14 (at 800°C, 25kbar), while partition coefficient values for aqueous fluid are found to be less than 1, suggesting chlorine has a strong partitioning preference for aqueous fluid. Our results show that Cl in apatite can be a very useful sensor for the Cl concentration insubduction zone fluids.

New backarc magma types, active boninite magmatism, fresh peridotites: reports of some recent Marine National Facility voyages to the south-west Pacific

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A number of research voyages of the Marine National Facility using RV *Southern Surveyor* have been conducted by 3 Australian-based research groups (CSIRO Exploration and Mining; University of Tasmania; ANU), together with other individuals from Australian universities, and international collaborators, in the active arc-backarc systems of the Southwest Pacific region over the past few years. Some of these voyages have been supported by Mineral Exploration Companies. Here we report from the ANU-CSIRO E&M voyages on some of the most significant results.

SS11/2004 (NoToVE) Northern Tonga Arc and Fonualei Rifts (FR): The first active submarine arc boninite volcanism has been identified at 'Volcano A' (Cooper, L. *et al* 2010, in review JGR Solid Earth), a twin-peaked edifice to the north-west of Tongatapu; The FR have captured all of the supra-subduction zone flux shutting down the adjacent volcanic front arc volcanoes. In terms of backarc basin magmas, the FR comprise a new global end-member characterised by extremely hot and refractory mantle sources overprinted by a subducted Pacific Slab-derived flux (Keller *et al.* 2008, JGR Solid Earth 11 B08S07, doi:10.1029/2007JB005451).

SS06/2007 (WeBiVE) West Bismarck Arc and reararc of New Britain: the first occurrence of mantle-derived peridotites recovered from an active, submarine arc front volcano (Ritter). Work in progress (Sarlae McAlpine) has documented a suite of harzburgite-lherzolite lithologies, including the most refractory (i.e., spinel Cr/Cr+Al ~0.9; Fo_{94}) harzburgite yet reported globally. The host basalt is a medium-K MgO-rich (~15wt%) tholeiite.

SS07/2008 (NoLauVE) north-west Lau Basin (supported in part by Teck and Nautilus Minerals): documentation of a network of rifts (Rochambeau Rifts; RR) rather than the putative Niua Fo'Ou spreading centre; discovery of two hydrothermally-active calderas astride the crest of the Northwest Lau Spreading Centre (NWLSC); tracking via $^3He/^4He$ of dredged glass samples of the ingress of the Samoan Plume into the north-west Lau Basin beneath the RR and NWLSC, but not penetrating south of the Peggy Ridge to the Central Lau Spreading Centre (CLSC) (Lupton *et al*. 2009 GRL 36, 17 doi:10.1029/2009GL039468); demonstration (by N. Dyriw, Hons thesis, ANU 2009) of increasing mantle wedge fertility from CLSC through NWLSC to RR, and coupling of $^3He/^4He$ enrichment with depth of melting. The RR tap a new global end-member backarc basin magma type in terms of extremely hot but also fertile character.

SS02/2009 northern Lau Basin (supported by Nautilus Minerals): documentation of extensive hydrothermal plume activity in the region, including identification of numerous, new likely vent sites on the CLSC and

northwards through the Lau Extensional Transform Zone to the PR; recovery of fresh harzburgite xenoliths from an active volcano near 'Volcano O'.

SESSION 04TD (TOPICAL: EARTH SCIENCE HISTORY)

Production of the Australian 1:250,000 scale geological map series

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This talk begins with a brief insight to the history that shaped the 1:250,000 scale geological maps that the Bureau of Mineral Resources (now Geoscience Australia) was responsible for producing. It then goes on to discuss the various processes that underpinned the production from photo-scale compilation sheets through to the first edition full colour map. The talk concludes with a review of the rigorous standards that were applied to this benchmark series of maps.

Overview and economic significance of first edition 1:250,000 geological mapping of Australia

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The forerunner of the Bureau of Mineral Resources was a group of geologists and geophysicists working in the office of the 'Commonwealth Geological Adviser' established in 1941, but within a year the office was renamed the 'Mineral Resources Survey' of which Harold Raggatt was the Director and Norm Fisher was the Chief Geologist. Towards the end of the war, Raggatt proposed the use of the geological sciences as a platform for post-war planning and the development of Australia's natural resources. Central to Raggatt's 1944 proposal to establish a national geological survey was the production of a uniform series of geological maps as a basis for petroleum and mineral resources assessment1. In March 1946, Cabinet approved the Mining Industry Advisory Panel's recommendation to set up a national geological survey body titled 'Bureau of Mineral resources, Geology and Geophysics' and in June 1946 the first positions in the new BMR were established, starting at 55 personnel and blossoming to a peak of 680 in 1982.

Of the nine major responsibilities that the BMR was charged with, the third, which was 'Undertaking, in cooperation with the States and Territorial mining departments, geological and geophysical surveys and other work associated with exploration' was undoubtedly the most significant. However, this function did not acquire any real momentum until 1949 when a request from the Queensland Government invited BMR to assist in a systematic eight-sheet geological mapping survey over a large tract of country centred on the Mt Isa mineral province, thus heralding a long period of continuous cooperation between Commonwealth and State surveys which began with Qld and continued on in WA. Also, despite non-standard mineral province geological mapping of the Northern Territory being initiated by BMR in 1950, systematic sheet-based mapping did not begin until the mid to late 1950s. Standard 1:250,000 geological mapping of SA, Victoria, and Tasmania was carried out solely by their respective State Geological Surveys while NSW was mapped almost entirely by the Geological Survey of NSW except for a few early Quarter Million sheet areas mapped and published by BMR.

Considering the entire 514 standard 1:250,000 geological map sheets covering the whole of Australia, nearly all have been finalised and published as first edition fully drafted hard copy coloured maps with extensive legends with each map including a list of up to a dozen or so names of the highly skilled geologists responsible for the veracity of each map and the name of the drafting departmental head responsible for its production and the year of publication.

The combined BMR and State Geological Survey quarter million mapping program began with the production of two first edition map sheets in 1951, Urandangi in Qld and Penola in SA. Over the next 20 years with increases in manpower, mapping resources and technology, geological map sheet production peaked in 1971 with a publication rate of 41 first edition coloured standard geological maps annually before tailing off over the ensuing period. By January 2001 after 50 years, the first edition mapping program was effectively completed with the publication eight quarter million coloured geological map sheets in SA centered around the far-flung

Noorina and Callabonna sheets in the year 2000. Over the past nine years the remaining eight standard first edition geological map sheets which occur over poorly outcropping areas in various parts of Australia have not been completed.

In terms of the economic significance of the first pass standard geological mapping program, it should be noted that post-war short term price booms in titanium (heavy mineral sands), uranium, and to a lesser extent added demand for tin and tungsten, manganese and base metals led to more than 100 mineral deposit discoveries during the ten years to1960, while keen eyed prospectors and geologists also discovered very large deposits of iron ore and bauxite during the decade. By the end of 1959, a total of 18 standard quarter million maps, or less than 4% of the continent had been published.

In 1949/50, minerals and energy exports represented just 5% of Australia's merchandise exports, with manufacturing exports also accounting for 5%, while farm, forestry and fisheries and other agricultural exports made up the remaining 90%. It took another 14 years for minerals and energy exports to increase a further 5% to reach 10% of total exports. However, in the year 1964/65 the value of mineral exports jumped 20% and for the next 14 years and up to 1984/85, the average annual growth rate in the value of Australian minerals and energy exports was 26%, never dropping below 10%. By 1985, minerals and energy exports by value was responsible for more than 50% of Australia's merchandise exports and the proportion stayed around the 47% level for the next 15 years till the end of the century. Following the boom in demand for Australian resources from China and elsewhere in the first 9 years of the 21st century, the value of the contribution of minerals and energy to Australia's merchandise exports for the 2008/2009 fiscal year reached an unprecedented high of 69%.

It is argued that the economic importance of the first edition mapping program should not be underestimated although the total degree and extent of its long-term significance has yet to be fully determined. However, there can be no doubt that this mammoth enterprise has laid down the basis for the further geological understanding of continental and offshore Australia and the result is indeed a template or guide to the potential mineral and energy resource treasures bound up in the rocks and formations now so consistently described and mapped. Nevertheless, the bigger question still remains; is there yet a role for the nation's premium geoscience authority to prosecute a major remapping program in areas of strategic or national significance despite having vacated this area of expertise some 25 years ago?

Reference

1 'Rocks to Riches', by Rick Wilkinson, 1996, Allen & Unwin.

Papua New Guinea and Indonesian Papua 1:250,000 scale geological mapping—tales from the past

Hugh Davies[1], Chris Pigram[2]
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The Australian Bureau of Mineral Resources was established in 1946 and provided geologists to the Papua and New Guinea Administration beginning in 1948. The resident geologists, based in Port Moresby and Wau, and volcanologists based in Rabaul, carried out local area investigations but for the most part had limited resources and manpower. Regional geological mapping by Canberra-based field parties began in 1956–57 in the eastern highlands (McMillan and Malone, 1960) followed by the mapping of the Musa Valley in 1958 (Smith and Green, 1961), Misima Island in 1959 (de Keyser, 1961), Woodlark Island in 1960 (Trail, 1967), and the D'Entrecasteaux Islands in 1961 (Davies and Ives, 1964). Despite the limitations faced by the resident geologists there were significant focused contributions notably by J. E. Thompson (including his benchmark papers on the Papuan ultrabasic belt, BMR Record 1957/77, and on the Punkuna (later known as Panguna) copper-gold prospect on Bougainville Island, Record 1962/39), and the mapping of parts of the same ophiolite by Davies in 1957 and Dow and Davies in 1960 (Dow and Davies, 1964).

Four-mile and then 1:250,000 scale mapping had proceeded in Australia since the early 1950s but it was only in 1966 that the concept flowed on to PNG, when the first 1:250,000 scale 'Preliminary Edition' was produced by Duncan Dow's South Sepik party. In 1973 the resident geologists were reconstituted as the Geological Survey of PNG. They contributed to all BMR mapping programs and independently completed the mapping of a number of sheet areas: Gazelle (Macnab), Huon and Bogia (Jaques and Robinson), Admiralty Islands (Jaques), Markham (Grainger and Tingey), Yule (Campbell Brown), Kavieng and Cape St George (Hohnen), and Port

Moresby-Kalo-Aroa (Pieters). Key to the production of the maps was the fine drafting by three PNG draftsmen (Rau, Eno and Baloiloi), under the guidance of George Millist, seconded from BMR.

Major Canberra-based mapping campaigns included the mapping of the Kubor Anticline in 1968 (Bain, Mackenzie, Ryburn), New Britain in 1969 (Ryburn, Johnson and others), southeastern PNG in 1967–68 (Davies, Smith, Pieters, Cifali, Tingey, Manser), and the South, West and North Sepik expeditions in 1966–7, 1971–2 and 1972–3 (Dow, Bain, Macnab, Smit, Davies, Hutchison, Norvick, Maffi, Sweet). Oil company exploration mapping and to a lesser extent mineral exploration were incorporated into the maps where appropriate.

All of the mapping programs in PNG were handicapped by incomplete aerial photograph coverage and inadequate and inaccurate base maps. These obstacles were reduced in 1969 when the Department of Defence made available side-looking radar imagery of much of the unmapped remote interior, and in 1973–74 when a concerted aerial photography campaign by the RAAF and a massive ground control effort by the Australian Army Survey Corp, resulted in the production of complete 1:100,000 topographic map coverage of PNG—a hazardous and little-recognised achievement. The pace of geological mapping accelerated in 1965-66 with the adoption of helicopter support and by the time of Independence in September 1975 there was almost complete coverage. Those who were involved owed a special debt to a select band of expert helicopter pilots, and to the expert and cordial support of BMR cartographers (notably Phil Boekenstein and Max Nancarrow) and editors. Essential support for resolving stratigraphy in both PNG and Papua was provided by palaeontologists, chief amongst whom were Belford and Skwarko.

The mapping of Indonesian Papua, the western half of the island of New Guinea, was undertaken as an aid project jointly between BMR and the Indonesian Geological Research and Development Centre (GRDC). The program included a training and development component for Indonesian geologists. It began officially in 1978, although some joint work had been done previously, and utilized aerial photography collected by the RAAF. Mapping began in the western Birds Head region and worked east. The west half of the province was completed before the program was curtailed in 1982 because of civil unrest. The program was led by Duncan Dow and Rab Sukamto and included BMR geologists Pieters, Pigram, Trail, Robinson, Ryburn, Williams and Bladon, and geophysicists Barlow and Johnson. Subsequently the GRDC produced maps of parts of the central range that incorporated data gathered by Freeport McMoRan Indonesia exploration geologists.

A geological map of PNG at 1:1 million scale was released in 1974 and at 1:2.5 million scale in 1978. A geological map of Indonesian Papua at 1:1 million scale was produced in 1986, based on BMR-GRDC mapping and on earlier work and air photo interpretation.

SESSION 04WD (3D MINERAL SPECTROSCOPY OF THE EARTH'S SKIN—1ST NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM)

Abstracts for this session available on the Convention website www.aesc2010.gsa.org.au

Friday 9 July

SESSION 05WA (3D MINERAL SPECTROSCOPY OF THE EARTH'S SKIN—1ST NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM)

Abstracts for this session available on the Convention website www.aesc2010.gsa.org.au

Poster abstracts

(grouped by theme and ordered by presenter surname)

DYNAMIC EARTH: FROM CRUST TO CORE

Geochronological, metamorphic and structural evolution of the Kanjamalai Hills, Tamil Nadu

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Gondwana reconstructions place the Southern Granulite Terrane (SGT), located in the southern tip of India between eastern and western Gondwana at a junction between the East African, Pinjarra and Damara Orogens. Determining the age, spatial extent, metamorphic and tectonic histories of different crustal blocks comprising the SGT is important in fully understanding the role of southern India in Gondwana. Despite extensive work on the SGT, significant ambiguity still exists over boundaries and evolution of crustal blocks due to the high grade often polyphase deformed nature of the rocks.

The Palghat Cauvery Shear System (PCSS) is an approximately 100km wide east-west set of anatomising shear zones juxtaposing blocks of contrasting structural, metamorphic and isotopic histories in the SGT that have been proposed to represent a Late Neoproterozoic – Early Cambrian structure associated with Gondwana amalgamation. The age and nature of the PCSS continues to be debated, particularly the P-T-t conditions and spatial extent of northern Late Archaean – Early Palaeoproterozoic metamorphosed Salem Block and southern Neoproterozoic – Cambrian metamorphosed Madurai Block. This study combines metamorphic, structural and geochronological data from the Kanjamalai Hills, situated in the north of the PCSS and on the southern margin of the Salem Block to determine the P-T-t conditions and age of metasediments and metaigneous rocks, which show field and petrological evidence for polyphase metamorphism. This study aims to determine the evolution of this ambiguous area of the PCSS and Salem Block by 1) determining if metamorphism at the Kanjamalai Hills is a) Archaean-Palaeoproterozoic consistent with the Salem Block, b) Neoproterozoic–Cambrian consistent with metamorphism synchronous with the amalgamation of Gondwana, or c) has undergone two metamorphic events, and 2) determining the provenance of the metasediments at Kanjamalai.

Mapping of lithologies and structural relationships of the study area of the Kanjamalai Hills has been completed and will be presented here. Detrital zircon U-Pb geochronology will be conducted using the Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICPMS) to determine crystallisation ages of metaigneous rocks and both provenance and maximum depositional ages of metasedimentary rocks. Additionally, P-T-t conditions of metamorphism will be constrained by combining conventional thermobarometry and pseudosections using THERMOCALC. Compositions for THERMOCALC and age of metamorphism will be determined by bulk rock geochemistry using X-Ray Fluorescence (XRF) for pseudosections, composition of minerals in equilibrium for thermobarometry using Electron Microprobe Analysis (EPMA), and *in situ* monazite dating using LA-ICPMS. The age of a subsequent metamorphic event will be investigated by Sm-Nd dating of small (1–2mm) garnets using Thermal Ionisation Mass Spectrometry (TIMS).

Lateral fault inversion and polyharmonic folding in the Budawang Synclinorium, Deua Valley, NSW, Australia

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The Budawang Synclinorium, located within the eastern Lachlan Fold Belt, south-east Australia, is a north-south elongate structure that is bounded by faults on both sides. The structure is somewhat of an enigma. In the north, where it extends beneath the Sydney Basin, it appears to be a simple syncline. Whereas at its southern termination it appears to occupy the core of a triangle thrust zone. Early to Mid-Devonian back-arc

rifting formed a graben, partly filled and flanked by the Comerong Volcanics. The graben fill includes bi-modal lavas, volcaniclastics and non-volcanic Mid- to Late Devonian sediments of the Merrimbula Group. East-west contraction during the Carboniferous Kanimblan Orogeny formed a structure that has been interpreted as a series of kink-folds (Cooper, 1992), a rounded syncline (Powell, 1983), a series of rounded folds (Wyborn and Owen, 1986), and a triangle thrust zone (Glen and Lewis, 1990). While these models may describe the style of deformation locally, no single model appears to describe the style of deformation over the entire strike length of the structure.

Structural work in the Deua Valley (Austin, 1999) described rounded folds with short (e.g., 2 m) to long wavelengths (e.g., 1 km) and kink folds in the Budawang Synclinorium, which is consistent with elements of the kink and rounded fold models. However, the style of folding is a combination of the two. Fold style is a function of bedding regularity and competency. In the Deua Valley area the Merimbula Group consists mostly of the Ben Boyd and Worange Point formations. The Ben Boyd Fm has regularly bedded competent/incompetent layers which commonly form kink-folds during contraction. This style of folding is consistent with Cooper's (1992) observations from the Shoalhaven Gorge. Conversely, the Worange Point Formation is variably bedded, consisting of thick sequences of incompetent mudstone with variable, but relatively thin inter-layers of competent sandstone. This bedding geometry facilitates formation of larger wavelength folds that enclose smaller-scale polyharmonic folds. Polyharmonic folding has never been proposed as a major deformation mechanism within the Budawang Synclinorium. Analysis of the Merimbula Group's enveloping surface in the Deua Valley shows the broad structure to be gently undulating, not a tight syncline. Hence, the simple syncline model of Powell (1983) cannot be strictly true for the entire structure, but may represent one end-member of a range of structures.

In the Deua Valley, the bounding faults both dip outwards from the axis of the Budawang Synclinorium and appear to have a reverse sense of movement, which is consistent with the triangle thrust zone model. However, the model requires the faults within the Merrimbula Group to have very large displacements. The observations of Cooper (1992) and Austin (1999) demonstrate that the majority of faults have very small displacements, related to dip-slip on locked-up fold limbs. Hence, the Budawang Synclinorium does not appear to be a true triangle thrust zone.

Several authors recognise that the Comerong Volcanics locally outcrop entirely outside the Budawang Synclinorium and this led Glen and Lewis (1990) to infer that a wedge containing Ordovician flych the below Comerong volcanics must have been thrust eastward over the Budawang Synclinorium. However, no structural data are presented from the rhyolites to confirm steep dips. Hence, the flanking rhyolites could be combination of sub-vertical feeder vents and sub-horizontal lava flows sitting on the flanks of the graben. Clay analogue modelling demonstrates that a thick competent layer (e.g., rhyolite) sitting elevated on the flanks and in the base of a graben, will not be extensively deformed during contraction. The majority of the strain will be taken up by incompetent units (e.g., Merrimbula Group above and Ordovician turbidites below). The competence of the rhylolite causes the orientation of the bounding faults to be laterally inverted during contraction, i.e., the faults reverse their dip and shear sense. Consequently, the rhyolite is only gently folded beneath the Merrimbula Group and in places the Ordovician (below the semi-horizontal rhyolite) is thrust up in the hanging wall of the laterally inverted faults, above the Merimbula Group.

Along strike variations in the structure of the Budawang Synclinorium are a function of two main factors: The layering geometry of competent/incompetent units within the Merrimbula Group; the variability of thickness and location of felsic volcanics within the Budawang Synclinorium, and on its flanks. These key variables allow the Budawang Synclinorium to partition strain in a number of ways at different localities.

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The tectonic evolution of the Atlantis Bank oceanic core-complex, south-west Indian Ridge

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Atlantis Bank on the south-west Indian Ridge (SWIR) formed 10–13 Ma by oceanic detachment faulting. Oceanic detachment faults are scarce in the immediate vicinity, leading us to suggest that detachment faulting at Atlantis Bank was triggered by a short-lived regional increase in the full-spreading rate along the SWIR and was preferentially localised adjacent to the Atlantis II Transform Fault, whose growth since at least 30 Ma was accommodated by long-lived asymmetric spreading and was under transtension ~8–20 Ma. Once detachment faulting commenced, spreading was highly asymmetric such that the detachment fault formed the principal plate boundary. U-Pb zircon dating suggests that the lithosphere was up to 18-km-thick and that magmatism continued relatively unabated. However, crustal accretion was focused at depth in the footwall of the fault leading to relatively enhanced accretion of the lower crust and reduced volcanism in the axial valley. The 1.5 km lower crustal section in ODP Hole 735B accreted rapidly, and cooled to below 365°C in <0.5 Ma, but anomalously young thermochronologic ages suggest later heating by hydrothermal circulation along fault zones at ~8–9 Ma. These results require a tectonothermal event that significantly post-dates detachment faulting. This event and the faulting which uplifted Atlantis Bank to sea-level were likely related to tectonics along the Atlantis II Transform, and specifically to the final stages of long-lived transtension caused by a rotation in the direction of plate-spreading 19.6 Ma.

U-Pb laser ICPMS zircon constraints on the depositional age and provenance of the Kurnool Group, Cuddapah Basin, southern India

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The unmetamorphosed Cuddapah Basin of Southern India, is one of the largest Proterozoic basins in India and despite its size, excellent exposure and accessibility, the >15km of stratigraphy within it are extremely poorly dated. In this poster we present new U-Pb zircon laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) data from samples from the upper part of the basin fill—the Kurnool Group—to constrain the maximum depositional age and examine the provenance of this part of the basin.

The Kurnool Group unconformably overlies the Cuddapah Supergroup. It consists of a cyclic sequence of sandstone/conglomerate, limestone and shale and is over 600m thick. The Kurnool Group is thought to be of Neoproterozoic age, based on bioturbation structures, Rb-Sr and K-Ar dating on kimberlite and lamprolite in diamondiferous pipes that cut the Cuddapah Supergroup, but not the basal formation of the Kurnool Group—the diamondiferous Banaganapalle Formation. However, no modern geochronology has been attempted in the basin and any absolute age constraints will significantly advance knowledge of the evolution of this part of India.

The stratigraphy of the Kurnool Group is as follows:

- Nandiyal Shale
- Kodikuntla Limestone
- Panium quartzite
- Owk Shale
- Narji Limestone
- Banaganapalle Formation

U-Pb LA-ICPMS data will be presented from samples of Panium Quartzite and Banaganapalle Formation. These data will provide a framework in which the evolution of the basin can be discussed.

The tectonic setting of the basin is also of interest as it lies directly west of the southern Eastern Ghats and is thought to post-date orogenesis in this region. Deep seismic soundings have shown that the basin thickens eastward, towards the Eastern Ghats, and suggestions have been made that the Kurnool Group may form a foreland-basin to the orogen. As part of the present study we aim to examine the evolution of the basin in terms of its tectonic architecture and its age and test whether the sediments are derived from erosion of the newly exposed Eastern Ghats in the early Neoproterozoic.

Textural relationships of monazite and allanite during prograde metamorphism

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Timing and rates of metamorphism are important to our understanding of the dynamics of orogenic systems. Allanite [(Ca,REE,Th)2(Fe2+,Al)3Si3O12(OH)] and monazite [(Ce,La,Th)PO4] are both useful chronometers—especially given the reaction whereby detrital monazite is replaced by allanite (at greenschist facies conditions; in rocks with moderate to high amounts of Ca), and whereby allanite gives way again to monazite at amphibolite facies conditions (Janots et al, 2009). The reactions mean that more than one meaningful age can be obtained from a single sample. From this, metamorphic rates (heating, cooling, burial, exhumation) can be calculated, providing powerful constraints on the processes involved in orogenesis. Recognising the prograde textures between allanite and monazite is therefore vital in finding geologically significant ages.

Samples from the Lepontine dome, Central Alps, Switzerland, have been studied to gain insight into the timing of Barrovian metamorphism and to better constrain the behaviour of allanite and monazite during this event. Barrovian metamorphic conditions in the Lepontine are well constrained in terms of pressure and temperature (Todd and Engi, 1997), but age data are scarce or lacking in many areas. The samples studied are metapelites and quartzites that record medium pressure amphibolite-facies metamorphism.

Two impure quartzite samples from Campolungo, in the north of the Lepontine dome, experienced lower amphibolite facies conditions. The samples are composed of predominately quartz, with minor amounts of white mica, chlorite, rutile, garnet and epidote. Allanite and other REE accessory minerals are present: thorite (ThSiO4), xenotime (YPO4), and monazite. Element maps of allanite grains show REE and Th-rich cores; an Y-rich, but Th- and REE depleted mantle; and a rim of Th- and REE poor epidote. Where epidote forms a complete rim around allanite grains, allanite is preserved s relics.

In one quartzite sample, where allanite is breaking down, new thorite grains grow at the periphery of the allanite crystal. Contrastingly, in another quartzite sample, allanite is replaced by xenotime and sometimes, monazite. What controls the product of the reaction is unclear, and could be related to bulk composition, availability of P, or the trace element chemistry of the unstable allanite. Unfortunately, the new phosphate grains are too small (<<10 μm) for in situ SHRIMP dating. In these samples, allanite is invariably texturally early, so allanite age data reflect a stage in the prograde path of the rock.

One sample from Nufenen Pass, also in the northern part of the Lepontine dome, has preserved distinct depositional layers: one markedly Ca-poor; the other with moderate Ca contents. In more calcic layers large garnet, clinozoisite, white mica and biotite are present as well as accessory allanite. No monazite has been observed in these layers. In the Ca-poor layers, comprising quartz, white mica, feldspar and minor garnet and tourmaline, monazite is present but allanite is absent.

Similarly, in pelitic samples which contain high amounts of Ca, clinozoisite and epidote are stable, no reaction to consume allanite occurs. In these samples allanite is texturally early, and age data reflect a prograde stage. These samples demonstrate that the growth and stability of these accessory minerals is subject to a chemical control, especially the Ca concentration.

In Ca-poor samples that reached temperatures above ~600°C, monazite is present and allanite is not. Either allanite was never present in these samples, or has been completely replaced by monazite. The peak metamorphic assemblage is, typically: garnet, feldspar, white mica, biotite, chlorite, ilmenite, and often staurolite, kyanite, and tourmaline. Monazite is commonly associated with chlorite and biotite, and is interpreted to have crystallised at or near peak metamorphic conditions.

Dating of the different accessory phases within compositionally distinct layers will therefore provide detailed information on prograde and peak metamorphic conditions of these rocks. These data permit determination of

timing and heating rates and will provide new cornerstones for the evolution of the Central Alps, one of the classical Barrovian metamorphic terrains in the world.

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Architecture of the Arrowie Basin, South Australia, based on deep seismic reflection data

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The Arrowie Basin in South Australia represents the last phase of sedimentation in the Neoproterozoic to Cambrian Adelaide Rift System. As part of the Onshore Energy Security Program funded by the Australian Government, Geoscience Australia (GA), in conjunction with PIRSA, acquired a 60 km long deep seismic line (08GA-A1) in 2008 across the Arrowie Basin, immediately to the west of the central Flinders Ranges. The basin is of interest for petroleum exploration because about 15 km to the south of the seismic line, the Wilkatana wells drilled in the 1950s encountered non-commercial bituminous hydrocarbons in the Cambrian succession. In 2009, Torrens Energy acquired a 41 km long seismic line (09TE-01) at Parachilna, about 90 km to the north of the GA 08GA-A1 line as part of their geothermal exploration program. In the vicinity of these seismic lines, the Arrowie Basin forms part of the essentially undeformed Stuart Shelf (in the west) and the Torrens Hinge Zone (a zone of faulting and folding in the east). The Torrens Hinge Zone occurs immediately to the west of the highly folded component of the Adelaide Rift System in the Flinders Ranges. Both seismic sections display a near complete Neoproterozoic succession, but with a variable thickness of the Cambrian succession, due to localised deformation, uplift and erosion. Seismic line 08GA-A1 shows that the Arrowie Basin is asymmetrical, varying in thickness from about 600 m in the west, up to 2500 m in the east. The major, east-dipping Yadlamalka Fault is a post-depositional thrust fault and defines the eastern limit of the Stuart Shelf on the eastern end of this section. To the south of the seismic line, recent mineral exploration drilling intersected the Beda Volcanics (part of the basal Neoproterozoic Callanna Group) in the hangingwall of the thrust, indicating that there has been at least 1200 m of pre-Cenozoic throw on the fault. A narrow, linear magnetic high on the aeromagnetic images is interpreted to represent the Beda Volcanics on the eastern side of the Yadlamalka Fault. In this seismic section there is only a thin remnant of the Cambrian succession, which occurs to the east of the Yadlamalka Fault. A series of east-dipping thrust faults disrupt the stratigraphic section in the easternmost part of the seismic section. These faults might be related, in part, to the currently active, east-dipping, Wilkatana Fault, which occurs immediately east of the seismic line and is associated with the recent uplift of the Flinders Ranges. By way of contrast, the Parachilna seismic line (09TE-01) imaged a much thicker (>1500 m) Cambrian succession above the Neoproterozoic units. In this section the Neoproterzoic-Cambrian succession is over 3000 m thick at the western end of the line and about 7500 m thick at the eastern end of the line. Here, Cenozoic sediments are relatively thick (up to 500 m) in places and there is a significant angular unconformity at their base. In the western part of the seismic line a relatively coherent sedimentary package is terminated by the east-dipping Ediacara Fault. To the east of the fault the seismic reflectivity is low, although weak reflections define a relatively low-amplitude, long-wavelength anticline. It is possible that the low seismic reflectivity could be caused by a Neoproterozoic diapir, similar to those which are common in the Flinders Ranges to the east. The seismic section indicates that the Ediacara Fault is a major structure and that it has been reactivated in the Quaternary. The Cenozoic sediments are uplifted in the hangingwall to the east of the fault; movement on the fault is also responsible for the recent uplift of the Ediacara Range to the north of the seismic section. Other faults in the section, to the east of the Ediacara Fault, also show minor displacement of the Cenozoic sediments. There is good seismic reflectivity near the eastern end of the line, where a steep-sided syncline preserves Cambrian Lake Frome Group in its core. We interpret this syncline to be possibly a footwall syncline to a west-dipping thrust fault. Overall, the two seismic sections show a transition from the Stuart Shelf in the west to the Torrens Hinge Zone in the east. There is a thin, relatively undeformed stratigraphic succession on the Stuart Shelf, whereas the Torrens Hinge Zone is dominated by thrust faults and fault-related folds. The thrust faults cut the Cambrian succession, suggesting possible movement during the Delamerian Orogeny, with Quaternary fault reactivation, due to displacement of the overlying Cenozoic succession.

Pressure-dependent Zr-in-rutile thermometry of western Chinese eclogites from varied tectonic settings

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The Zr content of rutile is a thermometer that can record even very high peak temperatures given the limited mobility of the high field strength cations Zr and Ti, and the complexity of coupled substitutions that incoprorate tyhem in common minerals. It can be used in a very wide range of rock types, given the simplicity and ubiquity of the system. The experimental calibration of Tomkins et al. (2007) showed a significant pressure dependence for this thermometer. We have applied this thermometer to rutiles from ultrahigh-pressure terranes in Western China, and found that it yields temperatures that agree well with previous estimates by other methods, as opposed to the systematically lower temperatures given by Zr-in-rutile thermometers without the pressure correction. Our temperature estimates correlate well with the tectonic settings of the eclogites, whcih are from both 'oceanic' and 'continental' collisional belts. Zr contents of rutile inclusions within garnet show gradual decrease from garnet core to rim, interpreted to record the temperature and pressure change during growth of the garnet. Some larger rutiles retain zoning which probably logs part of the prograde P-T path prior to incorporation in growing garnet. Rutiles trapped in garnets are unable to re-equilibrate easily during retrogression since they are effectively closed systems at the temperature and timescale of metamorphism, but those in the matrix can do so, providing retrograde *P-T* path information. Examples are shown where invalid temperatures are calculated from extremely high measured Zr content in rutile, always associated with retrogressive symplectites that include zircon as a breakdown product of a precursor phase. We show that in some cases, the rutile incoporates submicron-scale zircon inclusions which may have been formed in this way.

Developing the geology of New South Wales in a 3D framework

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The Geological Survey of New South Wales is developing a new approach to regional mapping that incorporates traditional field mapping, high quality geophysical data/interpretations, and historical data into an interactive 3D environment that is built progressively throughout the mapping process. This process allows for a high degree of rapid interactions between all disciplines involved, where interpretations are queried and developed and reassessed. The final product will be a robust traditional geological map, multi discipline derived cross-sections, and a 3D geological model able to be viewed in a 3D framework and available in a user friendly format that will enable the viewer to assess and query the final product.

The increasing ability of geological software packages to now integrate and visualise diverse data sets in 3D framework allows for a more critical evaluation and convergence of interpretations. All available data sets (SEGY, LAS, drill strings and surveys, cross-sections, magnetic and gravity data, as well as traditional surface mapping) can now be visually interrogated, and this allows for a holistic approach to developing a better understanding and interpretation of both the exposed and covered geology.

The GSNSW currently has three projects being developed in a 3D framework, the project areas are-

- Braidwood (1:100 000 scale map sheet)
- Koonenberry Belt (14 x 1:100 000 scale map sheets)
- Thomson (10 x 1:250 000 scale map sheet)

The geological mapping of the Braidwood 1:100 000 scale map sheet is an example of the integrations outlined above. The progressive development of a 3D modelling project is as follows:

- Apply multiscale edge detection analysis technique to high resolution gravity and aeromagnetic data to produce 'worms'. Points are created at the maxima of the horizontal gradient of gravity and magnetic data which defines edges of bodies at different upward continuation levels, and linked together to form 'worms'. These 'worms' are then imported into Paradigm™ GOCAD® to create an inferred 3D structural surface with X, Y and Z components.

- The ‘worm’ surfaces produced represent planes that separate geological bodies and/or structures at depth, with different petrophysical properties—specific densities for gravity data, and magnetic susceptibility for magnetic data.

- Simple unconstrained geophysical models are then produced along proposed cross-section lines using Encom’s ModelVision software.

- Geologists and geophysicists work together to construct a number of serial cross-sections (up to 9 sections per 1:100 000 sheet) that are then geophysically modelled to check and if necessary, modified for admissibility.

- Higher degrees of complexity are introduced into the ModelVison derived geophysical bodies based on the constraints imposed by the geological structures detailed in the cross-sections.

- Geological cross-sections (constructed in Geo-Logic Systems LithoTect™), mapped geology and geophysical bodies are imported into a 3D framework in GOCAD® where inconsistencies can be observed and if required, reinterpretations are completed.

- Complex solid geology, constructed in GOCAD® using geophysical/geological constraints, bodies are built between cross-sections and constrained by mapped geology and geophysical properties.

- Multifaceted GOCAD® produced bodies are then validated in ModelVision, and this requires that GOCAD® produced bodies be completely sealed and that boundaries between bodies be flawless.

- The geophysical interrogation of complex geological bodies that span more then one section line, allows the solid geology of the entire map-sheet to be forward modelled. Subsequent inversions run in ModelVision, while considering all the geology geometries in a spatial sense, generate a 2¾D geophysical model that will validate, or invalidate, the 3D geological model over the whole area and locate areas requiring further input. Validation of the 3D model is achieved in ModelVison by constrained inversion along multi-orientated lines.

GOCAD® plug-ins are currently being evaluated that allow forward modelling and inversion engines to be linked and compatible with 3D modelling software packages such as UBC-GIF and 3D Geomodeller.

Software currently used as part of the 3D process includes GOCAD®, LithoTect™, Encom’s Modelvision, UBC-GIF, Intrepid’s Edge Enhancement and 3D-GeoModeller with delivery to stakeholders as Adobe Acrobat 3D.

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Preservation of geochemical diversity of primitive magmas signals the occurrence of multiple melting regimes at the southern end of the North Fiji Basin

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The initial products of mantle melting are rarely preserved in whole rock compositions of volcanic rocks erupted within intra-oceanic arc settings. Because of this we are yet to fully understand the physical, chemical and thermal structure of the sub-lithospheric mantle and therefore the conditions that drive the formation of the overlying crust. The southern, mostly submarine portion of the Vanuatu arc, known as the Hunter Ridge, in the Southwest Pacific is an ideal location in which to study the nature and composition of primary mantle-derived magmas. The southernmost active spreading centre of the North Fiji Basin, which is propagating southward and impinging on the Hunter Ridge, dominates the geodynamic setting. Further, the Hunter Ridge is located along a portion of the Vanuatu arc where there is a transition from a zone of increasingly oblique subduction to a transform fault setting. At the intersection with the southward propagating spreading centre the Hunter Ridge is being split into two east-west oriented segments separated by a magmatically active rift zone. The atypical subduction dynamics have led to the eruption of primitive rocks that have in turn preserved a range of distinct primary (high-MgO) melts as olivine-hosted melt inclusions. These preserved melts have been systematically studied from two of the most mafic volcanic endmembers from the southern segment of the rifted Hunter ridge and the recently formed rift zone.

Magmas belonging to the island arc tholeiite (IAT), low-Ti IAT and boninitic series have erupted along the southern segment of the rifted Hunter Ridge (7–3 Ma). One of the most mafic end-members of the low-Ti IAT series is represented by a primitive olivine-phyric rock, D2-1, of picritic composition. The major and minor element compositions of the olivine-hosted melt inclusions provide strong evidence for the involvement of three distinct melts in the generation of D2-1, including a high-Ca boninitic (HR-Boninite) melt that persists over a prolonged fractionation interval (16.5–6.8 weight per cent MgO) and two melt types that each correspond with the IAT and low-Ti-IAT magma series from the Hunter Ridge referred to as HR-IAT and HR-LT-IAT, respectively and which are restricted to primitive olivines and extend over much shorter fractionation intervals (16.6–10 weight per cent MgO). The geochemical characteristics of these parental melts can be attributed to the combination of a depleted mantle wedge source that has been fluxed by slab-derived fluids carrying LILEs and subducted, sediment-derived partial melt that is enriched in incompatible trace elements.

Contrasting with the magmatism along the Hunter Ridge is a distinct and diverse range of magmas erupted within the Hunter Ridge Rift Zone (HRRZ) belonging to the tholeiitic/calc-alkaline, back arc basin basalt (BABB) and high-Mg andesite (HMA) series. The most mafic end-member of the tholeiitic/calc-alkaline series is represented by D3-1, a fresh olivine- and clinopyroxene-phyric basaltic rock. The compositions of its olivine-hosted melt inclusions indicate that three distinct melts were involved in its generation. The first is a relatively evolved melt, HRRZ-D3-1(I), with a short fractionation interval (9.6–5.5 weight per cent MgO). The second melt, HRRZ-D3-1(II), is slightly more primitive and has a greater fractionation interval (12.6–7.4 weight per cent MgO). The third melt composition is unique in having strong adakitic affinities. This melt type is referred to as HRRZ-HMA and has a fractionation interval intermediate to those of the other two melt types (13.8–8.8 weight per cent MgO). The geochemical characteristics of the parental melts are attributable to a depleted mantle source that was subsequently and variably enriched by three components, which include slab-derived fluids carrying LILEs, a slab-derived silicate melt and a partial melt from a BABB source originating from the southward propagating back-arc spreading centre that is driving the formation of the rift zone.

The results presented here focus on the geochemical modelling of the calculated parental melts and illustrate the utility of studying melt inclusions in primitive mineral phases to understand the initial stages of magma genesis. The compositional diversity of olivine-hosted melt inclusions provides strong evidence that more than one parental melt was involved in the generation of primitive volcanic rocks erupted at the southern end of the North Fiji Basin (NFB). The primary nature of these melts indicates that the onset of melting was triggered by several different subduction-related inputs in a tectonic setting characterised by atypical subduction features.

The significance of early hybrid and superposed folds for tectonic transport directions in Ordovician greywacke and slate of the Bermagui area, NSW

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Ordovician greywackes and slates in the Bermagui area of the Eastern Lachlan Fold Belt have undergone a complex deformation history, including local superposition of folds and cleavages, as well as multiple faulting and veining episodes. Two problems that have arisen concerning the early part of the deformation history are: (1) apparently contradictory time relations in the area (west- and east-facing F1 overprinted by upright F2, and upright F1 overprinted by west-facing F2) and (2) how a well developed slaty cleavage (the earliest deformation fabric, known as S* or 'near bedding parallel' cleavage) could form without any accompanying folding.

The writer suggests a new approach for analysing these structures which takes into account the likely mechanical responses of layered strata and deformation fabrics to subsequent strains. Thus, if bedding on early fold limbs rotates towards and remains within the extending sector of an incremental deformation ellipse, no new folds will develop. But cleavage within the layers may be overprinted by a later cleavage if the strain increments are non-coaxial, especially if the early cleavage is well developed and strongly refracted, as it is in pelites in the hinges of many folds in the Bermagui area. To refold bedding would require a greater change of incremental strain direction relative to the fold, or perhaps a switch of direction. Some models will be presented to illustrate how these effects may occur.

Using this concept, the early ductile deformation events in the area are interpreted as follows.

D_E. The earliest recorded event in the area was regional east-vergent inclined F_E folding with accompanying slaty cleavage in pelite.

D_W. D_E was followed by a regional west-vergent inclined D_W deformation which, over most of the region, only reoriented F_E folds to steep attitudes. These may preserve an early slaty 'S*' overprinted by crenulation in what are now upright hybrid folds. In places (e.g., Bermagui), D_W was sufficient to refold west-facing limbs of the early structures to form inclined to recumbent coaxial superposed west-facing F_W folds. These too may preserve early slaty 'S*' in the hinges.

D_U. D_W changed progressively to a steep deformation, D_U, as typically occurs towards the end of a recumbent fold episode. Again, over most of the region this would only have tightened the pre-existing steep to upright hybrid folds. However, where F_E folds were still preserved in near-original attitude (Murunna Point) or where F_W folds had developed (Bermagui), those folds may lie in the shortening sector of D_U and may therefore be refolded by upright coaxial F_U.

In this way, a variety of local and seemingly contradictory structural relations may be explained by a coherent sequence of tectonic events. The first would be east-directed thrusting (possibly related to subduction) and the second, west-directed thrusting or back-thrusting (perhaps collision-related). The third was accompanied by minor transverse wrench faulting and associated vein-arrays and was therefore a wrench-tectonic style with north–south stretching. Stripy, slaty and crenulation cleavages are texturally similar in the three deformations and so most likely formed during one thermal and orogenic event (dated ca. 445 Ma or Benambran by Offler and co-workers using white mica Ar-Ar).

The Lockhart Igneous Complex: Plutonic links with volcanism during Silurian rifting, eastern Lachlan Orogen, south-eastern Australia

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The Lockhart Igneous Complex (LIC) is a granite–gabbro complex situated in the axis of a middle-Late Silurian rift basin near Braidwood in the eastern Lachlan Orogen. The complex comprises a felsic host of biotite granite and granodiorite interlayered with mafic sheeted dykes or sills comprising orthopyroxene – clinopyroxene ± olivine gabbro, hornblende gabbro and hornblende dolerite. Importantly, mingling and mixing relationships are preserved at the contact between the mafic and felsic components, locally manifesting as zones of quartz diorite to tonalite laden with gabbroic enclaves. This intrusive system also includes several coeval high-level granitic plutons including the Ellenden Granite.

Directly to the north the intrusive complex is overlain by a middle–Late Silurian syn-rift volcanic sequence comprising submarine rhyolitic volcaniclastics and lavas of the Woodlawn Volcanics, overlain by pillow basalt of the Currawang Basalt—both volcanic units host significant VHMS mineralisation. Despite the spatial association and compositional similarities between the plutonic and volcanic rocks, a direct petrogenetic link has never been established due to a poor understanding of the timing relationships between the mafic and felsic components of the LIC, and a presumed Early Devonian age for the felsic components of the LIC and coeval high-level granites.

Preliminary SHRIMP U–Pb zircon ages obtained in support of recent remapping of the Braidwood 1:100 000 sheet show that the c. 428–424 Ma LIC and coeval high-level granites (c. 423 Ma Ellenden Granite) are contemporaneous with the c. 423–419 Ma Woodlawn Volcanics and Currawang Basalt. Furthermore, whole-rock geochemical data show that mafic phases of the LIC share several important geochemical characteristics with the Currawang Basalt, such as low K, a tholeiitic Fe-enrichment trend, and lack of significant REE fractionation. The felsic components of the LIC also have similar major and trace element characteristics to the Woodlawn Volcanics.

In the light of the new mapping, age and geochemical data, the combined plutonic and volcanic associations are reinterpreted as a largely undisturbed upper-crustal profile through a middle-Late Silurian rift basin—contact relationships around the plutonic rocks suggest they have not seen significant post-intrusion displacement relative to the overlying volcanic rocks. From this deduction, the architecture of the upper crust during the middle–Late Silurian can be reconstructed and involves high-level granitic plutons that intrude close to the sea floor and the base of the Woodlawn Volcanics. Discontinuous sills of similar composition also

intrude at higher levels within the Woodlawn Volcanic pile. At the same time deeper-level felsic magma chambers (approximately 5 km depth) were invaded by mafic melts, resulting in localised mixing and mingling. In the later stages felsic volcanism ceased and pillow basalts were erupted on the sea floor.

The new data suggest that the Ellenden Granite is a high-level subvolcanic pluton related to the Woodlawn Volcanics. The intrusion of this granite close to the middle Silurian sea floor may have been important in establishing the hydrothermal convection cells that drove VHMS mineralising systems, including those which produced the world-class Woodlawn Cu–Pb–Zn deposit. At the same time the injection of mafic melt into slightly deeper-level felsic magma chambers resulted in only limited hybrid melt generation, which is consistent with the bimodal nature of the volcanism. Mafic melt injection may have been the catalyst for venting of the felsic magma chambers, and/or may have provided the heat input required to initiate hydrothermal convection above the felsic chambers and ultimately VHMS mineralisation. Mafic magmatism outlasted felsic magmatism and culminated in the eruption of the Currawang Basalt.

The Silurian Kohinoor Volcanics, around Captains Flat to the south, also host VHMS mineralisation and may be related to the LIC system. Ultimately the LIC may provide vital insights into the development of VHMS provinces in the eastern Lachlan Orogen.

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Changing conditions of mantle wedge melting across arc as illustrated by changing iron isotopes compositions

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It is well established that subduction magmas are both more oxidised and hydrous than mantle-derived magmas from other tectonic settings. The slab is understood to have a key role in the source of these hydrous fluids and in the delivery of oxidative capacity to the mantle wedge. However the details of this process are much less well understood. Does water flux from the slab vary with depth? Does the oxidation of the wedge vary with depth? These are key questions that await resolution. As a new innovation, we have undertaken iron isotope analyses on a range of Indonesian basalts and andesites. The isotopes in question are stable isotopes and fractionation is the result of kinetic effects. Given preliminary results that suggest that exchange between melts and residues may be influenced by the presence of ferric iron-bearing minerals in the residues.

Active volcanoes in the eastern Sunda Arc, Indonesia are distributed across a wide range of position above the active Benioff Zone. These include the near fore-arc tholeiite suite from Ija volcano on Flores Island which is about 100 Km above the slab. Then at successively greater depths are the archetypal calcalkaline suites of Rinjani and Batur volcanoes on Lombok and Bali and then the rear arc alkalic suites from Tambora, Sangeang Api and Batu Tara. The latter approaching 200km above the slab. The fore-arc volcano Ija is clearly influenced by hydrous fluid flux from the slab, having high Ba/Th and U/Nb ratios. The strongly undersaturated alkalic suites from Tambora and Batu Tara are highly enriched in LIL incompatible elements, but do not have sufficiently anomalously high 87Sr/86Sr or Pb isotopic ratios or low 143Nd/144Nd ratios to explain this anomaly as entirely due to significantly larger components of subducted sediment. This implies that these rear arc volcanoes are the product of smaller percentage melting of the supra-slab mantle wedge.

δ56Fe values were determined. These show significant variation ranging from ~0 up to +0.3 close to the natural variation of the MORB–OIB basalt suite. The results of these analyses indicate:

- There is weak positive correlation with 143Nd/144Nd and negative with 87Sr/86Sr (and Pb isotopes)
- Fe is more fractionated (heavier) from above shallower Benioff Zone, perhaps where the slab flux is fluid – dominated? This might implicate the role of oxidised fluids, perhaps generated by serpentinite de-hydration?
- Deeper wedge melting seems associated with slab melting, indicated by higher Ce/Y, associated with less fractionated (lighter) Fe. Perhaps the deeper mantle wedge has lighter Fe due to prior heavy Fe extraction in the shallow wedge followed by entrained flow downwards?

- There is a very good negative correlation between Mg# and Fe isotopic composition, suggesting that fractional crystallisation involving magnetite depletes the magma in the lighter Fe isotopes.

Based on this very preliminary study, our conclusion is that Fe isotopes provide a new and novel tool with which to examine changing redox states in the sources of arc magmas.

Reducing the risk of sample contamination in geochronology

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No geochronologist ever wants contamination to occur in their samples. Similarly, no-one ever wants to be placed in a situation where they must admit that some of their analyses are, or may be, contaminated.

Recent technological advances in geochronological methods have enabled the analysis of smaller aliquots of minerals. In some geochronology techniques, such as TIMS (Thermal Ionisation Mass Spectrometry), and SHRIMP (Sensitive High Resolution Ion MicroProbe), it is now commonplace to analyse single mineral grains with diameters in the order of a few tens of microns.

Cross contamination of minerals is an ever-present risk in any mineral separation laboratory. Analysts must be confident that their data truly represent the rock being tested. During the analysis of single grains, a contaminant analysis may or may not contrast from the other analyses. Spurious analyses may well be accepted as a new geological discovery. In most cases, it is practically impossible to confidently detect which analyses are from contaminants, and which are not. The consequences of undetected contamination in geochronology samples include: spurious data leading to incorrect interpretation, the publishing of incorrect information and consequent professional embarrassment and loss of reputation. Costs associated with sample re-processing, and re-analysis are significant.

It is therefore essential to closely scrutinise the entire sample collection and mineral separation workflow, identify areas and processes of elevated risk with respect to contamination, and expend significant effort in the search for ways to reduce those risks. The first step is to ensure the best possible quality of the parent rock sample, in order to eliminate as far as possible the incorporation of foreign material from the sampling site. Secondly, a meticulous approach to cleanliness within the mineral separation laboratory, which includes rigorous cleaning of separation equipment, is essential. However, there are practical limits which apply to the amount of time which can be devoted to cleaning, and the extent to which additional cleaning effort will result in a commensurate improvement in contamination risk.

One effective strategy to reduce contamination risk is to dilute it. This can be achieved by ensuring that the original rock sample is as large as practically possible. When compared to the total time spent on cleaning the lab, the actual time taken to crush a rock is relatively small. For example, in the Geoscience Australia mineral separation lab, it currently takes about 3 hours to clean the crushing lab and equipment to a satisfactory level, yet rock crushing (i.e. splitting, coarse crushing, and milling) can be performed at the relatively rapid rate of <9 minutes per kilogram. The use of other equipment, such as a Wilfley table, can dramatically reduce a large sample to a relatively small concentrate of heavy minerals. If it is assumed that cleaning protocols reduce the risk of contamination to some constant background level, then multiplying the sample size by a factor, should reduce the contamination risk by that same factor.

The processing of larger sample volumes provides significant advantages resulting from the increased yield of best quality target minerals.

Comparison of dynamically recrystallised quartz rich microstructures utilising electron backscatter diffraction

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Dynamic recrystallised rocks are of interest to geologists as their microstructures provide essential information which can be used to interpret the conditions of deformation, the controlling processes of deformation and the kinematic strain path. Recrystallisation involves the formation/nucleation and growth of new grains. The

individual mechanisms by which recrystallised grains nucleate and grow, and other processes that might operate in tandem, such as grain boundary sliding, have specific, predictable effects on the crystallographic relationships between host and recrystallised grains or 'parent' and 'daughter' grains. Complete quantification of microstructures is now possible with the use of electron backscatter diffraction (EBSD), a scanning electron microscope (SEM) based technique (Prior et al., 1999). EBSD was used to measure the full crystallographic orientations of individual grains, which enables the study of misorientation relationships within grains and between neighbouring grains. Using the data it is possible to analyse the evidence and determine the controlling recrystallisation and nucleation mechanisms, as well as any other mechanisms which have modified the microstructure. EBSD has been used to quantify a variety of natural quartz rich samples which were deformed under various pressure and temperature conditions.

Stac B was collected from approximately 70m below the Moine Thrust zone, Scotland from Cambrian quartzite and exhibits 20% recrystallisation. CT210b was borrowed from Bernhard Stöckhert and was collected from the Sesia Zone, European Western Alps and exhibits a 35% recrystallised microstructure. I9 was collected from the Tonale Line, Adamello Pluton, NE Italy and exhibits a 45% recrystallised microstructure. The average neighbour-daughter (a neighbour-daughter is a recrystallised grain which is still in contact with an original protolith grain or parent, but not necessarily the one it recrystallised from) grain size for stac B 11.5 μm, whereas the average subgrain size of the parent grains for stac B is 17 μm. For I9 the average neighbour-daughter grain size is also 11.5 μm, whereas the internal subgrain size is 15.5 μm. So the subgrain size is larger than the size of the neighbour-daughters. CT210b exhibits subgrains and neighbour-daughter grains of the same size. The average angle of misorientation between the 'parent' and 'neighbour-daughter' grains is 10 to 15° for all samples. The parent grains in the samples exhibit internal deformation forming misorientation angles and subgrain boundaries of between 2° and 5°, but there is no systematic increase in misorientation from the centre of the parent grain to the edges in stac B or I9, but there is in CT210b. Each parent grain in the samples is surrounded by neighbour-daughter grains which have nucleated from other parent grains. Therefore there has been physical mixing of the neighbour-daughter grains.

For subgrain rotation recrystallisation to be the controlling recrystallisation mechanism it is expected that the neighbour-daughter grains are of similar size to the parental subgrains. This is not the case for Stac B and I9, but is for CT210b. Subgrain rotation recrystallisation should also produce a systematic increase in misorientation from the center of the parent grain to the edge. This is not the case for Stac B and I9, but is for CT210b, therefore the evidence shows that the controlling nucleation and recrystallisation for CT210b is subgrain rotation recrystallisation. The microstructure has been modified due to the mixing of neighbour-daughters between parent grains. Nucleation in Stac B and I9 may have taken place via bulging due to differences in the dislocation densities on either side of the grain boundary. Bulge size is not controlled by the subgrain size, so the size incompatibility is not an issue. Full isolation of the grain is achieved by the development of a bridging subgrain boundary and its conversion by progressive misorientation into a grain boundary. This process begins the rotation of the neighbour daughter grains. Further rotation is achieved by grain boundary sliding. The neighbour-daughter grains rotate until the misorientation builds up enough for them to be able to slide between parent grains causing mixing of the daughter orientations. This successive interaction of nucleation, recrystallisation and microstructural modification processes fits with the evidence observed from the microstructure in Stac B and I9. Grain boundary sliding can also be used to explain the microstructural modifications observed in CT210b.

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Compressional deformation and uplift of Australia's 'passive' southern margin

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Passive margins are generally considered to remain tectonically quiescent subsequent to continental breakup, and are predicted to experience progressive subsidence and no significant deformation during the 'post-rift' stage of their evolution. It is becoming increasingly apparent however, that many passive margins have experienced complex post-rift histories characterised by episodic uplift and compressional deformation. One

such margin is the southern Australian passive margin, which formed during Cretaceous-Palaeogene separation from Antarctica. The Cenozoic sedimentary successions of the Bight and Otway basins contain a number of regional (length scales >1000 km) unconformities and have locally experienced intensive compressional deformation characterised by folding and reverse faulting. Observations of Quaternary faulting and elevated levels of seismicity onshore south-eastern Australia show that this deformation is continuing to the present-day. We have been attempting to quantify the timing and magnitude of Cenozoic uplift and deformation along the southern Australian margin in order to determine the underlying causes and assess the impact of these processes on the hydrocarbon systems of the margin. Our integrated approach combines structural and stratigraphic mapping of 2D and 3D seismic reflection data with techniques for determining uplift such as apatite fission track analysis (AFTA), vitrinite reflectance (VR) and sedimentary rock compaction data. Ongoing seismic mapping is focused on defining the extent of regional unconformities of base Palaeocene, mid Eocene, mid Oligocene and late Miocene-Pliocene age. The mid-Eocene and late Miocene-Pliocene unconformities can be correlated with uplift-related cooling episodes resolved from a regional synthesis of AFTA data, which began between 55 and 40 Ma and 10 and 5 Ma, respectively. AFTA and VR data from the eastern Otway Basin show that erosion associated with the Miocene-Pliocene unconformity locally exceeds ~1 km, whilst seismic data show that major compressional structures of this age such as the Otway Ranges and Minerva and Nerita anticlines formed by reversals of motion along the normal faults that accommodated extension during formation of the margin. Both the mid Eocene and late Miocene-Pliocene unconformities and cooling episodes can be correlated with major reconfigurations of the boundaries of the Indo-Australian plate, and our results indicate that passive margins can act as sensitive tectonic recorders of intraplate responses to plate-scale stress reorganisations.

Petrogenesis of Jurassic Jiuyishan fayalite-bearing granites and tectonic implications

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Mineralogical, geochemical and in situ zircon U-Pb and Hf-O isotope analyses have been conducted on the Jiuyishan granitic rocks, which are parts of the late Mesozoic large magmatic province in South China. Secondary Ion Mass Spectrometry (SIMS) geochronology reveals a zircon crystallisation age of 154.1 $\pm$ 1.0 Ma. Petrography study demonstrates that early crystallised minerals fayalite and ferrosilite were followed by late crystallisation of Fe-rich biotite and hornblende, which testifies 'dry' and reduced nature of the parental magma. Geochemical characteristics such as high Ga/Al, FeO_t/MgO and K_2O/Na_2O ratios and elevated concentrations of high field strength elements (HFSE) and rare earth elements (REE), combined with high zircon saturation temperature, confirm that the Jiuyishan granites, with extended SiO_2 range (64.1–76.5%), are typical A-type granites. The evolved whole-rock Sr-Nd isotope compositions (initial $^{87}Sr/^{86}Sr$ ratios spread from 0.7151 to 0.7181 and εNd (t = 154 Ma) values vary from -9.2 to -5.0) and in situ zircon Hf isotope ratios ($\varepsilon Hf(t)$ mostly vary from -8.2 to -2.3), particularly the high zircon oxygen isotope ratios (mostly in the range of 8.0 to 10.0‰) clearly point to a source of crustal component dominated by sedimentary rocks. The low water activity strongly suggest that source for the Jiuyishan A-type granites were most probably dehydrated or melt-depleted in an earlier thermal event. Derivation of high temperature melt with high Fe content from a sedimentary source would certainly require voluminous mafic melt underplating, possibly related to the foundering of a previously subducted flat-slab.

Using soft-sediment deformation to date paleoseismic events in bore holes, IODP Leg 319, Kumano Basin, Nankai Trough, Japan

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This project tests whether soft-sediment deformation observed in a core can be used to date paleoseismic events. Wells typically do not offer the same paleoseismic data the trenching of a fault onshore might. However, in some instances constraining the timing of soft-sediment deformation might yield the timing of paleoseismic events.

Soft-sediment deformation is recognised by an asymmetric fold bounded above and below by flat, undeformed sediments. In a fore arc basin like the Kumano basin, there is little slope. A fold that does not

extend through deeper layers cannot be tectonic, rather is best explained as the result of seismic shaking. The timing of the fold would be constrained by the youngest layer folded and the oldest overlying layer that is unfolded.

Prior to the drilling of well C0009A, three geotechnical cores were acquired near that site. The first of those geotechnical cores has an asymmetrical fold in the upper 10cm of that core. The fold is best imaged on CT scans of the entire core. The fold cannot be due to the coring process because the fold is asymmetric and one limb is nearly vertical. The fold cannot be tectonic because 10cm from the top of the core are flat-lying strata, below the fold. The fold is interpreted to be soft-sediment deformation.

The timing of the fold will be determined by using oxygen-isotopes on foraminifera to place the strata on the sea-level curves, and with AMS ^{14}C dating of foraminifera to determine which curve the strata correlate with. Because the soft-sediment deformation is so near the surface of the sea floor, it is hoped that the constrained dates will bracket a known paleoseismic event.

The Andros detachment, Cyclades, Greece: time of shear zone activity and the original nature of the fault zone

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The Attic-Cycladic crystalline belt (ACCB) in the central Aegean region is a major tectonostratigraphic unit of the Hellenides. The ACCB records a complex structural and metamorphic evolution which documents various stages of the closure of the Neotethys ocean, the collision of continental fragments and extension-related exhumation. Two major structural groups of tectonic units with contrasting metamorphic histories can be distinguished, that are separated by low-angle normal faults. A pre-requisite to develop an improved tectonic history of the study area is dating of tectonic displacement along major shear zones. Such ages will provide important constraints for refining existing geodynamic models. On Andros, a notable detachment is exposed and we tested the possibility to date the time of shear zone activity by means of Rb–Sr geochronology. Furthermore, we used LA-ICP-MS U-Pb zircon dating to determine protolith ages for clastic metasediments occurring on both sides of the tectonic contact.

The metamorphic succession on the island of Andros can be subdivided into two tectonic units, the Makrotantalon Unit and the Lower Unit. The Makrotantalon Unit belongs to the upper group of units of the ACCB, which has not been affected by HP/LT metamorphism. The Lower Unit can be correlated with the Cycladic blueschist sequences, which experienced HP/LT metamorphism during the Eocene and a greenschist-facies overprint at c. 23–21 Ma [1]. Both units are separated by a low angle fault, which is well exposed along the NE coast of Andros [2]. In the NW part of the island the exact position of the detachment is difficult to localise, but the tectonic contact is roughly outlined by serpentinites. During this study, detailed field work focusing on the presumed contact zone revealed a key location within a metasedimentary succession that displays a weak angular unconformity with cohesive cataclasites and/or pseudotachylites.

Rb–Sr geochronology was carried out on 9 samples representing clastic metasediments, calc schists and greenschists that were collected within a distance of <5 to ~50 m on both sides of the detachment. To characterise the white mica populations used for geochronology, polished thin section were prepared from splits of the phengite separates. Electron microprobe analyses indicate variable compositions, suggesting the presence of mixed populations. Multigrain dating of such populations can not provide accurate and precise ages but only yields an upper time limit for tectonic displacement. For samples from the Makrotantalon Unit, internal mineral isochrons indicate apparent ages between 51 and 35 Ma. In the NW part of the island Rb-Sr phenite ages of samples collected below the contact zone vary between 56 and 30 Ma. In contrast, samples from the NE area yielded a relatively narrow range of apparent ages (c. 29–24 Ma). Most of the scatter observed in the new data set most likely records the influence of regional greenschist-facies overprinting at c. 23–21 Ma that caused incomplete resetting of pre-existing mica populations in the hanging and the footwall of the fault zone. However, the 29–24 Ma age group from the NE coast is considered to closely approximate the time of tectonic juxtaposition, indicating that activity along this detachment is older than previously assumed.

U-Pb dating of detrital zircon indicates maximum depositional ages of c. 260 Ma for the Makrotantalon Unit and of c. 170–160 Ma for the Lower Unit. These age constraints are consistent with interpretations suggesting an inverted tectonostratigraphy—rocks at the top of the succession are older than the structurally lower

sequences—implying that the contact between both units originally represented a thrust fault. Due to large-scale regional extension, this contact was later reactivated as a low-angle normal fault [3].

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In situ U-Pb and Sm-Nd isotopic systematics of monazites from metasediments in Mt Narryer, Western Australia: constraints on the tectonothermal history and provenance

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Knowledge of early crustal evolution is central to deciphering the evolution of the young Earth. Metasediments from the Mt. Narryer region in the Yilgarn Craton of Western Australia are of particular importance for the study of early crustal evolution because they yield Hadean (>4.03 Ga) detrital zircons (ref. 1); no crustal rocks have been found from the first 500 Myr of Earth's history. To better understand the tectonothermal history and provenance of these ancient metasediments, we have undertaken a combined U-Pb geochronological and Sm-Nd isotopic studies of monazites from these metasediments.

Monazite, a LREE phosphate mineral, is ubiquitous as an igneous accessory phase in granitic (sensu stricto) rocks and as a secondary accessory phase in a wide range of metamorphic rocks. Because monazite has high U and low common Pb contents, U-Pb isotopic dating can provide precise and accurate timing of igneous and metamorphic events. In addition, initial Nd isotopic ($^{143}Nd/^{144}Nd$) compositions at the time of monazite crystallisation provides constraints on whether the source magma is of juvenile 'mantle' origin or reflects a more extensive crustal reworking history. In this study, U-Pb dating and Sm-Nd isotopic analysis were carried out using in situ laser ablation-ICPQMS and laser ablation-MC-ICPMS, respectively.

The U-Pb isotopic analyses for ca. 500 monazite grains reveal that Mt. Narryer metasediments experienced two high-grade metamorphic events; one at ~3.3–3.2 Ga and another at 2.7–2.6 Ga, when peak granulite-facies metamorphism occurred. These results set a new minimum age of 3.2 Ga for deposition of the Mt. Narryer sediments, previously constrained between 3.28 Ga and ~2.7 Ga (ref. 2). Despite the significant metamorphic monazite growth, detrital monazites with ages up to 3.6 Ga survive with one sample having relatively high proportion of older grains. This could be primarily due to its high Fe and Mn bulk composition, leading to the efficient shielding of old monazite by garnet. The age populations of the detrital monazites indicate that the Mt. Narryer sediments were partly derived from 3.6 Ga and 3.3 Ga granitic rocks. No monazites older than 3.65 Ga have been identified, implying either that the source rocks of >3.65 Ga detrital zircons in the sediments contained few monazite (i.e., non-granitic rocks) or that >3.65 Ga detrital minerals experienced significant metamorphic events or prolonged sedimentary recycling, resulting in the complete dissolution or recrystallisation of monazite.

Initial $^{143}Nd/^{144}Nd$ ratios were obtained for the detrital and metamorphic monazites with well constrained U-Pb ages. A comparison of the Nd isotopic data from metamorphic and detrital monazites indicates that younger metamorphic monazites inherit their Nd isotopic signatures from pre-existing detrital monazites, implying that detrital monazites dominate the LREE budget during metamorphic monazite formation. The 3.6 Ga and 3.3 Ga detrital monazites have initial Nd isotopic ratios corresponding to those of the contemporaneous Meeberrie gneiss and granites in the Narryer Gneiss Complex (ref. 3), consistent with the derivation of Mt. Narryer sediments from them. We calculated Nd isotopic model ages for the monazites to estimate the mean mantle-extraction ages of their source materials. Most of the grains have model ages between 4.1 Ga and 3.6 Ga. This finding, combined with the lack of monazites having U-Pb ages older than 3.65 Ga, indicates that Hadean and Eoarchean crustal materials had significant contributions to Mt. Narryer sediment formation, but they were extensively reworked into younger crustal materials via crustal melting and/or metamorphism.

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New forced-oscillation methods for laboratory study of the seismic properties of cracked and fluid-saturated crustal rocks

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In shallow crustal environments ranging from earthquake fault zones to geothermal power extraction, seismic wavespeeds and attenuation are profoundly influenced by the presence of cracks filled with relatively compliant aqueous fluid. The expected frequency dependence of such poroelastic behaviour provides strong motivation for the development of new broadband techniques for the laboratory measurement of seismic properties. Accordingly, we are seeking to combine mHz-Hz forced-oscillation methods being developed at ANU with ultrasonic (MHz) wavespeed measurements at the University of Alberta to characterise the seismic response of cracked and fluid-saturated media across eight decades in frequency.

In the first phase of this project, we have developed flexural oscillation methods for use alongside the established torsional mode capability of our ANU laboratory, and established new procedures for independent control of confining and pore-fluid pressures. Our experimental assembly is a cylindrical beam comprising sections of varying cross-section fabricated from steel and polycrystalline alumina, along with the rock specimen, assembled in series within a close-fitting metal sleeve. In flexure, the beam functions as a propped cantilever, driven by an electromagnetically applied time-varying bending moment, and the resulting flexure is measured at two locations within the beam by parallel-plate capacitance displacement transducers sensitive to the local angle of flexure. The polarity of the drivers and of the displacement transducers can be reconfigured to allow the same experimental assembly to be studied in either torsional or flexural oscillation. Experimental results for flexural oscillation of a fused silica specimen, under high confining pressure within an argon gas-charged pressure vessel, are closely consistent with expectations from numerical modelling with a crude finite-difference approximation, in which the role of shear stress is neglected. Further progress in development of the flexural mode capability will be reported, including finite-element modelling of the stiffening effect of shear stress; modelling of the perturbing influence of interaction between the oscillating specimen assembly (especially the closely-spaced parallel plates of the displacement transducers) and the dense argon pressure medium; and the development of a practical strategy for inversion of the relative amplitudes and phase of the measured angles of flexure to infer the complex Young modulus of the poroelastic specimen. In parallel with these developments, we have prepared specimens with narrow distributions of crack aspect ratio by quenching cylindrical specimens of polycrystalline alumina and Cape Sorell quartzite from 1100–1400°C into liquid nitrogen.

The results of exploratory studies of these simple cracked media in flexural and torsional oscillation tested dry, and argon- and water-saturated, will be used to demonstrate the potential of our versatile new petrophysical facility.

Acknowledgment

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Strike-slip characteristics of the Willunga Fault at Sellicks Beach, Fleurieu Peninsula, South Australia

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The Willunga Fault is one of the active neotectonic faults bounding the western margin of the southern Mount Lofty Ranges in South Australia. It has a significant outcrop due to coastal erosion of disrupted Quaternary units at Sellicks Beach. The fault zone is defined by a distinct escarpment rising ~300 m from the coastal plains and extends ~30 km inland in an acuate manner from a NE-SW strike at Sellicks Beach. The Willunga Fault is comprised of numerous fault planes that include thrust, normal and strike-slip faults that make up a fault zone extending from the shoreline at Sellicks Beach to well back into the 300 m high range front. The neotectonic fault zones are characterised by brittle deformation with the fault gouge material consisting of a clay-rich, poorly sorted, angular fragments of country rock (quartzite, pelite) and in some cases stringers of coarse, iron-stained sand that has been dragged in from the Oligocene Port Willunga Formation or the younger terrestrial units (Seaford, Ochre-Cove, Ngaltinga, Pooraka Formations). Occasionally slickensides and micro-steps are present on the margins of clay-rich fault gouge, but this is rare and the determination of fault kinematics is difficult.

Topographic characteristics were extracted from the cross sections and digital elevation models generated from LIDAR and SRTM images of the Sellicks region. Tertiary and Quaternary sedimentary units such as the Port Willunga Formation provide important information on the amount of vertical offset either side of major fault zones. The Port Willunga Formation is found flat lying about sea level at Sellicks beach but tilted almost vertically closer to the Willunga Fault where it has been planed off and covered with younger Quaternary terrestrial deposits. About 12 km inland at Myponga, the Port Willunga Formation can be found outcropping at an elevation of about 250 m indicating ~ 250 m of vertical offset since deposition of the Port Willunga Formation ~34 million years ago.

Detailed structural mapping of fault exposures and deformed Cenozoic units was undertaken to determine the location and nature of the faults. Traverses through erosion canyons revealed the existence of several fault splays in addition to the well documented and distinct frontal thrust at Waterfall Creek. Fault planes tend to become steeper towards the range front and the faults appear to follow an *en echelon* strike pattern which gave rise to the hypothesis that the whole Willunga Fault Zone represents a positive flower structure typical of transpressional strike-slip system. The strike orientation of several low-angle thrusts at Sellicks is on average roughly E-W which is incongruent with the overall NE-SW trend of the Willunga Fault. Conversely, a series of roughly N-S striking normal faults containing distinctive clay-rich cataclastites were mapped along the shoreline. A series of steeply dipping faults found further inland trend more in line with the overall Willunga Fault Zone (NE-SW) and occasionally contain slickensides indicative of reverse-sinistral strike-slip movements. The presence of all three fault types in a relatively small area is characteristic of strike-slip fault zones where localised fault step-overs create transpression or transtension zones.

At Sellicks the change in orientation of the Wilunga Fault from NE-SW to more E-W has created a transpressional zone resulting in the development of a positive flower structure with low-angle thrust faults bounding the uplifted ranges while steeper strike-slip faults are found nearer the centre of the fault zone. The normal faults orientated perpendicular to the thrust faults are probably a result of detachment and collapse of the uplifted areas in an orientation orthogonal to the maximum compression. The orientation of all three fault types is in general agreement with fault patterns associated with a sinistral strike-slip strain ellipse. With the observations at Willunga fault, we propose that the western frontal fault zones (Para, Eden-Burnside, Ochre Cove and Willunga faults) of Mount Lofty Ranges are a series of horsetail splays emanating off a large N-S trending sinistral strike slip fault system.

Implications of contrasting patterns of inherited zircon in the Late Palaeozoic granites of the Lachlan and New England fold belts

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Exposures of the Lachlan (LFB) and New England (NEFB) fold belts in SE Australia are separated by the Sydney Basin. Granite is an important component in both belts. The granites in the LFB are mostly Silurian-Devonian; some in the north-eastern LFB are Carboniferous. Granites in the NEFB are Permian-Triassic in age. The zircon inheritance age pattern from the LFB Silurian-Devonian granites is the same as the pattern of detrital zircon ages from the enclosing Ordovician turbidites (Williams, 1992). Aitchison and Ireland (1995) found an identical inheritance age pattern in zircon from NEFB felsic igneous rocks near Port Macquarie (240 Ma), and therefore suggested that an eastern extension of the LFB underlies the NEFB. Here we report contrasting SHRIMP U-Pb ages of inherited zircon cores from Carboniferous-Permian granites of the two fold belts.

Two different patterns of age inheritance have been found in I-type Carboniferous (ca. 340–325 Ma) granites from the LFB. The Chapmans Creek granite in the Oberon Supersuite contains inheritance (n=30; ca. 2630–500 Ma) typical of the LFB pre-Carboniferous granites (and Ordovician turbidites). However, three granites in the Bathurst Supersuite (Tarana, Wuuluuman and Gulgong, n=40; ca. 1670–365 Ma) lacks the Archean-Proterozoic cores older than 1.7 Ga, but contains abundant Silurian-Devonian zircon cores that cannot be derived from the same source as the inheritance in the Chapmans Creek. Considering the distribution of exposed country rocks around the Carboniferous granites, the Chapmans Creek and Bathurst (Supersuite) probably contain Ordovician sedimentary, and Siluro-Devonian sedimentary and/or igneous materials, respectively. The two granite types have similar, compositional features (e.g., high Sr and low Y) and relatively juvenile isotopic compositions (e.g., 0.704–0.707 in $Sr_{initial}$; Shaw, unpublished data) that seem to be derived from deep sources. Also, the abundance of inheritance is low (less than 1–2% of total zircon), so the amount of crustal assimilation is probably small.

The granites of the NEFB consist mainly of early Permian S- and late Permian I-types. The S-type Banalasta (ca. 290 Ma) and I-type Inlet (ca. 250 Ma) granites were selected for this study. The Banalasta has a high abundance of inherited zircon, (up to 40% of the zircon grains), mostly of Carboniferous age (ca. 345–295 Ma). A small amount is as old as Ordovician. The Carboniferous inheritance is bimodal in age, with peaks at ca. 310 (n=14) and ca. 330 (n=13) Ma. The latter group is identical in age to the Carboniferous granites in the LFB. It is consistent with earlier suggestions that the S-type NEFB granites are derived from young (Carboniferous) volcanogenic and arc-related metasedimentary sources (e.g., Shaw and Flood, 1981). No Ordovician or Precambrian peak was found in the Banalasta granite (56 cores dated), and no inherited zircon at all was found in the I-type Inlet granite (66 cores dated). As the inheritance age populations in the NEFB granites (both S- and I-type) closest to the LFB are distinct from those in Lachlan granites, it is highly unlikely that the LFB extends under the NEFB.

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A new 3D model for architectural evolution of the Granite-Tanami Orogen

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The Paleoproterozoic Granites-Tanami Orogen (GTO) forms a part of the North Australian Craton (NAC). The oldest (ca. 1864 Ma) exposed rocks in the western part of the orogen consists of tightly folded, predominantly greenschist-facies turbiditic and pelagic sedimentary rocks that are interbedded with volcanic rocks and abundant dolerite sills developed in a back-arc basin setting. Most previous studies focus on one or two

geoscience aspect(s). It is uncommon to compare and to merge multiple datasets in order to establish one model that explains all available data. This contribution presents a new 3D geological model of the GTO based on integration of geological and geophysical data that reveals important and crucial insights into the evolution of the crustal-scale architecture of the region. The information gathered and interrogated on the early development of the orogen is helping to develop a better understanding of the Archean–Proterozoic transition in the NAC. Conjunctive interpretations of field geological observation, deep seismic profiles, and gravity and magnetic potential field observations suggest that the GTO forms an imbricated crust developed on a south-dipping, rifted Archean basement. This new rift-like model for the Paleoproterozoic development of the GTO has major implications for the early architecture of the orogen, such as the spatial controls of the ca. 1864 Ma rock succession and fluid transfer during formation of the ca. 1795-Ma orogenic gold mineralisation.

The 3D geological model of the orogen highlights the regional crustal architecture and leads to a better understanding of the earlier architecture that has never been described before, and the tectonic history leading to the deposition of the Paleoproterozoic successions prior to ca. 1795 Ma, which is the youngest age of granites that intrude the GTO.

Volatile subduction in alpine serpentinites

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The fate of volatiles during subduction of oceanic crust is of fundamental importance to the genesis of arc magmas and understanding mantle convection or degassing of the Earth. In order to provide direct constraint on the behaviour of noble gases during subduction for the first time, and improve correlation of noble gases with other mantle tracers, we have simultaneously investigated the noble gas and halogen composition of minerals and fluid inclusions in well constrained alpine serpentinites. Serpentinites form by hydration of mantle rocks exposed on the seafloor and contain up to ~14 wt % H_2O and ~0.5 wt % Cl. Serpentinites are widely recognised as the main pathway for subduction of H_2O and Cl into the mantle. Simultaneous noble gas and Cl analysis enables calculation of fluid noble gas concentrations linking the subduction of these distinctive tracers to that of H_2O.

Antigorite-schists from Erro Tobbio (Western Alps, Italy) have Br/Cl and I/Cl similar to marine pore fluids and atmospheric noble gas concentrations an order of magnitude higher than typical basalts. This suggests that the serpentinite protoliths were covered by sediments and serpentinised at a low water-rock ratio. Fluid inclusions in olivine-diopside-Ti-clinohumite veins within the antigorite-schists represent fluid released at the onset of antigorite breakdown. These fluids have higher Br/Cl and I/Cl values than the antigorite, reflecting halogen incompatibilities (I>Br>Cl); salinities of 12–40 wt % NaCl eq; ^{36}Ar concentrations of ~5–100 ppb; and $^{84}Kr/^{36}Ar$ plus $^{130}Xe/^{36}Ar$ compositions that range from seawater values to maximums of 2–3 times seawater.

The products of final antigorite breakdown, represented by chlorite-harzburgites from Almirez (Betic Cordillera, Spain) have Br/Cl and I/Cl values that are lower than the antigorites and noble gas concentrations similar to those of gas-rich basalts. These data suggest the 'noble gas subduction barrier' has an efficiency of ~85% for Ar and that subduction of noble gases into the deep mantle is extremely significant. The fluid inclusions within these rocks have salinities of 2–12 wt % NaCl eq.; ^{36}Ar concentrations of ~0.8–5 ppb; and the highest measured $^{84}Kr/^{36}Ar$ and $^{130}Xe/^{36}Ar$ values of up to 4–5 times the seawater values.

Taken together the data from Erro Tobbio and Almirez indicate preferential subduction of the heavy noble gases on the order Xe>>Kr>Ar and that noble gases are subducted more efficiently than halogens or water. Helium is probably unique amongst the noble gases, because atmospheric He is lost to space and cannot be subducted. Devolatilisation of the slab during subduction explains widespread 'atmospheric contamination' of noble gases in basalts which is most intense in arc and back arc settings. Deep-subduction of the heaviest noble gases means they can be correlated with lithophile elements for the first time. Ocean Island Basalts are characterised by lower $^{40}Ar/^{36}Ar$ ratios and excesses of atmospheric Xe relative to Mid-Ocean Ridge Basalts and also preserve variable lithophile element signatures that are characteristic of crustal recycling.

The systematic fractionation of the noble gases and halogens during subduction, means that combined noble gas and halogen analysis could provide a powerful tool for testing the origin of volatiles and incompatible elements in mid-ocean ridge basalts. Our results predict that alternative sources of volatiles and incompatible elements [including: recycling from the mantle wedge (shallow mantle); recycling from the subducted-slab

(deep mantle); introduction by seawater contamination during eruption; or depleted primordial-sources] could be distinguished by different ranges of Br/Cl, I/Cl, $^{84}Kr/^{36}Ar$ and $^{130}Xe/^{36}Ar$. Furthermore, we suggest that volatiles (e.g. CO_2) retaining a uniform ratio to non-recyclable ^{3}He are unlikely to have been recycled beyond the arc and back-arc settings that overly subducting-slabs.

Earth science applications for advanced secondary ion mass spectrometry

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Secondary ion mass spectrometry (SIMS) is a powerful tool for mapping and measuring elemental and isotopic ratios in minerals, materials and biological samples. The technique uses a high-energy beam of primary ions to sputter secondary ions from a sample surface, which are extracted to a mass spectrometer and counted. The Ion Probe Facility at The University of Western Australia, home to a Cameca NanoSIMS 50 and a large-geometry Cameca IMS 1280, provides unique, cutting-edge SIMS capabilities to the Australian research community.

The two state-of-the-art instruments complement one another well. The NanoSIMS 50 produces images by scanning a finely-focused beam (~100 nm) over the sample surface. This results in the ability to map the distribution of elements in mineral phases, Au in pyrite for example, with ultra-high sensitivity at the sub-micron scale. The fine spatial scale also allows the measurement of diffusion profiles across grains and grain boundaries. Furthermore, isotopic measurements and maps can be acquired, under favourable conditions, at the scale of a few microns. This is a particularly powerful technique for investigating the cycling of elements, such as C and N, in geomicrobiological systems at the scale of an individual microbe.

The IMS 1280 combines high primary ion current, high transmission at high mass resolution, and advanced detector electronics to achieve sub per-mil precision on *in situ* isotope ratio measurements. In contrast to the NanoSIMS 50, the IMS 1280 achieves a much higher precision at the expense of high spatial resolution, with a typical analysis crater measuring 15 microns in diameter x 1 micron deep. Examples of typical applications of the IMS 1280 include measurement of $\delta^{18}O$ signatures of zircons to ascertain crustal or mantle origins, *in situ* analysis of ancient hydrocarbons for biogenic signatures, measurement of mass independent fractionation of S-isotopes in ore bodies to infer ancient subduction, and inferences concerning palaeoclimates from $\delta^{18}O$ signatures of speleothems and biominerals. This poster demonstrates the capabilities of the two instruments by providing examples of real applications in the Earth Sciences.

The Ion Probe Facility represents a substantial investment from the Federal Government, the State Government of Western Australia, and The University of Western Australia to produce a truly world-class facility—it is the only facility in the world to house both of these state-of-the-art ion probes. NCRIS funding, through AUSCOPE and the Australian Microscopy and Microanalysis Research Facility (AMMRF), ensures that the Facility is available to all publicly funded Australian researchers and Industry.

Improved constraints on the timing and tempo of continental extension using low temperature thermochronology

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Low temperature thermochronology involves the application of temperature-sensitive geological dating techniques, most notably $^{40}Ar/^{39}Ar$, fission-track (FT) and (U-Th-Sm)/He (He) to reconstruct the thermal and topographic history of rocks. Integration of data from the last two methods applied to apatite (AFT and AHe) is sensitive to temperatures over ~120–40°C, a range characteristic of the upper few kilometres of the Earth's crust. Studies using these two low temperature thermochronometers have provided quantitative constraints on the timing and magnitude of movement on major controlling faults and rates of tectonic transport, particularly in Tertiary and still-active extensional tectonic settings.

A recurring problem often encountered in AHe thermochronometry however, is poor intra-sample replication resulting in wide age dispersion. This issue appears to be most prevalent in older, more slowly cooled samples and several possible explanations have been proposed. One such complication arises from the energetic emission of α-particles from the decay of U, Th and Sm, which may be ejected from the crystal/s being dated

or implanted into them from decay in closely juxtaposed phases. The ejection loss is commonly corrected for by using a well-established protocol. An alternative method is to remove the outermost portions of crystal surfaces (in the case of apatite ~20–30 μm) to eliminate the effects of ejection and possible implantation. This approach involves a mechanical air abrasion procedure (using a Krogh cell) and has been recently applied to He studies on Late Tertiary to Quaternary volcanic samples. For the He system this success can be attributed to the fact that a-ejection effects are developed on a far shorter length-scale than diffusion gradients. Where grains have cooled more slowly however, and a strong diffusion gradient has developed such an approach will lead to 'too old' ages. Apart from volcanic rocks, no abrasion results have been reported from other geological settings, which would allow for further evaluation of whether removal of the outer portion of grains also removes information relevant to interpretation of the thermal history.

We report the results of abrasion experiments on relatively rapidly cooled rocks from crystalline rocks in Tertiary extensional tectonic settings in the North American Cordilleran Orogen and the Gulf of California Extensional Province. In these areas conventional AHe analyses commonly show varying degrees of age dispersion, often substantially older than their co-existing AFT ages and independent age constraints. In most cases abraded AHe grains reduced dispersion markedly and ages clustered tightly within the predicted range, resulting in markedly improved constraints on the timing and rate of extension. This is explained by the effects of α-implantation due to residence of apatites in a 'bad neighbourhood' often observed by the proximity of apatite to high actinide-bearing minerals.

The potential for implantation of α-particles into grains, from primary or secondary actinide minerals, has received only limited attention. Evidence for significant natural α-fluxes in the near-surface environment is provided by surface features and He abundance studies on diamond. Intense α-damage induces a green colour centre in diamond, enabling visual assessment of natural α-implantation doses. Diamonds with transparent green coats and/or green spots occur in most primary and detrital diamond deposits worldwide, indicating that α-implantation rates into upper crustal minerals may be more significant than previously envisaged. Experiments on transparent green-coated natural diamonds reveal implanted ^{4}He concentrations, attributed to secondary uranium phases deposited by circulating groundwater. Implantation of α-particles into apatite grains could markedly increase AHe ages, dependent on α-dose rate, grain dimensions and actinide content.

The usefulness of AHe abrasion in reducing age dispersion depends on several factors, including the nature of the cooling history through the He partial retention zone. As a general rule of thumb, our findings so far suggest that where abrasion substantially reduces AHe age dispersion, then coexisting AFT data show a mean track length of ≥~13.3 μm (and unimodal track length distribution) or mean track lengths ≤~10.75 μm (accompanied by a broad track length distribution) where samples have cooled from within the higher temperature part of the apatite partial track annealing zone.

Geodynamic implications of a 2008 north–south deep seismic reflection profile across the Curnamona Province, South Australia

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In 2008, as part of its Onshore Energy Security Program, Geoscience Australia and PIRSA acquired 262 km of vibroseis-source, deep seismic reflection data as a single north-south traverse (08GA-C1) in the Curnamona Province in South Australia. This line started in the south near outcrop of the Willyama Supergroup, ran to the east of Lake Frome along the Benagerie Ridge, and ended in the north, to the north-east of the Mount Painter and Mount Babbage Inliers. Almost the entire route of the seismic traverse was over concealed bedrock, with only a few drillholes which could be used as control points. Overall, the crust imaged in the seismic section is relatively reflective, although the central part of the section contains an upper crust which has very low reflectivity. The lower two-thirds of the crust contain strong, subhorizontal reflections. The Moho is not sharply defined, but is interpreted to occur at the base of the reflective package at about 13 s two-way travel time (TWT), about 40 km depth. The highly reflective crust can be tracked, from the southern end of the seismic section, northwards for a distance of about 200 km. In the north, where rocks of the Mount Painter and Mount Babbage Inliers are exposed close to the section, the crust has a marked lower reflectivity, compared to the rest of the line. This contrast in crustal reflectivity suggests that the crust beneath the Mount Painter region is different from that beneath the Willyama Supergroup of the Curnamona Province in the

south, raising the possibility of an ancient crustal boundary between the two regions. Although not well imaged, a steep, apparent south-dipping boundary between the Mount Painter Inlier and the Curnamona Province is inferred. The Curnamona Province consists predominantly of the Paleoproterozoic (~1720–1640 Ma) Willyama Supergroup and coeval magmatic rocks. These rocks were deformed and metamorphosed during the ~1600 Ma Olarian Orogeny, which was followed by an early Mesoproterozoic magmatic event, producing the Benagerie Volcanics. In the southern part of the seismic transect, there are a series of north-directed thrusts cutting the Willyama Supergroup, consistent with mapped northwest-verging F3 folds in outcrop. These late structures overprint the earlier structures, which are difficult to observe in the seismic section. The Benagerie Volcanics are interpreted to be a relatively thin (up to 1500 m thick), subhorizontal sheet, with a gently undulating base. Immediately beneath the volcanic package is another non-reflective package, which may represent the preserved uppermost part of the Willyama Supergroup deposited between 1640–1620 Ma, and subsequently eroded off the now exposed older parts of the Willyama Supergroup. Rocks of the Willyama Supergroup can be tracked from the surface in the south to beneath both the volcanic rocks and the underlying, nonreflective package. The northernmost part of the seismic section crosses Mesoproterozoic rocks of the Mount Painter and Mount Babbage Inliers, which occur beneath a thin cover of Mesozoic to Cenozoic sediment. Here, the rocks are heavily faulted, with the main fault pattern having an apparent dip to the north-west. Several remnants of Neoproterozoic and/or Cambrian sedimentary basins are preserved beneath a thin cover of Cenozoic sediment. The thickest of the remnant basins occurs at depth to the south-east of the Mount Painter Inlier. Here, the Neoproterozoic sedimentary succession shows growth towards the north-west, implying the possible existence of one or more original syndepositional, extensional faults. This basin-bounding fault, with an apparent dip to the south-east, possibly represents reactivation of the ancient crustal boundary between the Curnamona Province and the Mount Painter Inlier. The present, near-surface boundary is a thrust fault with an apparent dip to the north-west, and has thrust rocks of Mount Painter affinity over the Neoproterozoic to Cambrian succession. This thrust displays no neotectonic activity, as it is covered by essentially flat-lying Mesozoic and Cenozoic sediment. This implies that the juxtaposing of the Mesoproterozoic rocks with the Neoproterozoic succession occurred during either the Delamerian or Benambran Orogenies. To the south-west of the seismic section, the Paralana Fault occurs at the range front and dips 25° to the west, beneath the northern Flinders Ranges. It is an active fault, thrusting Mesoproterozoic rocks of the Mount Painter Inlier over Pliocene and Quaternary sediments. The north-eastern continuation of the Paralana Fault is imaged in the seismic section as a zone of reflections with an apparent dip to the north-west, truncating Mesozoic sediments.

North Queensland geodynamic and mineral system synthesis

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Over the last year, Geoscience Australia's Onshore Energy Geodynamic Framework Project has undertaken a geodynamic synthesis of North Queensland, from the Paleoproterozoic to Recent, to:

- better understand the tectonic and geodynamic setting of existing mineral deposits within North Queensland
- provide a predictive capability, within the synthesised geodynamic framework, for extending potential regions of known mineralisation and identifying new mineralisation styles and commodities.

Geological data were synthesised on a regional, largely orogenic, basis to identify geological events and geodynamic cycles. The synthesis involved the compilation of available published (and unpublished) state geological survey data and data in the scientific literature. All data were captured in Geoscience Australia's internal PROVINCES and EVENTS databases and used to produce digital time-space-event plots for each region within North Queensland, which allowed comparison between regions and the identification of major geological events and geodynamic cycles.

To better understand the geodynamic setting of, and spatial relationships between known mineral deposits, a synthesis of significant mineral deposits in North Queensland was produced to help delineate possible extensions of mineralised belts based on our geodynamic interpretation. The team also used the geodynamic synthesis to predict areas of mineral potential outside of known mineralised districts or provinces. Prediction of mineral prospectivity conducted at the North Queensland scale provides a first-order guide to area selection for mineral exploration.

The tectonic development of the region can be subdivided into five periods, namely:

- Paleoproterozoic-Mesoproterozoic development; little direct evidence for convergent margin tectonics in the geological record.
- Rodinian breakup (rifting) and ensuing passive margin—ca. 825 to 515 Ma, that is, formation of the paleo-Pacific Ocean; also corresponds broadly to development of the Australian component of the Gondwana margin.
- Tasman Orogen—Delamerian to Hunter-Bowen Orogenies. Alternating extensional and convergent orogenic cycles, commencing in the Cambrian and continuing through to the Mesozoic, resulting in accretionary growth—as evidenced in the Lachlan, Thomson and New England Orogens.
- Mesozoic basin development, that is, Eromanga and related basins and Late Mesozoic magmatism (Whitsunday Event), related to the breakup of Gondwana.
- Tertiary rift basins and within plate magmatism (± hotspot activity), in part related to opening of the Coral Sea (and Tasman) Basins, via sea-floor-spreading, ca. 80 to 55 Ma.

Mineral systems are closely linked to these five periods of tectonic development. Paleo- to Mesoproterozoic deposits in the Mt Isa and Etheridge Provinces, including Zn-Pb-Ag deposits of the North Australian Zinc Belt, uranium deposits of the Mt Isa uranium field and iron-oxide copper-gold deposits of the Cloncurry district are associated with extensional basins and their subsequent inversion. Although no significant deposits are known to be associated with Rodinian breakup in north Queensland, deposits of this age are being recognised elsewhere in Australia, suggesting that this period of time may have unrealised mineral potential. Mineral deposits associated with the Tasman Orogen are many and varied, and include volcanic-hosted massive sulphide deposits (e.g. Thalanga) associated with backarc basins, lode gold deposits (e.g. Charters Towers) associated with contraction, and intrusion-related Au, Cu-Au and Sn-W deposits associated mostly with Permo-Carboniferous magmatism. The latter two periods are not well mineralised, although significant alluvial tin and gold deposits as well as bauxite deposits at Weipa formed during this time. Using the tectonic development described above and the distribution of known deposits, a series of mineral potential maps were constructed. As an example, the results suggest that the backarc basin represented by the Ordovician Seventy Mile Range Group has a similar age to arc-related deposits recently documented in drill core from northern New South Wales. This relationship suggests potential for an Ordovician arc system, and associated mineral systems, under cover through much of eastern Queensland.

Deformation patterns of the Wyangala Granite, Wyangala Dam district, Eastern Lachlan Fold Belt

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The late Early Silurian(?) variably foliated Wyangala Granite is a north-south trending S-type pluton in the Eastern Lachlan Fold Belt. It is a grey to white, medium- to coarse-grained, equigranular to porphyritic, often megacrystic, biotite granite and granodiorite. Near Wyangala Dam it is composed of quartz (20–35%), biotite (< 15%), K feldspar (microcline microperthite) (30–40%), plagioclase (~5–15%) and minor amounts of muscovite, white mica and cordierite (~1%). It is one of the most highly deformed plutons of the Wyangala Batholith with the foliation increasing in intensity towards its eastern edge. It intruded multiply(?) deformed Ordovician metasediments and volcaniclastics passively along pre-existing faults. ^{40}Ar-^{39}Ar dating of biotite by Glen *et al.* (1999) suggests the C foliation developed in the Tabberabberan event (~ 380 Ma) and this time is consistent with west-over-east thrusting in the Eastern Lachlan Fold Belt.

Mapping by Czarnota (2002) around Wyangala Dam within the granite indicated the development of kilometres-long, north-south, typically 200 metre wide linear shear zones spaced 200 metres to 1 km apart. These shear zones were defined on the basis of the grain size of K feldspar phenocrysts and the presence or absence of mylonite zones. Czarnota (2002) found a finer-grained phase of the Wyangala Granite with a similar geochemistry which showed similar final grain size suggesting that final grain size is a function of both crystallisation and grain size reduction. The underlying assumption in using K feldspar phenocryst size to

characterise strain is that the original distribution of phenocrysts was homogeneous across the district. This assumption may not be valid given observations of finer grained portions of the Wyangala Granite. Czarnota (2002) identified three high strain shear zones close to the eastern margin of the granite and three low strain shear zones further west. Crump (2004) and more so White (2005) mapped areas south of Wyangala Dam and found a continuation of the previously identified shear zones.

Densification of the station spacing across the district and the areas between honours mapping projects indicated that the north-south linear pattern of high strain zones was not as regular as originally mapped. A slightly modified scheme of low, medium and high strain using the K feldspar grain size, presence or absence of S-C fabrics and mylonites was adopted to create these new maps. A new map of the magnitude of the strain consists of rounded blobs and elongated rounded rectangular areas of higher or lower strain. There is a concentration of higher strain areas around the margins of the metasediments consistent with intensification of deformation at the contact between rheologically different rocks. This study indicates that a map based on the size of K feldspar phenocrysts and presence/absence of S-C fabrics and mylonites is not the best criteria to determine strain in deformed granites and that the presence of S-C fabrics and mylonite zones are probably a better criteria to separate low and high strain areas.

Detailed mapping of K feldspar phenocryst grain size distribution in areas of almost 100% exposure such as within a high strain shear zone south of Wyangala Dam or in shear zones defined within the Wyangala Dam spillway reveals a heterogeneous grain size distribution. There are significant areas of lower strain within previously defined high strain shear zones.

Mapping at regional, local and individual outcrop scale (such as the Wyangala Dam spillway) indicates that the north-south trending, linear zones of more deformed granite consist of hetereogeneously deformed granite with patches of highly strained granite mixed up with lower strain sections of granite. K feldspar phenocryst grain size variation is not as good a guide to the magnitude of the strain as the presence of S-C fabrics and mylonite development.

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Structural evolution of the Texas orocline: field observations from the hinge zone (Mosquito Creek, south-east Queensland)

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The Texas orocline, situated in the southern part of the New England Belt, is characterised by a pronounced curvature of the orogenic belt forming large-scale horseshoe-shape geometry. This orocline is the largest and most obvious orocline in the southern New England belt and is clearly recognised in geological, gravity and magnetic maps. In order to address the origin and evolution of this curved structure and its relationship with the Late Palaeozoic geodynamics of eastern Australia, we have conducted detailed field mapping in the hinge of the Texas orocline, in the area of Mosquito Creek (south-east Queensland). All rocks in the study area belong to the Texas Beds, and are comprised mainly of slates, volcano-clastic rocks, quartzites and mafic greenstones. Bedding is steeply dipping or vertical throughout the whole area and is commonly, but not always, parallel to the dominant cleavage. Three generations of structural features (D1-D3) have been recorded. D1 is associated with thin quartz veins that are generally oriented N-S. These veins are overprinted by D2, forming isoclinal folds. D2 is dominant throughout the hinge zone, and is predominantly expressed by a penetrative E-W fabric. This fabric is parallel to the axial planes of isoclinal folds, confirming its origin as an axial plane cleavage. D3 is characterised by kink folds and local crenulations, with axial planes typically oriented NW-SE and NE-SW. In a larger scale, the D2 fabric is recognised as the dominant structural grain, folded along the oroclinal structure. Therefore, we think that the D2 fabric represents a relatively high-strain deformation event that occurred prior to the development of the orocline. The process of oroclinal bending, in contrast, did not involve the development of penetrative cleavage parallel to the axial plane of the orocline

(~N-S), indicating a relatively low strain (<30%). Syn-oroclinal deformation could possibly be represented by the D3 structures.

Plate tectonic models in Melanesia

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Plate tectonic models of Melanesia have as their cornerstone the development of subduction complexes and flanking island arc systems, with an inherent acceptance of significant lateral displacements of crustal blocks. Subduction-arc complexes are, depending upon the model used, very variable in orientation and longevity, and may have flipped polarity, undergone plate roll-back, asiesmic subduction or have been choked. The gymnastics of these fundamental structures of the Earth's crust/upper mantle is a significant weakness of plate tectonics in Melanesia. Field observations tell the story.

During the Early-Late Miocene extensive tropical to sub-tropical platform carbonate development occurred across a region stretching some 5,600 km from SE Asia through New Guinea, Solomon Islands, New Hebrides to Fiji. In the hinterland surrounding and throughout the New Guinea islands, large platform carbonate blocks are relatively untectonised. Large carbonate slabs are intact on New Britain and New Ireland despite their location in interpreted active arc complexes and their flanking a major plate boundary. Evidence suggests that since the Miocene this large part of Melanesia has undergone little more than simple regional uplift.

The Ontong Java Plateau (OJP), the world's largest ocean plateau, is widely modelled as having collided with the Solomon Islands arc during the Miocene, resulting in amongst other things obduction of the leading edge of the plateau, the triggering of arc polarity reversal in the Solomons arc from NE facing to SW facing and initiation of subduction in the New Britain Trench. This is despite the sedimentary record of extensive Miocene carbonate platform development throughout Melanesia. The Miocene collision of the OJP is unlikely given the development of platform carbonate sedimentation across widespread quiescent, detritus-free environments.

The geology of the New Guinea islands (Manus, New Ireland, New Britain) is dominated by an intense steeply-dipping fracturing evident at all scales, from prospect to regional. NNW-trending horst and graben structures predominate across a broad zone of extension in the New Britain-New Ireland region. Some of the horst and graben faults on the Gazelle Peninsula have been shown to be deep-seated and continue through the crust. Not one low-angle thrust fault has been observed in the New Guinea islands, despite it being modelled as a convergent zone. Similar observations have been made in the field and from literature review in the Solomon Islands and the New Hebrides.

The basic three-fold subdivision of Eocene-Pliocene geology of the New Guinea islands-Solomon Islands north of the tectonic boundary defined by the contiguous San Cristobal Trench-New Britain Trench-Ramu Markham Fault is, despite lateral facies changes, remarkably consistent, indicating this large region is relatively intact and has not (during or post this long time period) undergone significant piecemeal displacements. This distinctive geological sequence contrasts with similarly aged sequences on the adjacent Australian plate. Late Eocene mafic-intermediate volcanics with minor limestone form basement throughout the region. The Eocene sequence is in-turn overlain by Late Oligocene-Early Miocene intermediate volcanics with minor limestone. Early-Late Miocene limestone sequences are thick and widespread and are present in the Bewani Mountains, Saruwaged-Finisterre Ranges, Manus, New Ireland, New Britain, Bougainville, Choiseul and Guadalcanal.

The 400 km long Papuan Ultramafic Belt (PUB) is widely accepted as a slab of upper mantle and oceanic crust obducted along a low-angle thrust onto the leading edge of the Australian plate. However, bounding structures in the NW and SE sections of the PUB are vertical with no evidence at any scale of low-angle thrusting. At the SE end of the PUB, unroofed Late Miocene-Early Pliocene granite on the summit of the 3,676 m Mt Suckling indicates at least 8 km of vertical movement over the past few million years. The enrichment of Pt-Pd in the NW and SE sections of the PUB suggests a continental influence. Elsewhere, Ir-Os-Ru is enriched in the central section of the PUB. Ophiolites worldwide are typically enriched in Ir-Os-Ru. PGE geochemical and structural heterogeneities suggest that geological processes and histories have varied throughout the PUB. For similar reasons as with the OJP, a Miocene emplacement of the PUB is untenable.

The concentration of subduction along the western Pacific margin can be measured by the fact that the region accounts for 92% of all deep seismicity. The asymmetry of plate consumption presents significant 'return flow'

issues for convection driven plate tectonics theory. There are significant mass balance issues related to the deep-seated processes of wholesale transfer of material to other parts of the Earth.

Geochronology and geochemistry of post-collisional Cenozoic alkali-rich porphyries in Eastern Tibetan Plateau, Yunnan, China

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The 1,000-km-long, north- and northwest-striking, Jinshajiang-Ailaoshan alkali-rich magmatic belt runs from the south-eastern margin of the Tibetan plateau to the plateau interior parallel to a major fault zone. The belt contains numerous hypabyssal, alkali-rich porphyries with ages ranging between 40 and 30 Ma, and numerous Cu (-Mo,-Au) deposits are spatially and temporally associated with the porphyries. The porphyries apparently formed in a post-collisional continental setting, post-dating continental collision between India and Asia (ca. 55 Ma). This magmatic belt thus can not be related to oceanic slab subduction, as in the traditionally interpreted typical circum-Pacific setting for the formation of porphyry Cu (-Mo, -Au) deposits. Here we report the geochronology and geochemistry of the alkali rich porphyries in the Dali-Jianchuan area, the middle segment of the Jinshajiang-Ailaoshan magmatic belt, in NW Yunnan province, and discuss their tectonic settings.

SHRIMP zircon U-Pb dating of the porphyries shows that alkaline magmatism was initiated at 36.93 ± 0.32 Ma and persisted until 33.06 ± 0.39 Ma, with a major peak at 35.5–35.0 Ma. The quartz syenite porphyry intrusion associated with the Beiya gold deposit was emplaced between 36.93 ± 0.32 and 36.35 ± 0.37 Ma. The granite porphyry associated with the Machangqing porphyry Cu-Mo (-Au) deposit formed at 35.0 ± 0.2Ma. The syenite porphyry associated with the Yao'an gold deposit formed at 33.43 ± 0.32 Ma. The porphyries intrude the non-metamorphosed sedimentary sequences outside or well away from the Ailaoshan-Red River shear zone, which has been proposed to be responsible for the magmatism. In fact, 40–30 Ma alkaline magmatism is widely distributed throughout northern and eastern Tibet and is not confined to major lineaments. Therefore, our geochronological and geological data support the view that there is no direct link between the alkaline magmatism and the strike-slip faulting. Rather, geochemical data require a regional lithospheric extension setting involving mantle processes (see below).

The Beiya intrusion consists mainly of quartz syenite porphyry, the Machangqing intrusion consists mainly of granite porphyry, and the Yao'an intrusion consists mainly of syenite porphyry. These intrusions are characterised by enrichment of total alkalis, especially potassium. Geochemically, the Beiya quartz syenite porphyry is equivalent to a shoshonitic rhyolite, the Yao'an syenite porphyry to an alkaline trachydacite, and the Machangqing granite porphyry to a high-K calc-alkaline rhyolite. They are all enriched in LREE and LILE (such as Rb, Ba, Sr, Th, U, and La), depleted in HFSE (such as Nb, Ta, Ti) and HREE, have high Rb/Sr, La/Nb, LREE/HREE ratios, with no obvious Eu anomalies. The initial $^{87}Sr/^{86}Sr$ ratios are high and ε_{Nd} values are low, close to enriched mantle (EMII). We consider these intrusions were derived from partial melting of the metasomatised lithospheric mantle (most likely the metasomatised, phlogopite-bearing peridotite source) beneath the western margin of Yangtze craton which had been previously subjected to the Paleo-Tethys oceanic subduction in the Triassic. However, the tectonic trigger for the upwelling of asthenosphere which caused the partial melting of the metasomatised lithospheric mantle remains unclear. Although these intrusions share similar features in tectonic setting, age and source region, they show differences in lithology and chemical compositions, which was probably due to differing degrees of partial melting of the source region. The Au mineralisation is considered to be associated with the intrusions of shoshonitic to alkaline series while Cu mineralisation with the intrusions of high-K calc-alkaline series in the Jinshajiang-Ailaoshan alkali-rich magmatic belt.

Age and basin evolution of the Cuddapah Supergroup, India

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The Cuddapah Basin is a crescent shaped Proterozoic intracratonic basin nonconformably overlying the Archean Dharwar craton of India. It covers an area of approximately 44500 km^2 and is one of the largest intracratonic basins in India. It is one of the largest well preserved Proterozoic basins in the world and also one of the least known and understood. Although it is believed to be Palaeo- to Meso-proterozoic there is no evidence of banded iron formations or glaciogenic sediments which both occur in other basins of similar age.

The Cuddapah Basin is separated into two sequences; the older Cuddapah Supergroup and the younger Kurnool Group both deposited during the Proterozoic. This study is focused on the age and deposition of the Cuddapah Supergroup. The Cuddapah Supergroup consists predominantly of clastic and chemical sedimentary rocks with minor intercalations of alkali to sub-alkali basaltic flows, mafic/ultramafic sills and ashfall tuffs in the lower part of the succession. The stratigraphy of the Cuddapah Supergroup includes four unconformity bound groups, the Papaghni, Chitrayati and Nallamalai groups and the Srisailam Formation (from oldest deposited to youngest). The Srisailam Group does not crop out at all in the study area. The Papaghni Group consists of the Gulcheru and Vempalle Formations, the Chitrayati Group consists of the Pulivendla, Tadpatri and Gandikota Formations and the Nallamalai Group consists of the Bairenkonda and Cumbum Formations. Each of the groups has a cyclic pattern to it, starting with deposition of conglomerates or quartzites grading into shales, this pattern is continued into the overlying Kurnool Group. The unconformable relationship between the cyclic lithostratic groups suggests a polyhistory basin.

This study of the Cuddapah Supergroup within the Cuddapah Basin aims to investigate the provenance and maximum depositional age of the sediments by using the U-Pb laser-ablation inductively coupled mass spectrometry (LA-ICPMS) technique to date detrital zircons. Possible provenance includes the nearby Eastern Ghats or the basement rocks of the Dharwar Craton. The study will also study the evolution of the basin, including a simple understanding of the structural evolution of the basin, the formation of the basin and how deposition changed throughout its history.

LA ICPMS data from detrital zircons of the Gulcheru, Bairenkonda, Pulivendla and Cumbum Formations will be presented. This will provide provenance ages of the sediments which, together with a structural transect of the area will be used to investigate the evolution of the basin.

Metamorphism of large hot orogens: revisiting the Eastern Ghats classic

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Large Hot Orogens may pertain to three flow modes of the crust, all of which weak, viscous channel material flows as a result of gravitational forces (Beaumont *et al.* 2006). Such viscosity of the crust requires high temperatures to be maintained over comparatively long time frames (as long as 80Ma: Chardon *et al* 2009). As such, there are implications for the heat source and associated tectonic environment. The Eastern Ghats Belt, India, is recognised as a classic example of a deeply exposed Large Hot Orogen of Meso- to Neo-proterozoic age ca. 1500 Ma to ca. 450 Ma (Mukhopadhyay and Basak, 2009, and references within). Rocks in the Eastern Ghats Belt comprise granulite-facies metasediments and voluminous felsic intrusives. The *ca* >300km-wide – >900 km-long belt has been subject to polycyclic high geothermal gradient tectonism, with pressures and temperatures as high as 1100°C, 12kBar (Shaw and Arima, 1996). Tectonic events have been linked to the Grenvillian as well as Pan African megasystems.

Thermo-mechanical models that shed light on crustal flow, and thus tectonic and thermal evolution, require robust metamorphic constraints. Pressure-Temperature-*time* paths link thermal data to the duration of tectonism, and additionally provide depth-time paths for rocks. The majority of previous studies on the thermal evolution of the Eastern Ghats Belt have utilised semi-quantitative univariant reaction grids and traditional thermobarometry in order to propose *P-T* paths. These results from these methods have lead to conflicting interpretations of the *P-T* evolution across the orogen. This either reflects (1) existing methodological limitations, (2) spatial and temporal variations in the thermobarometric evolution. However a

paucity of age-constraints and application of modern thermobarometric analysis in the Eastern Ghats Belt means that the significance of apparent variations in the PT-time evolution is unclear.

This current work is investigates the thermal and physical evolution of the Eastern Ghats granulite Belt in time and space, by integrating in situ U-Pb monazite geochronology with calculated phase diagrams (calculated using THERMOCALC). This integrated approach directly links geochronological data to the P-T evolution, thereby providing the first comprehensive P-T-time evolution framework for the Eastern Ghats Large Hot Orogen. Our new data allow for an appraisal of the duration of high geothermal gradient tectonism in the Eastern Ghats and the associated tectonic setting.

The CO_2 paradox in subduction zones: insight from partial melting experiments on altered oceanic crust

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Understanding the carbon recycling into deep Earth reservoirs and its connection to the exogene carbon cycle is crucial to understand the evolution of climate throughout geological time. Along subduction zones, organic matter, carbonate-rich sediments and carbonates formed during seafloor alteration of the oceanic crust are the main sources of carbon buried into the deep Earth. In the meantime, carbon is emitted into the atmosphere as CO_2 through arc magmatism. The analysis of the CO_2/3He and isotopic composition of these volcanic gas have suggested that 80% of the carbon originates from the metamorphism of the down-going slab (Varekamp et al., 1992; Marty and Tolstikhin, 1998). However, experimental studies on the stability of carbon-bearing phases in H_2O-CO_2-bearing basaltic compositions have shown that carbon remains trapped in carbonates up to 6 GPa and the fluid at sub-arc depth is, therefore, dominated by H_2O (Poli et al., 2009). Consequently, there is a CO_2 paradox when the input of subducted slabs (results from experimental petrology) and outputs of volcanos (results from volcanic gas geochemistry) are compared in the deep carbon recycling in subduction zones.

During seafloor alteration, the oceanic crust is not only enriched in H_2O and CO_2 but also in K_2O, which may affect the melting relationships in stabilising phengite at high pressures. We conducted experiments with a starting material of a synthetic K_2O, CO_2 and H_2O-bearing basaltic composition as a proxy of the altered oceanic crust. Solidus experiments were run at 2.5 and 3.5 GPa, 750–850°C in a piston-cylinder apparatus. The experimental results indicate that the solidus occurs at a temperature below 750°C at both 2.5 and 3.5 GPa. At T≥750°C, a high proportion of melt coexists with a carbonate phase, omphacite, garnet, epidote, rutile ± coesite and phengite. Between 750 and 800°C, the carbonate phase is dolomite and above 800°C, it is replaced by Mg-rich calcite. The evolution of phase proportions with increasing temperature suggests the following melting reaction:

Epidote+Phengite+Carbonate+Omphacite+H_2O+Quartz/Coesite = Garnet + hydrous, CO_2 bearing melt

Our experiments show that the solidus of the altered oceanic crust occurs below 750°C at 2.5 and 3.5 GPa. These pressure and temperature conditions are similar to those of the solidus in CO_2-free (700<T<750°C, Schmidt and Poli, 1998) basaltic and pelitic systems and also in CO_2-bearing pelitic system. The fact that the solidus temperature of the altered oceanic crust is not affected by the presence of CO_2 suggest that the fluid composition is H_2O-rich below the solidus and, therefore, that CO_2 remains trapped in carbonates as shown by the previous experimental studies.

The melting reaction is associated with the destabilisation of the carbonates phases, which leads to the release of CO_2, most likely dissolved in the hydrous melt. These results suggest that the altered oceanic crust, which is preferentially located at the top of the slab, may partially melt at sub-arc depths. This provides an explanation on how CO_2 is efficiently released from the subducted slab and suggests that a much larger portion of CO_2 can be recycled through arc volcanism than what previous experimental studies have predicted.

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A geodynamic modelling approach to constraining the location of Cretaceous subduction east of Australia

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We have used the geodynamic modelling code *CitcomS 3.0* to model the surface evolution of Australia since 140 Ma and constrain the location of the Cretaceous aged subduction zone that formed its eastern plate boundary. Australia's palaeogeography was profoundly influenced by mantle convection processes during the Cretaceous period. Eastward passage of the Australian plate over subducted slab material induced negative dynamic topography in eastern Australia, causing widespread timedependent subsidence and formation of a vast epeiric sea during a eustatic sea-level low. Although there exists a considerable amount of geological evidence for active convergence between Australia and the palaeo-Pacific (Panthalassa) at this time, the exact location of the subduction zone has remained elusive. To constrain the location of subduction we tested two end-member scenarios, one with the subduction zone directly adjacent to the continent, and an alternative model with subduction translated 23° east. Our forward geodynamic models incorporate a rheological model for the mantle and crust, plate motions since 140 Ma and evolving plate boundaries, implemented in the *GPlates* software. While mantle rheology affects the magnitude of surface vertical motions, the timing of uplift and subsidence depends critically on plate kinematic reconstructions and plate boundary geometries. Tectonic subsidence analysis using the backstrippping methodology was performed on 42 wells from the Eromanga and Surat basins in eastern Australia. This revealed Cretaceous tectonic subsidence trends with which to compare our modelled dynamic topography.

Simulations with subduction proximal to the active continental margin resulted in accelerated basin subsidence delayed by 20 Myr compared with these tectonic subsidence data. However this timing offset was reconciled when subduction was shifted eastward. Comparisons between whole mantle seismic tomography images and equivalent model temperature cross-sections further validate our proposed eastward shift in subduction. Finally an absence of subduction zone volcanism along Australia's east coast in the Early Cretaceous supports our conclusion that a back-arc basin existed east of Australia during the Cretaceous. Our results further reveal that mantle convection models that incorporate geological data can help to constrain past plate boundary configurations in an iterative sense.

Mantle peridotites from the active New Britain–West Bismarck Arc front

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Peridotites samples were recovered during the Marine National Facility Voyage (SS06-2007; WeBiVE) from three volcanic cones in the vicinity of Ritter Volcano in the New Britain-West Bismarck Arc system of Papua New Guinea. The Ritter suite is the first global occurrence of peridotites recovered from an active submarine volcanic arc front edifice, hosted by subalkaline basalt.

The peridotites are generally coated by basalt, and occur as rounded and angular blocks and fragments. The host basalt is a Cr spinel-olivine-bearing, medium-K, low-Fe tholeiite. It is the most MgO-rich basalt (~15wt%) discovered in the West-Bismarck-New Britain Arc system; the high-MgO might derive in part from the cumulative and/or xenocrystic nature of the olivine crystals. The mineralogy of the host basalt includes olivine ($Fo_{91.9\text{-}82.4}$), diospide-augite, and spinel. The spinel is highly refractory with Cr/(Cr+Al) > 0.8, akin to spinel in boninites.

The peridotites are pristine, predominantly harzburgitic in composition but also include lherzolite and orthopyroxenite. A single gabbro was also recovered. Preliminary petrological analysis of the peridotites shows complex textural relationships between the main minerals olivine, orthopyroxene, clinopyroxene and spinel. There are abundant indications of deformation textures including deformation banding in olivine and wavy deformation of exsolution lamellae in the pyroxene. Invasion of the peridotite by host basalt is evident in some samples.

Wedge-derived peridotites are extremely rare even in well-explored subaerial arcs. These samples will be studied in mineralogical and petrological detail and will offer a unique insight into the mantle below the New Britain-West Bismarck Island Arc.

Three-dimensional modelling in the Melbourne Zone, south-east Australia

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The Melbourne Zone is located in the southern portion of the Lachlan Fold Belt, central Victoria. Mineral exploration in this region is particularly hampered by a thick sequence of overlying turbidites, particularly rugged topography and dense vegetation. These factors make traditional exploration techniques either very difficult, or in some cases impossible. As part of the Rediscover Victoria 3D project, this study uses our current understanding of the surface geology, airborne magnetic, and land based gravity data to interpret subsurface structures, model their geometry and ultimately build a 1:250 000 scale 3D model of the Melbourne Zone. Modelling of the Melbourne Zone has been done from the ground surface to the Moho to further our understanding of the entire crust, and in particular, to understand the plumbing systems which control regional mineralisation styles. This model is presented in a highly portable format, and intended to be 'water-tight' which makes it valuable not only to the minerals industry, but also researchers or explorers interested in geothermal energy, groundwater aquifer systems, fluid flow modelling, geostatistics and many other disciplines.

The Melbourne Zone is a structural zone bounded by the Governor Fault in the east and north, the Mount William Fault (part of the larger Heathcote Fault Zone) in the north-west and a less well constrained transitional zone in the south-west. The main rock units in the zone are a conformable succession of Ordovician to Early Devonian marine turbidites and shales that have been intruded by numerous Devonian granitoids. The turbidite pile is deformed into chevron-folds cut by reverse faults and has a very low grade of metamorphism. It has been interpreted as having been deposited unconformably on Cambrian or older continental crust—the Selwyn Block.

Construction of the 3D model first required profile forward and inversion modelling of airborne magnetic and gravity data to be carried out. This provides an insight into the sub-surface distribution, and three-dimensional geometry of these structures. Profile models have been undertaken at regular intervals throughout the Melbourne Zone. These models have been constrained by surface mapping, magnetic susceptibility and density measurements. The largely non-magnetic upper crust (folded Ordovician to Early Devonian strata of the Melbourne Zone intruded by Devonian granite plutons) has been modelled using recently acquired density measurements, providing a good match with the gravity profiles.

These profile models provided the framework to build a 3D geological model of the Melbourne Zone. That is, the surface interpretation and profile models were imported into Gocad, and surfaces were created representing faults and granite bodies which honour these geological data. The top of the basement is modelled at around 10–15 km depth in the centre of the zone, and about 8–10 km depth in the south of the zone, reflecting a thinning of the folded cover sequence toward the south. This is consistent with outcrops of basement Cambrian rocks on the south coast of Victoria. Long wavelength magnetic anomalies in the Melbourne Zone are modelled as highly magnetic tabular bodies lying in the basement below the folded strata of the Melbourne Zone. The only rock type that matches the density and magnetic susceptibility is serpentinised ultramafic rock. Thus a large ophiolitic body is thought to exist in the upper part of the basement to the Melbourne Zone, at depths of 15–25 km in the central part of the zone, and 10–15 km in the south of the zone. This unit is correlated with the Cambrian mafic-ultramafic complex of Tasmania, agreeing with previous correlations of the Selwyn Block with Tasmania. Future work will use the 3D model as a constraint on 3D gravity inversion models in this region which will allow the 3D geometry of these bodies to be explored further and these correlations to be better defined.

Metamorphic and geochronological constraints within a proposed continental suture in southern India

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The metamorphic and deformational history of South India within the context of supercontinent assembly is a topic of considerable active research and debate. Much of the research and debate is focused on the Palghat-Cauvery Shear System (the PCSS, also having the proposed name of the Palghat-Cauvery Suture Zone), as it has been proposed by some workers as a major suture in the assembly of Gondwana (Collins et al, 2007),

delineating the site of closure of the Mozambique Ocean. Constraining geochronology as well as apparent eclogite facies rocks within the PCSS have been used as evidence for the PCSS representing a suture (Santosh et al, 2009). The proposed suture is interpreted to be the relic of a southward dipping subduction zone (Naganjaneyulu et al, 2009) on the basis that Cambrian-aged UHT granulites to the south of the PCSS were generated in a back-arc setting. Owing to few integrated metamorphic-structural-geochronological studies on rocks of the PCSS, the significance of the PCSS, particularly in regard to it representing a Cambrian-aged suture, is unclear. It is this hole in our understanding of the PCSS, and in a broader sense, the evolution of southern India, that this project seeks to address.

This project is focused on an area 10 km south of Namakkal in Tamil Nadu, South India. It is located in the centre of the PCSS and consists of strongly deformed mafic-dominated lithologies that record granulite and potential eclogite-facies mineral assemblages. Very little data is available for the Namakkal area; however, recent, unpublished Sm-Nd age data (Bhutani et al, 2007) suggests that peak metamorphism in this area occurred at 879 ± 9 Ma, with a second event occurring at ca. 540 Ma, resetting the Rb-Sr isotopes, but not the Sm-Nd isotopes. If the Sm-Nd age data is correct, the 880 Ma age of metamorphism has significant implications for tectonic models focused on the role of the PCSS that have recently been proposed.

Three stages in geological evolution have been recognised in the field at Namakkal. The first stage is identified as garnet-clinopyroxene-rich assemblages (potential eclogite) preserved in boudins. These boudins are surrounded by top to the south mylonite fabrics defined by garnet-clinopyroxene-hornblende-plagioclase assemblages (D_2). A third stage is identified as discrete D_3 shear zones interrupting the boudins with top to the south kinematics. Syn to post D_2 decompression-style textures with garnet being replaced by hornblende-plagioclase symplectites are also common. This structural evolution is interpreted to indicate potentially high pressure rocks exhumed during top to the south tectonic transport. Furthermore, the observed top to the south kinematics contradict the models that propose a southward dipping subduction zone.

This project will be one of the first to provide an integrated structural-metamorphic and geochronologic study of an area within the PCSS. This project will constrain the thermal and physical evolution of the Namakkal region using calculated metamorphic phase diagrams and conventional thermobarometry. The metamorphic findings will be linked to the tight structural framework that has been delineated for Namakkal. Sm-Nd dating of garnets from the same rocks used to determine the metamorphic evolution will be used to constrain the temporal evolution of the Namakkal rocks, and to shed further light on the findings of Bhutani et al (2007). This project will provide tight constraint on the evolution of the Namakkal region within the PCSS, and therefore, importantly, has broader context in terms of the significance of the PCSS in the evolution of southern India.

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Global models of coupled plate motions and mantle flow

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We show here a novel approach at modeling global mantle flow from plate re-constructions. A planetary surface is split in plates and velocities and/or drags are imposed to the plates. The consequent mantle flow is obtained through the integration of green functions on panels defining the external Earth surface and on internal boundaries. The method is solved through a fast approach that exploits multipole method, also exploiting KD trees for fast identification of near and far-field interacting elements. Furthermore the

calculation of the stresses and velocities only at the boundary of the systems reduces the total number of integration panels to a multiple of $N2$, instead of $N3$, where N is the 1D number of division.

The approach is directly implemented on distributed memory architectures will be perspectively port to a GPU architecture. Advantages of this approach are the possibility to directly have all surfaces defined as free, to use simple GMRES iterative solvers for the minimisation of the residuals and the straightforward coupling with other volume based computational methods as finite differences or finite elements for the heat diffusion and plasticity (faulting) implementation.

The metamorhic evolution of the eastern Warumpi Province

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The Warumpi Province is located along the southern margin of the Arunta Complex in central Australia. It is thought to be exotic to the North Australian Craton due to its distinct protolith ages and less evolved isotopic signatures (Close et al., 2004). It is separated from the North Australian Craton by the Central Australian Suture and is interpreted to have been accreted by a southward dipping subduction system during the 1640 Ma Liebig Orogeny (Scrimgeour et al., 2005b).

Within the southern Warumpi Province, the Iwupataka Metamorphic Complex overlies the Haast Bluff Domain. It is generally considered that the Iwupataka was deposited in the interval 1630–1610 Ma (Scrimgeour et al., 2005a), however some uncertainty means that deposition before the Liebig Orogeny cannot be ruled out (Scrimgeour et al., 2005a). The Iwupataka Complex is made up of quartz-rich metasediments, presumed felsic volcanics and granite and is capped by the Chewings Range Quartzite (Scrimgeour et al., 2005a). In the eastern Warumpi Province, 4 phases of deformation can be recognised (Teyssier et al., 1988). $D_{1\text{-}2}$ produced a bedding-parallel foliation and tight to isoclinal F_2 folds. $D_{1\text{-}2}$ is thought to be related to the c. 1580 Ma Chewings Orogeny, and was associated with pronounced top to the north transport along a low-angle foliation system. This contrasts with the south-directed tectonic transport inferred for the Chewings Orogeny elsewhere in the Warumpi Province (see for example the Mt Liebig area described in Scrimgeour et al., 2005a). This suggests either (1) that the undated deformation in the eastern Warumpi Province is not Chewings in age or (2) there are significant spatial variations in the kinematics of the Chewings Orogeny. The north-directed transport system is overprinted by upright F_3 folds, which dominate the structural trends in the Chewings Range. D_4 is defined by ductile faulting relating to the Devonian-Carboniferous Alice Springs Orogeny (Teyssier et al., 1988).

Very little is known about the metamorphic evolution of the eastern Warumpi Province despite the presence of metamorphically sensitive rocks. Mid amphibolite-grade aluminous metapelites interlayered with the Chewings Quartzite in the eastern Chewings Range contain early garnet-bearing assemblages that grew synchronously with D_1. In the quartzites, the foliation is defined by kyanite-muscovite-quartz. Garnet is overgrown by staurolite-andalusite-bearing assemblages that appear to have developed during D_2. This change in mineral assemblage implies either a down-pressure or up-temperature evolution associated with top to the north tectonic transport. This led to the establishment of a high geothermal gradient regime in the terrain, the origin of which is currently unknown. In this poster we present calculated metamorphic phase diagrams that place the first constraints on the thermal evolution of the eastern Warumpi Province. These are coupled with in situ LA-ICP-MS monazite dating to constrain the age of deformation.

New 1:20,000 scale geological maps and synthesis of the Isua supracrustal belt and adjacent orthogneisses, southern West Greenland: a window into the Eoarchaean

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The Isua area in the Nuuk region, southern West Greenland contains the Eoarchaean Isua supracrustal belt (mostly amphibolites derived from basalts, with chemical sedimentary rocks, felsic rocks and ultramafic units) and orthogneisses with similar ages that flank it to the north and south. These rocks suffered polyphase metamorphism up to amphibolite facies conditions and strain is generally high, but nonetheless the Isua area has most of the world's occurrences of Eoarchaean rocks preserved in a low strain state. This means that Isua area rocks can provide the least ambiguous data on the origin and tectonic evolution of Eoarchaean crust.

New Isua colour digital geological maps at 1:20,000 scale (observed outcrop geology and interpretive solid geology) and a synthesis of the Eoarchaean Isua supracrustal belt and adjacent orthogneisses are presented here. These incorporate advances in structural observations, re-interpretations of the lithologies and the large amounts of zircon dating produced since publication in 1986 of the last geological map of the entire Isua area. Essential in the synthesis is that the Isua area contains a southern ca. 3800 Ma terrane and a northern ca. 3700 Ma terrane. Many of the rocks in the two terranes of different age are broadly similar in appearance, but have been distinguished by U-Pb zircon dating. The boundary between the terranes lies within the Isua supracrustal belt and is most likely at a highly tectonised unit of chert, BIF and carbonate rocks named the *dividing sedimentary unit*, that contains sparse 3940–3750 Ma detrital zircons. In the ca. 3700 Ma terrane to the north, no >3750 Ma detrital zircons have been found.

The Isua supracrustal belt part of the ca. 3700 Ma northern terrane has three geochemically distinct sub-terranes dominated respectively by ≥3715 Ma boninites, ≥3715 Ma island arc tholeiites plus picrites and 3710–3700 Ma andesitic-dacitic rocks or sediments derived from them. In the Eoarchaean, these different arc-related rocks were imbricated and juxtaposed with the ca. 3800 Ma terrane along the dividing sedimentary unit, which was the structural décollement. The ca. 3800 Ma terrane is also interpreted as a complex arc assemblage, similar in origin to the 3700 Ma one, but containing small amounts of older ≥3850 Ma crust. The assembly of these different terranes occurred between 3690 Ma (youngest rocks unique to the northern ca. 3700 Ma terrane) and 3660 Ma (oldest distinctive intrusions common to both terranes). Hence our synthesis shows that Isua crustal evolution was by several juvenile crust formation steps restricted to the 3800 or the 3700 Ma arc-related terranes, followed by complex collisional processes with later tectonic partitioning. This resembles crustal evolution widely seen in other younger Archaean terranes, and points to a continuity of crust formation along convergent plate boundaries back to at least 3800 Ma.

Trench dynamics of the Northern Melanesian Arc

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The convergent zone between the Pacific and Australian plates is characterised by an elaborate interplay between various physical parameters, as expressed by the multitude of diverse morphologies that exist along its entire length. The long linear submarine ridges and troughs, arcuate island chains, the extensive plateaus, basins and island arcs, all of which are numerous throughout the region, comprise the record of a tectonic history punctuated by recurring cycles of compression, extension, and strike-slip motion. However these three plate tectonic processes need not be interpreted as long-lived 'cycles', but rather distinct processes that are dynamic over geologically-short timescales. A prime example of this can be seen today in the northern Melanesian arc of the SW Pacific, where the interaction of various tectonic forces has resulted in a mega-shear zone whose interface consists of numerous micro-plates and tectonic boundaries displaying rapid, dynamic evolution. Here we present an updated tectonic model of this region utilising published kinematic data in conjunction with constraints provided by subducted lithosphere dimensions. This model is analysed within various reference frames in an attempt to examine the elaborate interplay between the various physical parameters that characterise the region, and specifically how these parameters have influenced subduction zone migration velocity, development, and subsequent morphology. We propose that the Pliocene evolution of New Britain-San Cristobal Trench is one characterised by trench advance, and concordantly subduction at the North Solomon Trench has largely operated under trench retreat. The currently observed retreat at the New Britain Trench, and advance at the North Solomon Trench, has only recently been acquired, concurrent with arc-continent collision in New Guinea and the initiation of collision between the Ontong Java Plateau and the Solomon Islands Arc. Such trench dynamics appear to be reflected in the structural evolution of associated subducted lithosphere, an observation most apparent in the spatiotemporal correlation between New Britain Trench advance and the high slab dips exhibited by subducted Solomon Sea lithosphere.

Towards understanding Orogenic collapse: investigating the role of sub-continental lithospheric mantle using geochemical approaches

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Continental evolution is punctuated by the formation and destruction of orogenic belts. This thickening and thinning of lithosphere with associated creation and destruction of mountains, plateaus and basins is a fundamental element of how our planet evolves and is defined.

There are a number of differing models for the development of high plateaus and orogenic collapse, including lithospheric convective thinning, delamination and slab break-off. Importantly, the physical and chemical role of Sub-Continental Lithospheric Mantle (SCLM) is critical in many of these models.

The high Mg, high K magmatic rocks of the lamproite-shoshonite clan are recognised as the products of melting depleted SCLM which has been fertilised by metasomatic fluids. These rocks appear in the record of a number of orogens (Himalaya-Tibetan Plateau, Betic-Alboran Domain and western Mediterranean, Andes-Altiplano, Sierra Nevada, eastern Australia and the Carpathians) but their geodynamic significance remains disputed.

We have undertaken petrographic, geochemical and isotopic characterisation and modelling of shoshonitic rocks produced by single stage melting of SCLM source regions during and after collapse. These small volume, small degree partial melts provide a robust picture of the state of the lithosphere at the time of melting, and contain parent-melt and source region information. This is in contrast to the majority of SCLM studies, which are focused on the refractory xenolith record, providing an opportunity for comparison.

This study compares shoshonite data from Tibet (continent-continent collision), the Andes (continental arc) and the Betic-Alboran domain (post collisional), which reveals distinct trends in major and trace element patterns. One key observation is that within the simple bivariate Mg# vs K_2O (measure of the degree of depletion and fertilisation respectively), each orogens' distinct trend projects back towards Mg# 70 (to a composition in equilibrium with depleted mantle). However, each trend records a different degree of pre-fertilisation (K_2O concentration at Mg# = 70), and in the case of the Tibetan and Alboran (SE Spanish) shoshonites, an even earlier depletion history is revealed.

This information used in conjunction with isotope studies (Hf, Os, Sr, Nd) of the same rocks can be used to inform models of lithospheric evolution during orogenic collapse. Using this approach, similarities between shoshonites from very different tectonic settings are conspicuous, and may suggest a common theme of SLCM behaviour regardless of specific tectonic setting.

New insights into the post-rift depositional history of the Mentelle Basin based on seismic facies mapping

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New 2D seismic data acquired in the Mentelle Basin by Geoscience Australia in 2008–09 has been used for a seismic facies study of the post-rift succession. The Mentelle Basin is a large deep to ultra deep-water, frontier basin located on Australia's south-western margin about 200 km south-west of Perth. The study focused on the post-rift sequences deposited following the breakup between Australia and Greater India. Stratigraphic wells DSDP 258 and DSDP 264 provide age and lithological constraints on the upper portion of the post-rift succession down to mid-Albian strata. The depositional environment and lithology of the older sequences are based on analysis of the seismic facies, stratal geometries and comparisons to the age equivalent units in the south Perth Basin.

Fourteen seismic facies were identified based on reflection continuity, amplitude and frequency, internal reflection configuration and external geometries. They range from high continuity, high amplitude, parallel sheet facies to low continuity, low amplitude, parallel, subparallel and chaotic sheet, wedge and basin-fill facies. Channel and channel-fill features are common in several facies as well as a mounded facies (probably contourite) and its associated ponded turbidite fill. A progradational sigmoidal to oblique wedge facies occurs

at several stratigraphic levels in the section. A chaotic mound facies, probably comprising debrite deposits, has a localised distribution.

During the Valanginian to Hauterivian breakup on the south-western margin, the Mentelle Basin was characterised by extensive syn-depositional volcanism. Sedimentary packages comprising interbedded marine sands and silty clays were deposited predominantly in the western Mentelle Basin surrounded by paleo-highs or areas of non-deposition. Marine-deltaic sediments prograded from the east and south into the main post-rift depocentre. Post-breakup thermal subsidence began in the Hauterivian with sedimentation dominated by a widespread high continuity, parallel sheet facies. From the Aptian through to Campanian, considerable accommodation space was created in the western Mentelle Basin. Sediments deposited during this period are characterised by several parallel to divergent sheet facies in the eastern Mentelle Basin and to the south these grade into a time-equivalent prograding deltaic wedge facies. A regionally extensive, shelf-slope wedge facies occurs to the west of the Margaret Hinge Zone which separates the shallow- and deep-water parts of the Mentelle Basin. Sedimentation rates in the Albian were very high (>45 m/my) with an intra-slope basin developing over the western Mentelle Basin. The Albian section is characterised by an extensive basin-fill facies occurring throughout the western Mentelle Basin and in the northern part of the eastern Mentelle Basin. These two facies both comprise deep marine black mudstones, recovered by DSDP 258.

Towards the end of the Albian period an open marine environment was established across the Mentelle Basin and clastic sedimentation switched to carbonate sedimentation with the deposition of Turonian and Cenomanian chalks and Santonian to Campanian chalks and limestone. In the Middle Eocene, the margin of the Mentelle Basin collapsed resulting in flexure along the Margaret Hinge Zone and rapid deepening of the western Mentelle depocentre. The deep marine carbonate sedimentary section corresponding to this period is often condensed, discontinuous and extensively eroded. It is characterised by several extensive channelised sheet facies in the eastern Mentelle Basin and channelised sheet and mound facies in the western Mentelle Basin. Carbonate chalk and ooze slump deposits just west of the Margaret Hinge Zone are probably associated with Eocene fault reactivation and margin collapse in the region.

Seismic facies analysis of the post-rift sequences in the Mentelle Basin has contributed to a better understanding of the depositional history and sedimentation processes in the region, as well as provided additional constraints on regional and local tectonic events.

Calibrating cosmogenic ^{21}Ne geochronology for application to Quaternary volcanic chronology, landscape evolution and palaeo-climate change

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Cosmogenic nuclides, such as ^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al and ^{36}Cl, are induced in surface rocks and minerals by cosmic ray reactions and can be used to date exposed surfaces. Cosmogenic exposure dating techniques are thus powerful tools for determining the timing and rates of many geomorphic processes (e.g. glacial retreat, soil erosion, palaeo-seismicity, landslides), with important implications for landscape evolution and palaeo-climate change. In addition, the cosmogenic ^{21}Ne method has significant potential for dating young (<100 ka) volcanic rocks and substrates.

Although the study of cosmogenic nuclides for dating and other purposes continues to gain popularity, the associated errors obtained by these methods are typically either poorly specified or significantly higher than those of other geochronological methods. Despite its potential, the ^{21}Ne cosmogenic exposure dating method has received more limited attention, largely due to uncertainties in cosmogenic production rates and perceived analytical and interpretative constraints.

The aims of the current study are: i) to further develop the ^{21}Ne chronometric method for application to Late Pleistocene and Holocene volcanic chronology; ii) to reduce systematic errors associated with cosmogenic exposure dating in general by inter-calibrating cosmogenic ^{21}Ne age data with ^{40}Ar/^{39}Ar and ^{14}C dating results.

The above aims are being addressed in a similar way to previous cosmogenic ^{3}He studies, by measuring the cosmogenic ^{21}Ne content of olivine and pyroxene from <100 ka basalt flows that have also been dated by other methods (^{40}Ar/^{39}Ar, and ^{14}C techniques). Basalt flows satisfying criteria for both the cosmogenic ^{21}Ne (and ^{3}He) and ^{40}Ar/^{39}Ar chronometric methods (> 50 kyr) have been collected from several key localities in western

Victoria, the Mojave Desert in California and Mt Etna in Sicily. Additional (younger, <20 kyr) basalt flows that have been dated previously by ^{14}C methods (Licciardi et al., 1999, 2006) have been collected from well-documented localities in Iceland and Oregon. This range in sample sites is necessary to test latitudinal and altitudinal scaling models for cosmogenic nuclide production rates.

Initial cosmogenic ^{21}Ne results have been obtained for several basalt flows in western Victoria (Newer Volcanic Province) and indicate exposure ages of ~40–60 kyr (Gillen et al., 2010). $^{40}Ar/^{39}Ar$ step-heating analytical protocols for dating such young whole rock basalt have been trialed for a number of western Victoria flows, in an effort to improve analytical precision. Preliminary $^{40}Ar/^{39}Ar$ age data for several western Victorian flows indicate ages ranging from ~60–400 kyr. These results will be used to facilitate further analytical developments to improve ^{21}Ne and $^{40}Ar/^{39}Ar$ precision levels.

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The petrogenesis and evolution of the Western Ravenswood Batholith, north-east Australia

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The Ravenswood Batholith situated south-west of Townsville, Australia, covers over 6000 km2 and is host to the world class Charters Towers goldfield. The Batholith represents a major phase of Paleozoic continental crustal growth in Eastern Australia. The main intrusive events were during the Ordovician (470–450 Ma) and Silurian-Devonian (450–400 Ma) periods. The heterogenous nature of the Ravenswood Batholith is well recognised by a diversity of the igneous rock types, which include granites, granodiorites, tonalites, diorites, gabbros, and basalts. The felsic intrusives are predominately of I-type character. Despite extensive gold exploration in the region over last century, there has been little previous work on the geochemistry, petrology and geochronology of the igneous rock bodies. In particular, very few of the plutons have been age dated using robust radiometric techniques. There is currently a lack of knowledge with regard to the granitoid emplacement mechanisms, igneous relationships, the tectonic setting and temporal evolution of the Batholith and there is little information regarding any genetic link between gold mineralisation and magmatism at a local and regional scale in the Charters Towers area.

This study examines the felsic to mafic plutonic bodies from around the Charters Towers region in the western part of the Batholith. In particular, we focus on samples from a deep drillhole (2000m) recently drilled by Citigold Ltd, which represents a unique opportunity to sample deeper levels of the Batholith in the vicinity of the mineralisation. Samples were petrographically examined and then analysed for major and trace elements by XRF and laser ablation (LA) ICP-MS, respectively. Several key samples were also processes for U/Pb zircon geochronology. The aims of this work are; (1) to describe the petrology and geochemistry of the granites present in the western Ravenswood Batholith, and to determine, possible source rocks and conditions of melting; (2) to improve our understanding of the temporal evolution of the Batholith; (3) to delineate the geological processes involved in the evolution of the Batholith (including magma mixing, crustal melting, fractional crystallisation and restite umixing); (4) to determine the tectonic setting in which the Batholith formed and to place this into the context of crustal growth along the eastern edge of Gondwana and; (4) to determine the any spatial, temporal or genetically link between magmatism and gold mineralisation.

Important findings of this work to date include; (1) discovery of a high Mg- dacite at ~88m of the deep drillhole—so far, igneous rocks of this character have not been recognised in the region; (2) the recognition of high-Ti and low-Ti suites of basaltic rocks (3) a dominance of diorite in the deep drillhole, which may indicate that mafic lithologies may be more prominent in the Batholith than previously thought, (4) a wide spectrum of igneous rock compositions, which indicates a complex crustal growth history for the Batholith.

We will soon obtain trace element geochemistry of the samples, which will help in evaluation of the tectonic setting in which these rocks formed and will aid correlation of rock units across the Batholith. U/Pb dating of zircons separated from a number of intrusive units will further delineate the temporal evolution of this crustal block, and will provide important constraints on the relationship between magmatic episodes and gold mineralisation.

High-resolution imaging of the core–mantle boundary with PcP-P seismic traveltime data

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South-eastern Australia is favorably positioned relative to much of the Pacific Rim and SE Asian subduction systems for recording of *PcP* phases from subduction zone earthquakes. *PcP* seismic phases bounce off the core-mantle boundary (CMB) and are valuable for investigating this complex region in the earth, especially when they are compared to *P* phases that travel nearly the same path except for close to the CMB. In this way, anomalous differences between *PcP* and *P* can be attributed to differences at the CMB. Differential *PcP-P* phases are best recorded between approximately 25–75 deg, which is precisely the distance of SE Australia relative to the subduction zones of Indonesia, Papua New Guinea, Tonga/Kermadec, Philippine, Izu-Bonin-Mariana, and Japan. As such, any seismic stations deployed in this area have potential for accurate *PcP-P* travel time studies.

Since 2001, Australia's WOMBAT array has been leap-frogging across the continent. Each subarray within WOMBAT consists of 30–50 short-period seismometers with solid-state recorders deployed for 6–12 months. Station spacing is 20–50 km, resulting in high-resolution coverage at the continent scale. To date, over 500 short-period stations have been deployed in SE Australia. Furthermore, the lack of anthropogenic noise for most stations, and the presence of low attenuation in parts of the upper mantle, enable good signal-to-noise ratio. With the large number of subduction zone earthquakes in an appropriate distance range for a *PcP-P* study and the dense station distribution, we obtain unprecedented high-resolution coverage of the core-mantle boundary in this region.

We use the WOMBAT data to analyse differential *PcP-P* travel times to examine the seismic structure at the base of the mantle. Surface projections of *PcP* bounce points are clustered directly beneath the large region spanning northern Australia and mid-latitude regions of SE Asia, significantly improving resolution of the deep mantle beneath this area. From a preliminary dataset using only 100 stations, we record high quality *PcP* for several thousand earthquake-station pairs; we expect significantly more high quality *PcP-P* measurements from all 500 stations. Our goal with this new dataset is to produce high-resolution images of the seismic structure at the base of the mantle.

Plate–mantle interaction modelling using parallel fast multipole boundary element method and multigrid finite differences

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Causal relationships linking plate and mantle interactions are poorly understood despite strong observational evidence and advances in tomographic imaging, mineral physics and geodynamic modelling. Technical diffculties implementing the intrinsic multi-scale nature of the problem limit advances in fully coupling the regional tectonic scale of a single subduction zone. The employment of modern techniques as the boundary element method represent a breakthrough in the field and has enabled modelling the direct interaction of mesoscale entities with the global feedback of the 3D globe. Such numerical methods overcome the limitations of classical finite difference and finite element methods employed in geodynamics and solve the problem of computational scalability, yet they require a less trivial implementation. The fast multipole is a revolutionary approach that tackles the difficulty of handling the intricate volume meshes and high resolution data by reducing the total number of points to a multiple of N^2, instead of N^3, where N is the 1D number of division. This approach was recently tested and applied at various scales in a series of papers by Morra et al. (2007, 2008, 2009), using k-dimensional trees for fast identification of near and far-field interacting elements, and implemented with MPI parallelised code on distributed memory architectures. As the method is based on

a free-surface, it allows easy volume mesh sampling of physical quantities and enables direct integration with multigrid finite difference study of heat advection and diffusion within the mantle.

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Physical and chemical characteristics of crustal rocks in the mantle transition zone: experimental constraints at 15–23 Gpa

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Seismic tomography has provided us with dramatic images of subducting slabs piling up in the Mantle Transition Zone (MTZ), and in some cases cascading down into the lower mantle as a consequence of gravitational instabilities induced by mineralogical phase transitions (Zhao, 2004). Geochemical, including isotopic, studies of ocean island basalt (OIB) volcanism related to plumes arising from the MTZ, lower mantle, or 'D' layer at the core-mantle boundary suggest that deeply subducted slabs carry with them crustal rocks, formed at Earth's surface, into the deep mantle source region for OIB-related plumes. These crustal materials, which have interacted with the atmosphere or hydrosphere, include continental sediments (whose signature is evident in 'enriched-mantle', or 'EM-type' OIBs), and basaltic oceanic crust (whose signature is evident in 'HIMU-type' OIBs). Although the mineralogy of these lithologies at MTZ pressures are known to some extent from laboratory experiments, there are very few constraints on the trace element composition of their constituent minerals at the P-T conditions of the MTZ and the lower mantle. This information is crucial to the proper interpretation of the isotopic 'message' that OIB lavas carry from the deep mantle. Mineral physicists have made considerable progress in building a database of thermoelastic parameters (e.g., density, bulk modulus, thermal expansivity) for constituent minerals in the MTZ and lower mantle, as well as key phases in crustal rocks at these pressures (e.g., stishovite, kyanite, majorite). These data allow the densities of deeply subducted crustal lithologies to be calculated, and when compared to the ambient mantle, their relative buoyancy provides an indication of whether they will sink or float at any depth in the MTZ or lower mantle. Thus in principle, one can determine where deeply subducted crustal rocks should settle, and what their detailed chemical composition should be, constraining both the nature (mineralogical and chemical) and location of the source region for plume-related OIBs. This approach is epitomised by our recent work on the mineralogy and phase equilibria of continental sediments at 15–23 GPa (Rapp et al., 2008), and in-situ measurements of the thermoelastic properties of K-hollandite using synchrotron radiation (Nishiyama et al., 2005). We are currently conducting phase equlibria experiments on natural MORB compositions at P-T conditions appropriate to the MTZ, and characterising the major-and trace-element characteristics of the high-pressure phases in these experiments by electron microprobe and laser-ablation ICPMS, respectively. Key phases in hydrous MORB at 15–23 GPa include majoritic garnet, stishovite, Na-hollandite, NAL-phase, and a new, previously unidentified Fe-Ti rich aluminous phase. We have obtained trace-element data for some of these phases using laser-ablation ICPMS, and use this data to assess the mobility of certain key trace elements in hydrous MORB that has been subducted into the MTZ. P-V-T equation of state parameters will then be used to calculate the density of individual minerals in this high-pressure phase assemblage, and these will be combined according to modal proportions in order to estimate the density of MORB residuum relative to ambient mantle throughout the MTZ and into the lower mantle. Ultimately, we hope to constrain where in the deep mantle subducted crustal lithologies will come to rest, and what they will consist of, from a geochemical perspective. These results will provide a better understanding of the nature and location of the source region for plume-related OIB magmas.

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New imaging results from the WOMBAT seismic array project in south-east Australia

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Since 1998, a series of passive seismic array deployments have taken place in south-east Australia, resulting in an unprecedented coverage of over 500 seismic stations throughout Tasmania, Victoria, New South Wales and South Australia. The large volumes of data recorded from distant and local earthquakes, atmospheric and oceanic disturbances, and various sources of natural and cultural activity, has enabled the crust and upper mantle beneath south-east Australia to be imaged in great detail. To date, most of the research based on this data has focused on 3-D tomography of the upper mantle using relative arrival times from distant earthquakes, with limited attempts at combining data from the various sub-arrays of WOMBAT.

In the last year, a series of studies have been carried out that seek to exploit various classes of data from the multiple arrays. Results from three of these studies will be discussed in this presentation. These include (1) Combined teleseismic tomography of mainland south-east Australia, which images the P-wave velocity structure of the lithospheric mantle; (2) ambient noise tomography of mainland south-east Australia, which images Rayleigh wave group velocities; (3) simultaneous inversion of wide-angle data (from an independent study) and teleseismic data from Tasmania for Moho geometry and the P-wave velocity structure of the crust and upper mantle.

The three studies outlined above have produced a variety of interesting results that help improve our understanding of the deep geology and tectonic evolution of the Lachlan and Delamerian orogens. For example, the combined teleseismic tomography results clearly show that the mantle lithosphere of the Delamerian Orogen underpins the Stawell Zone in western Victoria; that the Central Subprovince of the Lachlan Orogen sits above a zone of elevated P-wave velocity, possibly implying the presence of Proterozoic continental material; and that there is some evidence for the existence of the Selwyn Block beneath the Melbourne Zone. One of the main results from the ambient noise tomography, which images shallow crustal structure, is the presence of a distinct low velocity anomaly beneath the Murray Basin, which may correspond to the presence of a pre-Tertiary infrabasin. The simultaneous inversion of active and passive source data from Tasmania reveals a detailed lithospheric model of Tasmania. One of the main results from this study is that there is no seismic evidence that supports the presence of a crustal scale suture zone beneath the Tamar River; rather, we find a strong velocity transition zone some 50 km to the east, and infer that it represents the change from siliciclastic continental crust of Proterozoic origin, to younger mafic crust of oceanic origin, likely emplaced by repeated orogenic cycles from what was originally a passive margin.

Future work with WOMBAT includes continued roll-out of new seismic arrays in New South Wales and Queensland over the next two years, and jointly inverting all different data types (teleseisms, ambient noise, receiver functions, local earthquakes) to constrain a detailed 3-D model of the crust and upper mantle beneath south-east Australia.

Structure and tectonic evolution of the central Eastern Ghats Province, India: Araku-Anantagiri-Visakhapatnam

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The central Eastern Ghats Province forms part of the Eastern Ghats Orogen, which is a Mesoproterozoic to early Neoproterozoic belt extending over 1000 km along the east coast of peninsular India. The orogen is thrust west over the Dharwar/Bastar craton, which makes up the southern part of cratonic India. The Eastern Ghats have been divided into a number of provinces by Dobmeier and Raith (2003) that are interpreted to have separate tectonothermal histories. At the latitude of this study, an east-west transect through the orogen passes through the Eastern Ghats province (from the east coast at Visakhapatnam, westward into Orissa) and then bisects that Jeypore Province before reaching the Dharwar/Bastar craton. This study is focused on the

enigmatic Eastern Ghats Province that records several high temperature and ultra high-temperature metamorphic and deformational events in the late Mesoproterozoic and through the Neoproterozoic.

In most Rodinia reconstructions, the Eastern Ghats Orogen marks the site of a continent-continent collisional zone between Mesoproterozoic India and the Mawson continent that consisted at the time of the Gawler craton and its extension into Antarctica. The area of this study is located in the region of this proposed suture zone. The central Eastern Ghats Province is composed of predominantly metapelitic gneisses and quartzites with inclusions of calc-silicates repeatedly metamorphosed to granulite facies. Unusually for a Proterozoic orogen, these metasedimentary gneisses have markedly high heat production values that may have assisted in the region obtaining the high metamorphic temperatures recorded. These metasedimentary gneisses have been intruded by alkaline melts which post-date the formation of the foliation. Previous research has dated the ages of detrital zircons to between 2.7 and 1.8 Ga.

This presentation will present a structural transect through part of the central Eastern Ghats Province to demonstrate the relative age constraints determinable from the rock relationships in the region. New U-Pb detrital zircon ages obtained using the LA-ICP-MS technique will be used to determine the maximum depositional age and provenance of the metasedimentary sequences. The provenance work is particularly important in trying to determine the nature of the protoliths of the Eastern Ghats Province and to determine whether it is an inverted Mesoproterozoic passive margin succession, or whether it is an exotic terrane that accreted to India during late Mesoproterozoic collision.

Mechanism of formation and age of charnockite magmatism in the Palghat-Cauvery shear system, southern India

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Holland, 1900, defined charnockites as ‘A hypersthene bearing granite’ which was later redefined by Pichamuthu 1969, ‘A quartzfeldspathic rock with orthopyroxene (Opx)’. The ambiguity in these definitions resulted in some horrendous terms used to describe charnockites which resulted in much confusion amongst researchers and a variety of published papers trying to better define a charnockite. Frost & Frost 2008, aimed to redefine these ambiguities and discrepancies and stated charnockites are an ‘An Opx – (or Fayalite) bearing granitic rock that is clearly of igneous origin or that is present as an orthogneiss within a granulite terrain’. This definition was generated because Charnockites are an assemblage of foliated metamorphosed igneous rocks that share genesis through differentiation of the similar parent magmas and can also be a result of metasomatic dehydration metamorphic processes. They are commonly found in granulite-facies metamorphic terrains in the form of massif blocks or waxy green lenses or selvages that contain either garnet bearing or garnet absent varieties. They are therefore are an exposed piece of deep continental crust of the Earth; however it is still unclear how to distinguish between Charnockites that are metamorphic origin and those that are of igneous origin.

The study area sits within the southernmost tip of the Indian Shield which encompasses the Archaen Dharwar Craton and a significant terrain of high grade (amphibolite–granulite facies) rocks known as the *Southern Granulite Terrain* (SGT) (Chetty et al. 2006). The SGT consists of multiply deformed Archaean and Proterozoic magmatic and high grade metamorphic rocks (Chetty et al. 2006). This terrain has been formally been divided into crustal blocks which are divided by approximately E-W trending shear zone systems; the main dividing zone is the Palghat-Cauvery Shear Zone (PCSZ); separating Archaean cratons from Palaeo- to Neoproterozoic SGT. This shear zone is widely accepted amongst researchers as the continuation of the ancient Betsimisaraka suture of Gondwana that is evident in Madagascar (Collins et al. 2007). The main field site is adjacent to the small village of Ayyarmalai, approximately 34km SE of Karur township, in Tamil Nadu, Southern India. It has a large prominent 311m high granite outcrop, flat plains and to the west with several charnockite quarries. While no research has been completed in this area before and very little geochemical analysis has been completed on Southern Granulite Charnockites, age dating has been done in Southern India with unpublished zircon SHRIMP ages determined from the Sankaridurg granite near Salem which shows 542 Ma ages.

This study will produce valuable geochemical data on Charnockites i.e. whole rock and mineral chemistry, trace elements, isotopes (Nd, Sr, Pb, Th, K, Hf, O, Rb, Sm), and aim to determine the key features that identify a metamorphically derived Charnockite from an igneous. Dating of charnockite emplacement or the dehydration event using zircon geochronology of newly formed zircons will provide a comparison with other

charnockites in Southern India (Rimsa et al, 2007). Thermobarometry and fluid inclusion analysis will help constrain the formation conditions. This study will provide evidence of any pattern or trend changes in Rare Earth Elements and whether it changes going into these veins i.e. what is getting depleted and what is getting enriched and what this means in a bigger tectonic context in regards to the PCSZ. Our early results indicate that charnockite emplacement may be a result of dehydration metamorphism initiated by large scale CO_2 fluxing.

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Curie depth map from airborne magnetic data—a tool to study tectonic settings of Gawler Craton, South Australia

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Crustal magnetism is produced by ferrimagnetic minerals, especially magnetite and/or titano-magnetite, distributed in rocks throughout the crust. Magnetisation is strongly temperature dependent, and ferromagnetic minerals lose their main magnetic properties at the Curie temperature (~580$_o$C). Generally, temperature in the crust increases with depth. Therefore, with the known magnetic mineral assemblages of the crust and geothermal gradient it is theoretically possible to calculate the 'Curie depth', where ferrimagnetic minerals become nonmagnetic. Alternatively, if it is assumed that the vertical distribution of magnetic minerals in the crust is homogeneous, the 'Curie depth' can be estimated from spectral analysis of magnetic data. The depth to the bottom of the magnetic anomaly source can be interpreted as a proxy for the 'Curie depth'. By using spectral analysis of magnetic data to deduce the depth to bottom of magnetic anomalies, we have generated a 'Curie depth' map over the Olympic Dam supergiant iron-oxide-copper-gold-uranium mineral system in the Gawler Craton of South Australia. Interpretation of the area benefits from high quality airborne TMI data, as well as magnetotelluric and deep seismic reflection data, and local heat-flow determinations.

The 80m gridded TMI data were processed with 1) magnetic transformation to the pole, 2) removal of linear regional trend and 3) upward continuation to a height of 1 km to remove high frequency near surface noise. An overlapping moving window technique to 2D TMI data in the study area was implemented to subdivide the TMI grid of the 300 km x 300 km study area into several overlapping rectangular windows. The dimension of the window and the amount of overlap are carefully chosen, so that the spectral contents possess the necessary low wave-number components. The chosen window size was 90 km by 90 km, and window centres were 36 km apart to provide a 65% overlap. The 2D power spectra was calculated for each window via the Fourier transform technique, using a 5% cosine taper and appropriate roll-off to minimise possible edge effects. The 2D power spectra were transformed into 1D azimuthally averaged radial power spectra. The 'Curie depth' for each data window was then estimated semi-automatically via slope picking and least squares methods. Finally, the 'Curie depth' estimates at the 49 window centres were gridded using a 5 km cell size to generate the 'Curie depth' map of the study area.

The new results show a large range of Curie depths across the north-eastern Gawler region, with the deepest area being an ovoid-shaped feature 55 km long by 35 km wide, and up to 40 km deep, centred approximately beneath Olympic Dam. The Olympic Dam orebody is associated with high surface heat-flow relative to the surrounding area. Modern geothermal fields with high heat-flows, such as Yellowstone in North America, tend

to have shallow Curie depths because magnetite reaches the 580$_{o}$C Curie depth at shallow levels. The combination of high-heat flow and deep Curie depth at Olympic Dam indicate that heat production at this location is strongly partitioned in the shallow crust, and that the geothermal gradient beneath Olympic Dam must be nonlinear for most its crustal column. The dependence of the interpretation on the assessment of a homogeneous distribution of magnetic minerals requires further assessment.

The deeper 'Curie Depth' beneath Olympic dam may indicate reduced heat production within the mid and lower crust, which may in turn be related to a depletion of uranium and other radioelements. Thus, the 'Curie depth' anomaly could be interpreted as a deep crustal alteration footprint for the Olympic Dam mineral system. Further potential field analysis and comparison with seismic and MT results is ongoing to investigate the nature of the 'Curie depth' anomaly and verify the applicability of this method for deep crustal imaging.

AusMoho: the Moho map of the Australian continent

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Seismic data coverage of the Australian continent has greatly increased of the last 10 years, providing us with the opportunity to update our knowledge of the depth and nature of the crust-mantle transition across Australia. We present a new crustal thickness map of Australia estimated from the compilation of seismic receiver functions, seismic reflection and refraction profiles. This map represents the current status of the AusMoho project, which ultimately aims to image the Australian continental crust with a 50 km resolution.

Currently the Moho map consists of over 250 data points and includes data from 3-component broadband and short-period stations deployed in the last 15 years and large-scale seismic reflection and refraction profiles conducted in the last 35 years.

The new Moho map provides information about the present day large scale crustal structures that define the geological provinces of Australia and will supply much needed constraints for use in tomographic imaging of the earth below. The most striking feature of the new Moho depth map is the short wavelength transition from the thickest Proterozoic crust (61 km) in central Australia with the thin crust (~30 km) of Phanerozoic eastern Australia. Current projects in New South Wales, South Australia and Queensland will provide additional points and the BILBY array through the centre of Australia will provide more detail where the crustal thickness is changing rapidly.

New results from the South Australian seismic arrays

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We present new results from two arrays in South Australia. The Gawler array consisted of 35 short-period seismometers deployed across the Gawler Craton for an 8-month period (2008–2009). Station spacing is approximately 50 km and the area covered by this array runs from Port Lincoln in the Eyre Peninsular to Leigh Creek just west of the Flinders ranges. The Curnamona array consisted of 34 short period instruments deployed over the area between the Flinders ranges and the New South Wales border fro a 6-month period in 2009. Station spacing for this array was approximately 60km.

Instruments were deployed as part of the earth imaging and structure component of AuScope and are intended to provide broad scale earth imaging of the two areas. These two regions of Australia are currently of particular interest for the supply of geothermal energy and there are many ongoing industry projects in the area.

We present the results from both surface wave tomography and receiver function analysis for these two arrays. Ambient noise, mainly from the ocean, is utilised to construct dispersion curves. These dispersion curves contain information about surface wave velocities that can be inverted to produce tomographic images. Surface wave velocities are sensitive to thermal anomalies and sedimentary basins and are therefore of interest with respect to geothermal exploration. Receiver functions utilise information from distant earthquakes to image structural boundaries in the lithosphere such as the Moho. This information will provide additional coverage for the AusMoho project.

iEarth: a new collaboration for inverse modelling in the earth sciences

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The year 2010 sees the establishment of *iEARTH* a new consortium open to researchers from all Universities, Government labs and Industry with a common interest in the solution of inverse problems in the Earth Sciences. Originating in Australia the *iEARTH* consortium has the goal of generating new science for understanding the solid Earth and its environment, including the parameters that control the Earth's physics, its present tectonic regime, and how its behaviour is expressed in the long term rock, sediment, ocean and climate record. Because our observations are made at (or very near) the Earth's surface, all knowledge of the Earth's interior is based on indirect inference. As a consequence numerical inversion and data assimilation are used to explore the link between Earth's heat, its physics, chemistry as well as its mechanical and biological behaviour. The purpose of *iEARTH* is to provide a unique opportunity to bring experimentalists, theoreticians and computer scientists together to combine our efforts, to share, challenge and inform. The overarching long-term aim of this collaboration is to move Earth Sciences from an empirical observation based science into a truly quantitative data-intensive science. This will allow us to develop long term understanding of how the Earth has evolved to produce the environment we require, distribute the resources we depend on and create the hazards we live with.

Constraints on gold and base metal mineralisation within the Wau Structural Basin in Papua New Guinea

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The Wau structural basin (graben) is located within the Morobe goldfields in the Morobe Province of Papua New Guinea. The graben is the host of major gold and silver deposits including Hidden Valley, Hamata, Kerimenge and Eddie Creek deposit. Geological, geochemical, geophysical and structural data compilation and analysis indicates a south-west magmatic origin of the Wau Graben mineralisation. The sulphur isotopic study of the sulphur in pyrites from the mineralised lodes suggests the source of sulphur not necessarily of magmatic origin but that of a mixture of magmatic, meteoric and sediment-derived sulphurs. Whole rock geochemistry revealed the Morobe Granodiorite and the Edie Porphyry as calc-alkaline intrusive rocks which have compositions that are LREE-enriched between the 'Marianas Arc' and 'within plate' magma series. This suggests that continental rifting of the Australian Plate and Woodlark Plate have possibly triggered magma generation within the plate boundaries. Field mapping and petrography revealed more mafic constituents within the Edie Porphyry than the Morobe Granodiorite which designates a more mafic and replenished magmatic source for the Edie Porphyry. Thermobarometric calculation from mineral chemistry data further suggests that the Edie Porphyry intruded at 2–6 kbars, 770–790°C. Structural data indicate common north-east and north-west structural trends associated with the rock types and gold and base metal mineralisation. Late north-south structures emergent through abrupt compressional movements while east-west structures developed through extensional events of continental rifting and divergence.

Rayleigh and love wave ambient noise tomography of Australian continent

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We present Rayleigh and Love wave phase and group wavespeed maps for the Australian continental crust and upper mantle. The cross-correlation of ambient seismic noise has recently become an important tool in seismology to image the subsurface. By cross-correlating the seismic noise signals recorded at two different seismic stations, it is possible to extract a 2-D seismic response of the Earth between these receivers. The extracted signal is dominated by surface waves, which can be used to extract dispersion characteristics for geophysical inversion. In this work, we cross-correlate all of the available 3-component broadband datasets collected at stations deployed by RSES-ANU and permanent networks across Australian continent deployed during the last 18 years. The vertical components of interstation correlations are dominated by Rayleigh type surface waves, where transverse-transverse correlations contain Love wave. We filter these waveforms with a

narrow band filter between 5 and 100 seconds to measure the group and phase velocities of the Rayleigh and Love wave. The measurements are then inverted with a nonlinear tomographic technique for mapping the 3-D velocity variation from upper crust to upper mantle across the continent. The Moho depth is determined by a separate inversion step, where the all of the dispersion measurements are jointly inverted. The resulting tomographic images mark major velocity changes caused by sedimentary zones and cratons.

Quantifying the bending radius and bending dissipation during subduction with 3D geodynamic models

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Subducted slabs are considered to provide the main driving force for plate motion and mantle flow in the Earth's interior. Slabs drive flow in the mantle due to viscous tractions between the slabs and ambient mantle, and mantle flow itself provides tractions at the base of the plates, which could thereby facilitate plate motion. More importantly, slabs drive plate motion as they are coupled to their trailing plate and act as stress guides, thereby directly pulling on their trailing plate.

Because slabs and their plates at the surface are assumed to be effective stress guides, it could be thought that they must be strong relative to the ambient upper mantle. But if plates and their slabs are very strong, then they will exert large resistance to break and bend at the subduction zone hinge, and could thereby potentially stall the subduction process and with it plate tectonics. Thus, one could also expect slabs and plates to be relatively weak. Due to such contradicting expectations and the complex rheology of the lithosphere and mantle, the relative strength of slabs and the energy dissipation at the subduction hinge remain a matter of considerable debate.

Three-dimensional laboratory subduction models are presented that investigate the influence of the slab/upper mantle viscosity ratio (η_{SP}/η_{UM}) on the slab bending radius (R_B), with η_{SP}/η_{UM} = 66–1375. Here, R_B is non-dimensionalised by dividing it by the upper mantle thickness (T_{UM}). The results show that R_B/T_{UM} varies with time, reaching a maximum when the subduction velocity is maximum at a time just prior to the slab tip reaching the 670 km discontinuity, followed by a rapid decrease and then a more constant R_B/T_{UM}. Furthermore, R_B/T_{UM} increases approximately linearly with increasing η_{SP}/η_{UM} for the investigated viscosity range.

The model results show that the slab bending force (F_{Be}) and the energy dissipation during bending at the subduction zone hinge (Φ_{Be}) are small compared to the negative buoyancy force of the slab (F_{Bu}) and the potential energy release during sinking (Φ_{Bu}). Maxima in Φ_{Be}/Φ_{Bu} ($\approx F_{Be}/F_{Bu}$) are reached in the early stage of subduction when R_B/T_{UM} is minimum and the slab tip is at 220–440 km depth. Maximum Φ_{Be}/Φ_{Bu} increases with increasing η_{SP}/η_{UM}, with Φ_{Be}/Φ_{Bu}(max) = 0.06, 0.11, 0.18 and 0.22 for η_{SP}/η_{UM} = 66, 217, 709 and 1375, respectively. For subduction depths >220–440 km, Φ_{Be}/Φ_{Bu} = 0.02–0.11 for all viscosity ratios. Assuming that in nature η_{SP}/η_{UM}<1000, as implied by geoid observations at subduction zones, slab geometry and subduction kinematics, and that viscous dissipation during plan view curvature of the slab is ≤1%, the models predict that in nature most of the slab's potential energy is used to drive mantle flow (on average 88–97% and minimally 81%), whilst only a small component is used to bend the subducting plate at the hinge (on average 2–11% and maximally 18%). Applying the model predictions for R_B/T_{UM} and Φ_{Be}/Φ_{Bu} to natural subduction zones implies that in nature $\eta_{SP}/\eta_{UM} = 1–7 \times 10^2$ and $\eta_{UM} = 0.8–2.7 \times 10^{20}$ Pa·s.

A reconnaissance study of $^{176}Hf/^{177}Hf$ ratios in zircons from the New England Batholith

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Zircon Hf isotopic data from granites belonging to each of the five supersuites of the batholith have a range of ε_{Hf} values consistent with mixing between crustal and mantle-derived magmas. In general, those granites from supersuites with low $\delta^{18}O$ and low $^{87}Sr/^{86}Sr$ initial ratios (Sr_i) contain zircons with a range of ε_{Hf}, the higher values of which suggest a moderate to high mantle-derived component, while zircons from supersuites with higher $\delta^{18}O$ and higher Sr_i have lower ε_{Hf} indicating a larger amount of crustal component.

The Clarence River supersuite, the most primitive in the batholith, have zircon ε_{Hf} values in a single sample ranging from of +11 to +22, representing depleted mantle model ages (T_{DM}) from ~450 Ma to ages less than an emplacement age around 250 Ma. A similar range in ε_{Hf} has been found in the Valla pluton, one of the most eastern granites of the batholith.

Combined zircon data from 3 samples of the zoned I-type Walcha Road pluton (one sample from each of the zones—mafic margin, intermediate zone, felsic core) have zircon ε_{Hf} values ranging from of ~+5 to ~+16, equivalent to T_{DM} ages of ~670 Ma to ~270 Ma, the latter age approximating the age of emplacement. Published data on the zoned pluton indicates the felsic core has more primitive $^{176}Hf/^{177}Hf$ ratios than in the mafic margin. Zircons from a micro-granitoid enclave have ε_{Hf} values from ~+5 to +14, similar to those of the host.

Six samples from the Uralla plutonic-volcanic complex of the Uralla supersuite give zircon ε_{Hf} values between ~+5 to +13, equivalent to T_{DM} ages between ~750 Ma to ~400 Ma. The Kentucky diorite, a mafic cumulate has a significant crustal component with zircon ε_{Hf} variation of ~+6 to ~+9 units.

For the Bundarra supersuite ε_{Hf} values are within the range ~+5 to +13, and T_{DM} ages between ~720 Ma to ~400 Ma, similar to the Uralla supersuite.

A much older crustal source age is suggested for the Hillgrove supersuite with ε_{Hf} values between –0.1 to ~+13, and T_{DM} ages between ~950 Ma to ~400 Ma.

Important points from this study are:

- The recognition that most granites, including I- and S-types are not the products of single source components as previously considered but are a mix of fractionated mantle-derived melts and crustal partial melts. The range of zircon $^{176}Hf/^{177}Hf$ ratios is a record of the mixing process.
- Some felsic plutons or parts of zoned plutons are more isotopically primitive than intermediate or mafic members and could result from mixing of two (or more) felsic source components, one a primitive fractionated (residual) basalt, the other (or others) crustal partial melts.
- The oldest T_{DM} ages of a zircon population reflects the minimum age of the oldest crustal end member. For those supersuites of the batholith with low Sr_i, low $\delta^{18}O$ and high ε_{Nd} (Clarence River and Moonbi) and where melting is presumed to be lower crustal, T_{DM} ages suggest a Neoproterozoic basement (~650 Ma) for the New England Orogen.
- Melt generation for the Uralla Bundarra and Hillgrove supersuites with older T_{DM} ages is considered to have occurred principally at or above the transition between Neoproterozoic basement, and a mix of Palaeozoic accretionary material with older continentally-derived sediments from the west.

Contribution of mantle convection to the Miocene reversal of the Amazon River

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It is well established that major changes in drainage patterns across northern South America occurred in the Miocene. Such observations have been associated with the disappearance of the Pebas fluvio-lacustrine system and northward draining systems, and subsequent formation of the eastward-draining palaeo-Amazon River. While some authors have attributed flexural mechanisms associated with Andean uplift to such changes, the contribution of mantle convection to surface palaeo-topography has never been evaluated for South America. The subduction of the Farallon and Phoenix plates, and most recently the Nazca Plate, provide sinking slab material that is overridden by the westward moving South American Plate. The coupling of mantle dynamics to surface kinematics presents a time-dependent mechanism to drive the surface evolution of South America. Recently developed high-performance computing geodynamics software, *CitcomS*, coupled to the plate kinematic *GPlates* software, now allows for the reconstruction of past mantle structures in a context of dynamic plate boundaries and velocities. We integrate plate motions, seismic tomography and stratigraphic data and use an adjoint modelling approach, an iterative procedure that uses forward and backward modelling, to best recover initial conditions. We evaluate the contribution of mantle-convection to surface

elevation, and find that an evolving dynamic topographic low since the Late Cretaceous can be attributed to up to 40 m of mantle convection-driven subsidence per million year across the central and eastern basins of South America. Subsequent uplift of up to 70 m/m.y., which also migrates east, is predicted along the western margin from approximately 40 Ma. Using geodynamic model output we generate digital palaeocontinental elevation models back to 76 Ma correcting for dynamic topography and eustatic sea level effects. We attribute long-wavelength dynamic subsidence and uplift, in conjunction with flexure from Andean uplift, to Miocene changes in the lowlying Pebas system in the western Amazonas and formation of the palaeo-Amazon River. Our methodology can be applied to other fluvial systems, including within Australia, to obtain tighter constraints on the timing and direction of flow.

3D Victoria's basin and basement model building workflow—creating the next generation of exploration tools for Victoria

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A sophisticated, crustal scale 3D geological model of Victoria is being developed by GeoScience Victoria as part of the Rediscover Victoria 3D project, providing the next generation of tools with which to explore Victoria. The fully attributed 1:250 000 scale 3D model will incorporate the onshore and offshore geology of the state, and integrate Palaeozoic basement with younger sedimentary basins, facilitating the analysis of complex energy and mineral resource systems at all scales, and the regional controls on their development. The model is being built in stages. The first stage Bendigo Zone 3D model was released in mid 2009. Initial products of the western Victoria 3D model, incorporating the Stawell, Grampians-Stavely and Glenelg zones were released earlier this year, with more integrated models to follow.

In this instance, we illustrate a typical workflow developed by GeoScience Victoria's 3D modelling team. The workflow involves the development of a series of serial sections across the modelled area, perpendicular to major structural trends, forming a framework on which the model is built. All available geological and geophysical information including field mapping, drill-hole data, potential field data and its derivative datasets (eg. worms), seismic data where available, digital terrain models, and depth to basement results are used to constrain a surface fault network interpretation and serial section construction. An agreed stratigraphy is defined for the model region. Serial sections are then digitised into a 2¾D potential field forward modelling package. Common rock property attributes are assigned to units in the sections. Forward modelling of the interpreted geometries then allows a first order assessment of the validity of the starting geometry. If necessary, geometries are modified to obtain closer agreement between the observed and calculated response. Sections are then 'hung' in GoCAD and visualised with any applicable datasets. Surfaces are constructed to represent major crustal basement blocks, all major faults, intrusions, basement to basin regions and appropriate tops of major stratigraphic units. Once the model (or parts thereof) is built, a voxet representation of the model is produced and inversions are run to further refine the physical property models, and geometries of the inverted bodies. This is of particular importance in regions between serial sections, and in areas of cover lacking constraining data.

To date, few regional 3D geological models have been built that incorporate detailed basement and overlying basin geometries. 3D Victoria is developing workflows which allow integrated models of this type to be built. Such models enable the identification of major control structures within the basement and an analysis of how these structures have influenced basin development. The integrated 3D model will provide critical 3D data for existing minerals and energy exploration programs as well as next-generation exploration targets, including potential geothermal sources and geosequestration sites. It will allow integrated studies of complex systems such as the pressure regime within a basin undergoing simultaneous irrigation from onshore freshwater aquifers, drawdown of offshore oil and gas reservoirs and injection of captured carbon dioxide. The model will also make available valuable 3D constraints for future 'value-add' projects such as numerical deformation, fluid flow, maturity and heatflow simulations, as well as 3D GIS analysis and prospectively assessment.

Final model outputs are stored in GeoScience Victoria's 3D Model Management System (3DMMS) which is a geospatially aware database developed for GeoScience Victoria by Runge Ltd. This system allows models to be stored with associated metadata and searched or queried accordingly. Importantly, the 3DMMS also provides a visualisation and delivery mechanism. Explorationist can visit our office, upload their 3D data into a secure and confidential part of the database and then visualise their data with whichever of our model objects they choose (in stereo in our 3D visualisation room if they wish). It does not matter what format the company data

is in or what projection or coordinate system is used as conversions are handled on the fly by the 3DMMS and the user is able to look at any of the stored (open file) data, select useful objects and then download them in whatever format and projection they choose.

The Alcurra Suite and implications for orthomagmatic Ni-Cu-PGE mineralisation during the Giles Event, central Australia

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Mafic rocks emplaced during the Mesoproterozoic (c.1075 Ma) Giles Event, in the Musgrave Province of central Australia, host significant orthomagmatic Ni-Cu-PGE mineralisation, the most notable being the Nebo-Babel deposit. The discovery of this deposit has directed considerable exploration interest towards the range of voluminous and widespread mafic and ultramafic intrusions that have traditionally been grouped into the Giles intrusions. These intrusions form part of the Warakurna Supersuite (the magmatic expression of the Giles Event), which outcrops over 1.5 million km^2 of central and western Australia and forms the c. 1075 Ma Warakurna large igneous province.

Recent mapping in the western part of the Musgrave Province (the west Musgrave Province) by the Geological Survey of Western Australia has shown that the Giles Event in this region was not a simple short-lived event but rather a complicated series of events. Within this region, the many phases of both mafic and felsic magmatism traditionally grouped into the Warakurna Supersuite were accompanied by extensive shearing and large-scale folding and took place as a series of punctuated events over a period as long as 60 Ma. At least five generations of mafic magmatism are recorded, including emplacement of major layered mafic-ultramafic intrusions, various intrusions of massive gabbro and leucogranite, compositionally evolved ferrogabbro and ferronorite sills, as well as several distinct generations of dolerite and gabbro dykes.

A new SHRIMP U-Pb zircon date of 1067 ± 8 Ma for a copper-mineralised dyke provides a direct constraint on the age of one magmatic event related to mineralisation. This age is identical to that of the 1068 ± 4 Ma Nebo-Babel intrusion (Seat, 2008). Both intrusions are geochemically similar to the Alcurra Suite, a late phase of the Warakurna Supersuite, which forms dolerite, gabbro, olivine gabbro, ferronorite and ferrodiorite dykes and sills. The Saturn pluton and smaller gabbroic bodies immediately north of the Cavenagh intrusion (an area that includes several significant Cu-Ni-PGE-Au prospects) also show geochemical similarities with the Alcurra Suite. In the west Musgrave Province, the Alcurra Suite is generally an evolved Fe-rich, and incompatible trace-element-rich suite of tholeiitic intrusions which extends from the Walpa Pulka Zone (in the north-east of the west Musgrave Province), across the west-north-west trending Tjuni Purlka Tectonic Zone and south-westwards, into the Mamutjarra Zone. Rocks of the Kullal dyke swarm cover a similar geographical extent as the Alcurra Suite, are possibly the same age, most likely crystallised from a similar (or the same) mantle source and, thus, might also form part of the Alcurra Suite. Rocks of the Alcurra Suite (including Kullal dykes) are geochemically distinct from other mafic rocks emplaced during the Giles Event, and from other dyke suites in the region.

Dykes and intrusions of the Alcurra Suite post-date the major layered mafic-ultramafic intrusions and massive gabbro of the Giles Event. Alcurra intrusions were emplaced both along the west- to north-west trending margins of the layered mafic-ultramafic intrusions, and along north-east-trending conjugate extensional fractures resulting from north-east–south-west compression. The north-east-trending conduits and their intersection with west-north-west trending lithological boundaries or structures are potential sites for magma mixing and may be realistic targets for orthomagmatic mineralisation.

If the orthomagmatic Ni-Cu-PGE mineralisation developed at Nebo-Babel relates to a specific type or episode of mafic magmatism, within the geological complexity now apparent in the west Musgrave Province, the distinctive geochemistry and structural and chronological relationships of the Alcurra Suite represent a significant exploration tool.

Reference

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The northern margin of the Ferrar Large Igneous Province: the petrogenesis and differentiation history of the Red Hill dolerite-granophyre, Tasmania, and the Wisanger Basalts, Kangaroo Island

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The mid-Jurassic Ferrar Large Igneous Province (LIP) extends 3000 km from Dronning Maud Land in Antarctica, across the Transantarctic Mountains to its most northerly outcrops in Tasmania, Kangaroo Island and New Zealand. This large igneous province coincides with the footprint of the Cambro-Ordovician Delamerian-Ross orogenic system. Like the prior orogen, it shows a linear distribution, it also shows no systematic age variation from one end to the other. This is in contrast to some other Mesozoic flood basalt provinces (e.g. the Central Atlantic Magmatic Province) that are often roughly circular and conspicuous for their radial dyke swarms. We infer a direct linkage between the early Palaeozoic orogen and the source of the Jurassic LIP.

The chemistry of the Ferrar represents the extreme end-member amongst Mesozoic LIPs, with features more typically associated with arc-related magmas or upper continental crust (relatively high SiO2 content mafic rocks with enriched LIL element geochemistry, relatively low HFSE (Nb, Ti) and with radiogenic isotopic compositions more a akin to those of Proterozoic granites than of Jurassic asthenospheric mantle). Various arguments including marked homogeneity preclude crustal contamination of mantle-derived melts and require a homogenous single source. These characteristics have prompted speculation on the source of these magmas. Proposed models generally invoke the presence of upper continental crustal material in an originally-depleted mantle peridotite source (Hergt et al., 1989; Hergt et al., 1991; Molzahn et al., 1996; Foden et al., 2002). However their abnormal, relatively high silica major element chemistry may imply alternative non-peridotite sources such as eclogite or pyroxenite. Both subduction and lithospheric foundering may introduce mafic and crustal sedimentary materials to the sublithospheric mantle (e.g. Kay and Kay, 1993; Lustrino, 2005; Elkins-Tanton, 2007). However, delamination is also consistent with the isostatic uplift, rapid exhumation and sediment shedding and deposition of flysch deposits observed at the cessation of convergent deformation in the Delamerian-Ross Orogen (Turner et al., 1993; Turner, 1996; Turner et al., 1996). Abundant 15–20kbar eclogite xenoliths transported by South Australian Jurassic kimberlites may indeed be direct samples of this delaminated material. The broad regional thermal upwelling (Tappert et al., 2009) of a curtain-like zone of the mantle stretching the length of the Pacific Gondwanan margin in the Jurassic may have resulted from the combined impact of thermal equilibration of the foundering delaminated eclogite lithosphere together with significant radiogenic heating.

In this study we demonstrate that the mafic eclogites sampled by South Australian Jurassic kimberlites (Foden et al., 2002) are feasible sources for the Ferrar LIP suites. We also show that the tholeiitic dolerite to granophyre differentiation trend that these magmas follow at a number of localities, including Red Hill, Tasmania, (McDougall, 1962) leads to A-type granite end-member melts. This accords with models of Turner et al., (1992) and Whalen, (1996). Our new iron isotope data shows that this extreme fractionation process leads to granophyre with heavy δ^{56}Fe values, a feature shared with the A-type granites.

Experimental study of monazite/melt trace element partitioning

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Monazite is a common accessory mineral (LREE,Th)PO_4 and is the major host of LREE, Th and U in the Earth's crust. It is an ideal mineral for Th, U-Pb dating because of its high closure temperature and low common lead content.

During melting the presence of monazite as a residual phase could produce enrichment in the restite of elements that are strongly incompatible in other circumstances (Rapp et al, 1987). Monazite also plays a critical role in the fractionation of REE relative to each other and could be responsible for granites with unusual REE patterns. Recently monazite has been identified as an important player in the melting of sediments within subduction zones and magma generation at subarc depths (Hermann and Rubatto, 2009).

Experimental determination of monazite-melt partitioning was performed at conditions relevant for melting within the crust and in subduction zones. The starting composition was a synthetic granite mix with about 8

wt% H_2O and doped with trace elements corresponding to 0.5–2.9 wt % of monazite. Experiments in a piston-cylinder press were performed at 10 kbar over the temperature range from 800 to 1300°C with steps of 100°C. Additionally, a pressure series form 10 to 50 kbar with steps of 10 kbar was conducted at 1000°C.

Experiments at temperature >800°C and pressure <30 kbar produced melt with monazite. At lower temperature additional quartz and plagioclase appeared in the experimental charges. At higher pressures, kyanite, coesite, jadeite, apatite, zircon and allanite start to crystallise. Monazite was produced in all experiments but with very small grain size (<5µm), making it impossible to determine the trace element composition of monazite alone. As alternative, LA-ICP-MS analyses of monazite-melt mixes were performed and the monazite composition was calculated using regression analysis.

Preliminary results show that monazite solubility decreases by a factor of two at pressures above 20 kbar relative to 10 kbar. However, because high pressure experiments produced different melt composition and higher water content, changes in monazite solubility are likely a combination of pressure and melt composition. The study of monazite composition has shown that only REE, Th, U, Y and As strongly partitioning into monazite, whereas other trace elements (Li, Be, B, Sc, Ti, V, Mn, Sr, Zr, Nb, Ba, Hf, Ta, Pb) have partition coefficients lower than 10. Monazite has the highest preference for LREE, with a decrease in partitioning coefficients for Sm, MREE and HREE. Partitioning coefficients for Th are much higher than for U.

The new experimental data confirm the important role of monazite in fractionation of REE, Th and U relative to each other in melting and crystallisation processes and give for a first time a numerical basis for calculation of these effects, as a function of pressure and temperature.

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Giant Plagioclase basalts from north-eastern part of Deccan Volcanic Province, India

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The giant plagioclase basalts (GPBs) with plagioclase phenocrysts that reach up to 3 cm in length are found near Jabalpur in the north-eastern part of the Deccan Volcanic Province (DVP). The thickness of the basalt flow that contains the GPBs is ~ 20 m. This contribution presents mineral chemistry and whole rock geochemistry of the GPBs. This new occurrence of GPBs has implications for existence of local crustal magma chambers, feeders and vents in the north-eastern part of the DVP.

The GPBs contain large (0.5–3 cm long) phenocrysts of plagioclase (An_{58} – An_{64}) in a fine grained matrix consisting of plagioclase, augite, Fe-Ti oxide minerals and glass. The plagioclase phenorysts display normal zoning and corroded borders and contain abundant, small post-crystallisation melt inclusions. Also included within large plagioclase grains are small rounded grains of plagioclase with different compositions (up to three generations). Some plagioclase crystals show resorption and reverse zoning. Single crystals show core to rim variations of up to 10% An. All these disequilibrium features in the GPBs reflect magma mixing, recharge and complex convection effects in a magma chamber.

In the Jabalpur section, the GPBs have the most evolved compositions with lowest Mg#s (42–46) and MgO (4.16–5.08%), Ni (28–48 ppm) and Cr (70–102 ppm) abundances. Also, they have the highest abundances of incompatible elements (TiO_2: 2.72–3.10%, P_2O_5: 0.30–0.34%, Nb: 15–19 ppm, Zr: 162–194 ppm, Sr: 278–365 ppm, and Ba: 175–235 ppm). All samples are moderately enriched in light-REE ($[Ce/Yb]_n$ = 3.00–3.14).

The GPBs define a good correlation between MgO and most major and trace elements. Some of these variations can be explained by fractional crystallisation model. Variations in the ratios of highly incompatible elements reflect heterogeneity in the source and/or magma mixing. Furthermore, low Y/Nb ratios (average = 2.08) suggest crustal contamination was minimal, which would have influenced these element ratios. Modeling calculations were carried out to quantitatively evaluate the source mineralogy and the amount of partial

(batch) melting. Partial melting modeling suggests that lavas from the Jabalpur section were derived by about 6% melting of peridotite containing no garnet. The primary magmas were derived from a relatively shallow mantle source.

The plot of Ba/Y ratio against Zr/Nb ratio reveals that the GPBs are compositionally similar to the Mahabaleshwar formation of the western Deccan. However, compared to the Mahabaleshwar lavas, these GPBs are chemically more evolved with lower Mg#s, and MgO, Ni and Cr abundances, and higher concentrations of LILE (Sr, Ba) and HFSE (Nb, Zr). These compositional features suggest that the GPBs are the products of fractional crystallisation of a parental magma similar to the Mahabaleshwar magma generated in this part of the DVP.

High pressure metamorphism during intracratonic orogenesis in the Amata region, Musgrave Province: physical conditions and rates

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The Petermann Orogeny in the Musgrave Province, central Australia, is one of the most deeply exhumed, really extensive and well-preserved intracratonic orogens on earth. The contractional orogenesis occurred *c.*550Ma (Camacho *et al,* 1997) many hundreds of kilometres away from any plate margin. The result of such deformation fragmented formerly contiguous sedimentary basins and exhumed lower crustal rocks (14 kbar, 40 km) now exposed in the core of the orogen. The exposed orogenic core is of particular interest as it preserves sub-eclogitic to eclogitic (~12 kbar, ~650 ºC) facies rocks (Camacho & McDougall, 2000) in discrete, yet crustal-scale mylonitic shear zones. The eclogitic mineral assemblage has been dated at 547 ± 30 Ma (Ellis and Maboko, 1992; Camacho *et al*., 1997). It is well known that eclogite facies rocks record cool thermal conditions, and on this basis it has been suggested that the thermal conditions of the crust were not only regionally cold (~9°C km^{-1}) during the Petermann Orogeny but that the deformation and heat (shear heating) along the shear zones was extremely short-lived (<1 Ma; Camacho *et al*, 2009).

Regionally cool thermal conditions invoked by Camacho *et al* (2009) tend to indicate that lithosphere is strong and not prone to significant deformation or exhumation, counterintuitive to the accepted notion that a regionally warm lithosphere will localise strain and deformation (Sandiford *et al*, 2001; Sandiford & Hand, 1998; Cull & Conley, 1983) owing to thermal weakening. Exhumation and exposure of the Petermann orogenic core occurred over a relatively short (~30 M.y.) time span (Forman, 1966; Wells *et al*, 1970; Camacho and McDougall, 2000), indicating that significant overburden must have been efficiently removed (by erosion) in order to expose rocks from approximately 40 km depth. If continual exhumation/uplift occurred, there is an implication that the crust was warm enough, and therefore thermally weak enough, to continue to undergo localised deformation and allow high-*P* rocks to reach the surface. Once the formerly contiguous Centralian Superbasin (?a thermal blanket) had been dismembered by continued orogenesis, the Musgrave crust was still weak enough for localised strain to deform and continue the exhumation of high-*P* rocks. Thus, a paradox exists, as the exhumation of high-*P* rocks over an appreciable time span (30 M.y.) appears to demand that the lithosphere is thermally weak, yet the most deeply exhumed part of the orogen contains thermally refrigerated rocks. How is this so?

Investigation of the *P-T*-time evolution of the 'cold' high-P will give invaluable insight into the thermal state of the lithosphere and its duration during the intracratonic deformation of the Petermann Ranges Orogeny. There currently exists two possible explanations. One, in accordance with Camacho *et al* (2009), is that heating in the shear zones was very rapid and deformation occurred in regionally cold crust. However, there is a possibility that the regional thermal regime was in fact hot, but deformation was able to rapidly move (bury and exhume) the high-*P* rocks through the crust, with the implication that the rocks were never able to thermally equilibrate with the regional thermal structure. In this research, these two possibilities will be explored by constraining the *P-T* evolution (using calculated phase diagrams) for rocks inside, outside and near the high-*P* shear zones, and linking this information to *in situ* geochronology collected from the same rocks used to determine the *P-T* evolution. This study will be the first of its kind to explore the Petermann Orogeny using such an integrated approach. The research into the thermal state of crust and the duration of metamorphism will determine whether the core of one of the world's major intracratonic orogens developed in a hot and weak crust or a cool and strong crust, and, more broadly, will provide greater insight into the mechanisms for development of eclogites in intracontinental regions.

New geochronology from the Biranup Zone of the Albany-Fraser Orogen: Paleoproterozoic magmatism and Mesoproterozoic reworking

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Due to reworking on the margins of stable Archean cratons the histories of Proterozoic collisional belts are commonly cryptic. One such example is the Albany–Fraser Orogen which is considered to represent the Mesoproterozoic continent–continent collision of the combined North and West Australian Craton with the combined East Antarctic and South Australian Cratons. However, the exact timing of this collision and its various juxtaposed components remain poorly understood. Furthermore, a substantial volume of the orogen resides under the cover of the Eucla Basin. The Kepa Kurl Booya Province represents the crystalline basement of the Albany–Fraser Orogen and is itself divided into the Fraser, Biranup, and Nornalup Zones. The Biranup Zone consists predominantly of Paleoproterozoic gneisses, whereas the Fraser Zone is dominated by 1300 Ma meta-gabbroic rocks.

Recent geochronology of the Biranup Zone has refined our understanding of its evolution. Eighteen meta-igneous samples of zircon or baddeleyite, collected from a broad region of the eastern Biranup Zone have been dated by ion microprobe. They record igneous crystallisation ages, for the initial protoliths, between 1706 ± 12 Ma and 1625 ± 4 Ma. These dates indicate that the Biranup Zone extends from the southern Albany–Fraser Orogen to the north-east between the Yilgarn Craton and the Fraser Zone, encompassing a distance of over 1200 Km.

In the eastern Biranup Zone, a cross-bedded psammite has yielded a unimodal detrital zircon population of 1689 ± 6 Ma and was intruded by granite at 1685 ± 8 Ma. Hence, granite emplacement occurred very shortly after sediment deposition. Folded leucosomes in a migmatitic monzogranite yield a U-Pb zircon date of 1676 ± 6 Ma, which is identical to that for the crystallisation of later axial planar leucosomes at 1679 ± 6 Ma. Migmatisation must have preceded folding, with subsequent leucosome injection, along the axial planes of folds. Therefore, a deformation phase is constrained to c. 1680 Ma. This deformation event was followed by intrusion of a suite of granitic to gabbroic rocks, with distinct mingling and hybridisation textures, dated at 1665 ± 5 Ma. This sequence of events indicates a rapidly evolving crustal block within a dynamic tectonic environment. The general lack of Archean zircon inheritance suggests that the Biranup Zone represents an outboard terrane that was subsequently accreted onto the Yilgarn Craton margin. Given the unimodal detrital population and the rapidly evolving tectonomagmatic history, with sedimentation, magmatism, deformation and migmatisation all within 10 Ma, the lithological and temporal constraints thus imply a late Paleoproterozoic outboard arc-related setting for the Biranup Zone.

U–Pb dating of zircon from two meta-igneous units within the Fraser Zone yields a weighted mean date of 1298 ± 4 Ma, synchronous with Stage I of the Albany–Fraser Orogeny. In contrast to the Fraser Zone, the eastern Biranup Zone records metamorphic zircon overgrowth at 1197 ± 6 Ma, which is the first direct evidence of Stage II Albany–Fraser Orogeny activity in this part of the orogen. Combined with results from the central Biranup Zone, this indicates high-temperature reworking along the entire Biranup Zone dominantly at 1200–1180 Ma. Dating of fracture-filling zircon, in the eastern Biranup Zone, also indicates that a period of crustal uplift and cooling occurred between 1270 and 1197 Ma, consistent with the division of the Albany–Fraser Orogeny into two stages.

Age similarities between the reworking of the eastern Biranup Zone and the ultra high-temperature metamorphism of the Musgrave Province are compatible with a Mesoproterozoic extensional event in both areas at c. 1200 Ma. A temporal correlation may be made between the earlier c. 1300 Ma events (Mount West Orogeny) in the Musgrave Province and Stage I of the Albany–Fraser Orogeny, as recorded in the Fraser Zone and a suite of granites emplaced into the central Biranup and Nornalup Zones (Recherche Supersuite). These Stage I events may relate to accretion of the Biranup arc system along the Yilgarn Craton margin.

Multiple seismic analyses of the SEAL3 array dataset to determine crust and lithosphere structure in central New South Wales

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The geological structure of south-eastern Australia is a complex accumulation of multiple Palaeozoic orogenic belts that abut the Precambrian Australian craton. A lack of outcrop due to extensive Mesozoic-Cainozoic sedimentary and volcanic cover sequences has limited direct access to much of the Palaeozoic substrate, resulting in a variety of plausible tectonic models that satisfy the limited data that is available. Possible explanations for the complexity include multiple coeval subduction zones in an oceanic setting, and orogen-parallel strike-slip tectonics in an intracratonic setting (e.g. Betts et al, 2002; Spaggiari et al, 2004). Recent high-density short period and broadband experiments conducted by Australian National University (ANU) (e.g. SEAL2, SEAL3, and EVA) canvass south-eastern Australia with a station spacing of approximately 50km, thus providing an ample data set to characterise the lithospheric and upper mantle structure of this region with high-resolution body-wave tomography. The ultimate goal of this work is to combine multiple data sets from these rolling arrays into one cohesive seismic image of the south-eastern Australian crust and lithospheric mantle in to determine the lithospheric transitions between different orogenic terrains within the Delamerian and Lachlan orogens. Here we present results and an integrated interpretation of P-wave teleseismic tomography, receiver function analysis, and ambient noise dispersion for the SEAL3 array (Oct 2007-Dec 2008). The SEAL3 deployment was located in central and southern New South Wales and consisted of 55 three-component short period instruments. The receiver function and ambient noise data are simultaneously inverted to determine the crustal depth in the region. The analysis yields a thickening crust toward the South-east where Moho depths in central NSW are ~25–38km and increase to 45–50km in mountainous south-eastern NSW. In order to image the regional lithosphere, we perform a teleseismic P-wave tomography using a P and PcP arrival data set on the order of 1,000s paths from the SEAL3 array. With the combination of the teleseismic tomography and the simultaneous receiver function and ambient noise analysis to constrain the lithospheric and crustal structure respectively, we aim to determine the lateral and depth extent the individual terrains. Future plans are to start building upon the results from the SEAL3 data set and expand the use of multiple analyses of seismic data to other similar high-density array datasets collected by ANU within the last decade.

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Constraining the thermal evolution of a large intracontinental orogen

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The 580–530 Ma Petermann Orogeny occurred in Central Australia more that a thousand kilometres from any Neoproterozoic plate margin, and more than 500 m.y. after the amalgamation of the Australian craton during the assembly of Rodinia (Camacho and McDougall, 2000; Wade et al., 2008). Extensive north-south compression during the Petermann Orogeny was accommodated along numerous crustal-scale shear zones, including the Woodroffe Thrust, Mann Fault and Davenport Shear Zone. Deformation is strongly concentrated in the vicinity of these structures and includes substantial crustal thickening and basement-cored isoclinal folding in the foreland basin (Edgoose et al., 2004; Flöttmann et al., 2004). Top to the North thrusting resulted in the exhumation of high grade lower crustal rocks from approximately 40 km depth (equivalent to 14 Kbars) (Scrimgeour & Close, 1998; Camacho et al., 1997). Exhumation during the Petermann Orogeny also resulted in the dramatic geophysical character of the continental interior, manifest as the one of the largest gravity gradients on Earth.

The age of Petermann orogenesis is relatively well constrained in selected regions. U-Pb dating of metamorphic zircon and titanite from the Bates region (Western Australia) suggests that peak conditions occurred at around 570 Ma (Raimondo et al 2009). A number of thermochronometers (^{40}Ar-^{39}Ar hornblende, biotite, muscovite; and Rb-Sr muscovite, biotite; Camacho & McDougall 2000) have been applied in the central and eastern parts of the orogen, and these suggest that orogenesis had largely terminated by c. 530 Ma.

In terms of the thermal record of the Petermann Orogeny, the eastern core of the orogen records up to sub-eclogitic facies mineral assemblages in the Davenport Shear Zone that formed at between 12–14 kbar and temperatures around 600–650°C (Camacho et al., 1997). Westward, the core appears to be hotter, with temps around 700–750°C and pressures equal to or less than the eastern core (reference??). The duration of metamorphism in each of these locations is uncertain, with estimates ranging from approximately 25 M.y. in the apparently hotter, more migmatised and more pervasively deformed western portion (Raimondo et al 2009), to very short-lived (1 Ma) and restricted to discrete mylonitic shear zones further east (Camacho et al 2001, 2009). The deformation and thermal regime described by Camacho et al. implies a cold, and subsequently strong crust, opposite to the interpretation of Raimondo et al (2009). The divergent views on the thermal regime presented imply that the crust is responding variably to the same thermobarometric constraints.

In order to understand more completely what thermal regime prevailed, and for how long, during the Petermann Orogeny, this project is investigating the *P-T*-time evolution of rocks from a region (Mann Ranges) midway between the studies of Raimondo et al (2009) and Camacho et al (2001, 2009). The thermal state and its duration is particularly important to study as it has implications for the rheology of the deforming crust during the Petermann Orogeny. The rocks in the Mann Ranges preserve evidence for pervasive as well as discrete deformation, and contain mineral assemblages conducive to calculated phase diagram analysis (e.g. kyanite-clinopyroxene-garnet-plagioclase assemblages). Zircon and titanite from microstructurally-consrained locations within these rocks will be dated in situ to provide a link between the age and duration of metamorphism and the thermal and physical structure of the orogen. This study is the first integrated metamorphic (calculated phase diagrams) and in situ geochronologic study to be undertaken on the Petermann Orogeny, and will shed light on the conflicting views for the thermal evolution of this world class intracratonic orogen.

Simulating Australia–Antarctica break-up and fault development along Australia's southern margin using Pplates deformable reconstruction software

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Until recently, tectonic reconstructions have been limited by (1) the assumption that tectonic plates do not deform, or (2) the inability of software packages to simulate deformation. The assumption that plates do not deform is based on the earliest ideas about plate tectonics. This assumption has led workers dealing with plate tectonic reconstructions to introduce new micro-plates to explain the inconsistencies observed in different place circuits (e.g. the Somalian plate). However, we now know that the oceanic and continental crust deform. Therefore, tectonic reconstructions must begin to address this point, without the need to invoke more and more micro-plates to resolve inconsistencies in rigid plate circuits.

The second point, that software cannot simulate plate deformation is no longer an issue after the development of Pplates. Pplates is an open-source tectonic reconstruction package that allows geologists to build both classical (rigid) plate reconstructions as well as deformable plate reconstructions. To do this, the software uses one or meshes to move data back and forth in time. Each of these meshes is deformable in order to simulate deformation of the crust. This software also allows geologists to import and deform GIS data.

Here we report the initial results of a deformable reconstruction of the Australian and Antarctic plates, from the timing of rifting prior to Gondwana break-up, to the present. This reconstruction also shows the timing of major fault development in the sedimentary basins along Australia's southern margin. Future work aims to simulate development of major crustal features on the Australian and Antarctic plates, and to incorporate palaeogeographical interpretations from the sedimentary record. Our ability to simulate extensional deformation associated with continental break-up has implications for both global tectonic reconstructions as well as reconstructions of individual sedimentary basins.

Incorporation of strategic fieldwork into 3D modelling workflows

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GeoScience Victoria's first phase of crustal-scale three-dimensional modelling of the Western Lachlan is under way, with the central and western portions of the fold belt recently completed. The Bendigo Zone was the first area to be modelled due largely to its prospectivity, high quality of structural mapping, detailed biostratigraphic control and the location of the recently acquired deep seismic profile. Modelling results will be used to improve our understanding of the crustal scale 3D architecture underpinning the state and the control it exerts on fluid flow dynamics related to gold and other mineralisation, hydrocarbons and geothermal systems.

The Bendigo Zone model covers the geology of basement rocks east from the Avoca Fault to the Mount William Fault Zone and south from the Victoria–NSW border to the margin of the Otway Basin. Much of the outcropping bedrock across the zone consists of sandstone and mudstone sequences of the deep marine Castlemaine Group, which were deformed in the Late Ordovician–Early Silurian Benambran Orogeny. Large-scale faults predominantly strike north–south and steeply dip to the west. Precambrian rocks do not occur at surface, but are inferred to lie at depth.

Throughout the initial stages of the modelling process, GeoScience Victoria's 3D team adopted the integrated modelling methodology originally utilised by PMD*CRC and adapted it to their own unique needs. Model building workflows in the 3D visualisation environment were also refined to create robust construction techniques applicable to both onshore and offshore model building as well as integrated modelling of both basement and basin blocks. This technique also changed the fieldwork practices of mapping teams. Problematic areas requiring targeted fieldwork were quickly identified, ground-truthed and results reincorporated into the model, providing geologists with real-time evaluation of their interpretations.

The Bendigo Zone model utilised over 20 serial sections with key structural features constrained at surface by 1:50 000-scale geological mapping and projected along strike into areas of cover using traditional 2D aeromagnetic and gravity data. Cross-sections were refined using geophysical forward modelling, inversion and derivative datasets, while subsurface geometries were interpreted and constrained from the deep seismic profile. Surface building in the 3D environment quickly identified a number of inconsistencies requiring further field based data collection and interpretation. Biostratigraphy, inversion modelling and seismic data revealed large sediment volume problems in previous geological models for the Bendigo Zone. Initial serial cross-sections and modelling suggest the presence of a folded and faulted Cambrian sequence of approximately 5–8 km thick under the Ordovician Castlemaine Group west of the Redesdale Fault. Further analysis indicates that this Cambrian package must gradually wedge out towards the east ahead of an imbricate system of south-west dipping thrust faults, interpreted to account for most of the thickening in the hanging wall of the Mount William Fault. These inferred faults are probably Tabberabberan (Middle Devonian).

The interplay between flexible, targeted fieldwork and 3D modelling has proved an extremely powerful tool for GeoScience Victoria. It has allowed geologists to identify, check and reinterpret geometric inconsistencies that may not be apparent to the mapping teams during the course of a more orthodox mapping campaign.

Understanding the geodynamics of ocean basins using satellite magnetic observations

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Global-scale geophysical datasets are a fundamental tool in understanding the geodynamic evolution of the world's ocean basins. Gravity data derived from satellite altimetry yield gravity anomaly maps with a continuous coverage across the oceans. By contrast, the most up to date global compilations of magnetic from surface/near-surface data still contain large gaps in the data coverage, in particular over the oceans where only sparse shiptracks may be available. An alternative method to investigate the crustal magnetic field of the Earth is to use datasets based on satellite observations.

Models of the Earth's crustal field derived from satellite observations are of much lower resolution than maps derived from airborne/seaborne/land measurements. Magnetometers aboard earth-orbiting satellites provide a continuous coverage of magnetic field observations across the globe. Maps of the crustal magnetic field of

the earth have been generated since the 1970s with the resolution of the derived crustal magnetic field models improving over time. Recent models such as MF6 are derived using data from the CHAMP satellite, orbiting at an altitudes less than 350 km, and models the crustal field down to spherical harmonic degree 120 (equivalent to a wavelength of 333 km).

Magnetic anomaly maps generated from the MF6 model at geoid altitude provide a coarse image of the fabric of the ocean crust. Magnetic lineations within oceanic areas have been shown to correlate on a global scale with ocean spreading lineations defined by ocean age isochrons. At a smaller scale these lineations are segmented or truncated along fracture zone trends defined in gravity anomaly maps.

We investigate the potential for these data to better constrain the link between mantle and tectonic processes that form oceanic crust. We do this by comparing the magnetic data to other global datasets such as the ocean age, spreading rate and seafloor roughness.

Can geodynamic modelling help resolve the India–Eurasia collision controversy?

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The India-Eurasia collision is a first order tectonic event that has dominated the tectonic evolution of Eurasia in the Cenozoic. However, the timing of the initial continental collision between India and Eurasia is controversial, with the onset of contact occurring somewhere between ~55 Ma and ~35 Ma. Constraining fundamental parameters such as the extent of the pre-collision margins of Eurasia and Greater India, and the consequential timing of their contact, are essential boundary conditions that need to be incorporated into tectonic models.

The established school of thought proposes an earlier 'soft' collision with an initial contact between Greater India and the southern Eurasian margin at ~55 Ma, and a subsequent 'hard' collision when convergence rates drop significantly. However, there is an enigmatic 20 Myr lag between the proposed ~55 Ma collision and major regional tectonic and geological responses, such as orogenic events, plutonism and volcanism**,** and major Cenozoic plate reorganisations in Southeast Asia.

An emerging school of thought addresses this problematic 20 Myr time lag by proposing an alternative embryonic collision between Greater India and an intra-oceanic subduction system in the Tethys at ~55 Ma, followed by the main continentcontinent collision between Greater India and Eurasia at ~35 Ma. This alternative scenario is supported by multiple and unique ophiolite emplacement episodes interpreted from the regional geology, while also no longer requiring an inferred large and speculative extent of Greater India.

We aim to discriminate between the two existing and dominant hypotheses regarding the onset of the India-Eurasia continentcontinent collision by integrating plate tectonic reconstructions with a finite-element mantle convection modelling code (CitcomS 3.0). Our plate kinematics are based on the Müller et al (2008) tectonic model, with a True Polar Wander-corrected absolute reference frame for times prior to 100 Ma and a moving-hotspot reference frame from 100 Ma to the present. We also incorporate an updated model for the evolution of the Tethys and Panthalassa.

We test the competing pre-collision margin geometry scenarios and their temporal effects (i.e. timing/chronology) on the India-Eurasia collision, as well as investigating the consequences of introducing a proposed intra-oceanic subduction system and associated island arc in the NeoTethys. The advancing northern margin of Greater India may have bulldozed and suffocated this intra-oceanic subduction zone prior to the main continent-continent collision. The competing hypothetical scenarios are implemented in linked plate kinematic and mantle convection models.

The subduction-driven temperature fields predicted by the convection models are then compared to the observed mantle shear velocity heterogeneity of the mantle obtained from global tomography. Mantle tomography can be used to image and infer the Earth's interior structure based on regions of anomalous seismic velocities. Our model output will allow us to determine which scenario yields results that best represent present-day mantle structure below the geographic collision window. The tomographic sections derived from our model output may help identify the source of the subducted slab material from the various Tethyan ocean basins which have been consumed by successive accretion events of Gondwana-derived continental slivers onto the southern Eurasian margin.

Our methods can be applied elsewhere to validate or test the spatio-temporal parameters related to accretion of terranes, where oceanic crust and other crucial evidence has been destroyed by subduction and collision.

The origin of organic matter in surface sediments of the Australian Continental Shelf from compound-specific $\delta^{13}C$ and $\Delta^{14}C$ analysis

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The organic matter (OM) content in sedimentary rocks and old marine sediments provides a wealth of information for inferring environmental/climatic conditions, both in the marine water column and adjacent continental areas, at the time the sediment was deposited. However, in order to properly interpret the OM signal in old sediments and rocks it is necessary to understand first how this signal is recorded in contemporary sediments. Such task still presents two related challenges: on the one hand, there is the wide variability of factors and processes that affect the composition of sedimentary OM until its final burial; on the other, there is our ability to characterise such sedimentary OM so that such factors and processes dictating its composition can be recognised for contemporary environments.

The most informative techniques for characterising sedimentary OM consist of coupling measurements of bulk compositional characteristics of OM (i.e. the carbon stable-isotope composition ($\delta^{13}C$) of total organic carbon (TOC), the OC/TN (organic carbon/total nitrogen) ratio and the radiocarbon content ($\Delta^{14}C$) of TOC) with compound-specific $\delta^{13}C$ and $\Delta^{14}C$ analysis of organic biomarkers. In particular, the ^{14}C measurements of individual biomarkers have led to a new understanding of the sedimentary OM in recent marine sediments at different levels, such as: identifying the effects of sedimentological, oceanographic and diagenetic processes, estimating timescales of transport and accumulation of the different OM inputs, increasing the capability of identifying and quantifying the different OM inputs. Continental margins account for more than 90% of the global marine OM burial.

In this project, surface sediment samples from two contrasting environments of the Australian continental shelf (the tropical Arafura Sea and the temperate SE Australian margin) were studied using compound-specific $\delta^{13}C$ and $\Delta^{14}C$ analysis coupled with bulk OC/TN, $\delta^{13}C$, and $\Delta^{14}C$ analyses of OM.

Three of the four samples from the cross-shelf transect from the Arafura Sea show similar bulk OM composition, which is predominantly marine. The most inshore sample (on the basis of bulk OM analyses alone) seems to be composed of a mixture of terrestrial and marine OM; however, the concentration, distribution and $\delta^{13}C$ values of some individual lipid biomarkers (i.e. *n*-alkanes, *n*-alcohols, sterols, and hopanoids) do not support such interpretation, suggesting instead recycling, from photosynthetic organisms in the photic zone, of inorganic carbon derived from the oxidation of OM in the Holocene sequence; ^{14}C measurements of some selected compounds provide further support for the latter interpretation.

Samples from the SE Australian margin were collected from near the mouth of the Shoalhaven River (NSW) and along a N-S transect constantly at mid-shelf water depths (90–110m), which, on the basis of previous sedimentological studies, is consistent with the presence of a mud belt derived from fluvial sources. Furthermore, surface sediment samples were collected also from the river bed above the tidal limit (in order to constrain the OM input from the catchment) and from the estuary. Bulk OM analyses suggest that carbon transported by the river consists mainly of recent C_3 land plant derived material mixed with variable contributions of fossil (i.e. coal- or kerogen-derived) OM, and OM stored and reworked in soils. Little changes in the bulk OM composition occur while OM is temporarily stored in estuarine surface sediments. Once exported to the oceanic environment the bulk composition of sedimentary OM is dramatically affected by autochthonous contributions almost erasing the terrestrial signal. At the same time throughout the whole river-estuary-continental shelf system, surface sediments show a constantly positive and significant correlation between TOC and silt + clay content. Carbon stable-isotope and radiocarbon analyses of individual biomarker compounds and as well XRF and XRD measurements of the clay + silt particle size fraction provide strong insights into the role of both mineralogy and residence times of OM within major bioactive reservoirs on the changes in OM composition throughout its transport from catchment areas to surface marine sediments.

This study represents one of the few applications of radiocarbon compound-specific analysis to tropical marine sediments (in this case the Arafura Sea), and it is a first attempt to quantify the residence times of OM in reservoirs where major changes may occur during transport from the terrestrial to the marine environment, and how these residence times affect the changing composition of OM.

The use of electromagnetic induction (EM and AEM) surveys for dryland salinity management: the applicability for mapping and monitoring activities in upland landscapes

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Electromagnetic induction methods, performed from both the ground (EM) and airborne (AEM), are claimed to be particularly relevant for salinity mapping and land management. Advantages of the EM include the speed and ease at which metrics can be collected, the relative accuracy of the instruments, the non-invasive nature of the measurements and the ongoing improved data presentation possible. This paper investigates the use of the Geonics EM38 (<1.5m bulk depth) and EM31 (<6m bulk depth) instruments for salinity research in upland landscapes of southern Australia. Ten sites on the uplands of the Southern Tablelands of New South Wales where dryland salinity is a recognised major environmental issue, were intensively surveyed. A suite of strategic abiotic and biotic (faunal and floral) indicators were chosen to identify possible associations with the EM instruments. Piezometers were installed and soil profiles were investigated to depths of ~4m at three sites in an attempt to ground-truth the EM readings. All sites were restricted to two lithologies; Ordovician quartzose metasediments and Silurian felsic volcanics and associated metasediments of the Lachlan Fold Belt. EM surveys were performed during two seasons, autumn and spring of 2005 (different soil moisture regimes) to investigate temporal variation. Extreme spatial and temporal variation of bulk conductivity (ECa) was apparent at all sites, especially where soil and vegetation degradation was apparent. Analyses of the EM data included the direct use of the apparent EM readings (ECa), depth ratio conversions and 1D inversion. Results showed strong associations (correlations—$p<0.001$) between the EM38 (ECa) and soil surface abiotic parameters; pH, slaking, scald, electrical conductivity ($EC_{1:5}$) and surface compaction. Less strong correlations ($p<0.05$) with geology (Silurian lithology generally produce higher ECa values) and reaction with HCl. However, associations showed an inverse relationship with depth, with the EM31 in vertical dipole (i.e. 6m bulk depth) yielding few correlations with the abiotic parameters, including $EC_{(1:5)}$ and scald. Correlations with ECa and the biotic parameters were generally not as strong, especially as depth increases. This inverse relationship between depth and surface effect is apparent between the two instruments (i.e. EM38 gives stronger correlations than the EM31) and within the instruments (i.e. stronger correlations with the shallower horizontal dipole). It was evident that the instruments respond not only to increased salinity levels, but to a number of other factors including soil moisture, the depth to the clay-rich B horizon (i.e. on duplex soils) and conductive (ferrous) minerals. As these factors are highly heterogeneous spatially and in the case of soil moisture and salinity levels, temporally variable, interpretations of the ECa readings are generally problematic. The EM38 however, does provide valuable information for both salinity management and environmental outcomes, especially when used in the horizontal dipole (<0.75m depth). Conversely, the EM31, was not considered to be particularly useful for either of these objectives, especially in the vertical dipole, rendering its applicability for mapping and monitoring questionable in heterogeneous upland environments. Additionally, although AEM, which measures to a minimum 3m bulk depth, but generally much deeper, has been promoted as being one of the most applicable techniques for salinity mapping and management, but this research indicates that at this present stage, AEM is also highly questionable in upland landscapes, where spatial and temporal variability operate at different scales to the measurements being taken. The results from the depth ratios (and to a lesser degree the inversion profiles) between seasons indicates that the predominant hydrological activity (i.e. changes between the two seasons) in these landscapes is generally within the top 1m of the soil profile, further indicating that the processes are surface derived, occurring as lateral interflow above the semi-impermeable B horizon, and not induced from so-called rising groundwater. In other words, the hydrological processes are predominantly top-down soil-bourne, rather than bottom-up as the rising groundwater model stipulates. Indeed, no evidence was found linking salinity expressions with a rising groundwater problem, as the current rising groundwater model demands. We therefore suggest that future investigations regarding salinity management in these and similar upland environments across southern Australia should focus on soil surface parameters, rather than the deeper profile as is the present practice. The EM38 is particularly useful for this purpose and interpretations are enhanced with the use of depth ratios and inversion of the ECa readings.

The use of electromagnetic induction (EM) surveys for ecological research and sustainable holistic agronomy management activities in heterogeneous upland environments

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Electromagnetic induction (EM) techniques that measure bulk soil profile electrical conductivity have been extensively used for pedological geophysical investigations and are being increasingly utilised for environmentally focused objectives. These include soil physical and chemical attributes such as soil salinity, moisture content, ferrous mineral content and types, depth to, and thickness of clay-rich horizons (particularly of relevance for dryland salinity investigations), however, very few studies have been performed to date which investigate associated biological functioning. The possible advantages of utilising EM techniques for environmental and ecological applications, including conservation management activities, are considerable, as the electromagnetic instruments have previously proven to be both rigorous and efficient for related investigations. Large areas can be surveyed extremely rapidly, efficiently and non-invasively. This can be simply achieved by carrying the lightweight instruments on foot, or attaching to vehicles such as quad bikes. This paper investigates the applicability of these ground based electromagnetic induction instruments, namely the Geonics EM38 and EM31, which measure bulk conductivity to approximately 0.75m and 1.5m (EM38) and 3m and 6m (EM31) in horizontal and vertical dipoles respectively, for providing information regarding environmental (and ecological) factors. These include surface vegetation attributes, soil organic matter and bulk respiration (CO_2 production), epigaeic macro-invertebrate information and the presence of frogs and reptiles. Ten sites on the Southern Tablelands of New South Wales were intensively surveyed during 2004–2006. All sites were located in yellow box (*Eucalyptus melliodora*) and red gum (*E. blakelyi*) grassy woodland reserves (listed as an Endangered Ecological Community) in relatively good condition (i.e. reduced grazing regime, little weed incursion, relatively uncleared etc). Metrics were collected along 50m long transects and involved both biotic and abiotic attributes, including Landscape Function Analysis methodology which focuses on soil surface and hydrological processes. The EM surveys were conducted during autumn and spring 2005, to investigate temporal variations. Results indicate that the EM38 yielded strong correlations ($p<0.001$) with most of the abiotic and many of the biotic metrics, especially the vegetation attributes. However, correlations with faunal attributes were generally not evident. Strong (negative) correlations ($p<0.001$) are consistent between the EM38 (ECa) in both dipoles (depths) and the presence of soil organic matter (measured with the application of H_2O_2), surface rainsplash protection, perennial vegetation, litter, type of vegetative cover (i.e. sparse or dense grass, trees or bare soil), bulk soil respiration (predominantly microbial CO_2) and the Soil Evaporation Potential (as measured from a number of surrogate indicators). The few associations that were attained with fauna are difficult to explain, with weak negative correlations ($p<0.05$) between the EM38 (both dipoles) in autumn and the presence of ants (no correlation in spring), and positive weak correlations ($p<0.05$) between the EM38 in vertical dipole (1.5m depth), spring and all the EM31 dipoles except horizontal (3m depth) in spring with the presence of reptiles. The correlations with the EM31 were not as strong as the EM38, with all abiotic and biotic metrics showing an inverse relationship with depth. In fact, the deeper readings from the EM31 (i.e. vertical dipole at 6m depth) yielded no strong correlations ($p<0.001$) with any biotic metrics. It should also be noted that similar correlations with the EM readings (ECa) were attained with surface soil electrical conductivity ($EC_{1:5}$) measurements and the biotic indicators. Moreover, abiotic metrics likely associated with ecological processes, such as pH, surface compaction and soil slakeness also yielded strong correlations ($p<0.001$) with the ECa readings, particularly the EM38. The correlations yielded with the biotic indicators in particular, are likely associated with soil moisture levels, depth (and type?) of the clay-rich B horizon and soil salinity levels. This research confirms that in these landscapes, the EM38 provides valuable information on not only abiotic attributes, but also ecological attributes, particularly those associated with the presence and condition of surface vegetation. The EM31 is less useful, especially in the deeper measuring vertical dipole (if utilised, the shallower horizontal dipole should be preferentially used). We therefore recommend that the EM38 be further investigated for environmental and ecological investigations in other landscapes, from other regions and where applicable, it should be included in relevant monitoring activities.

Change point modelling for detecting regime shifts in paleoclimate data

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At present there are no physical theories that confidently predict when and how often the climate system experiences transitions or rapid changes. Our information is largely empirical and based on geochemical proxy data. Although these studies use different tools to resolve various aspects of climate change at different time scales, they basically all solve a regression problem. That is, geochemical measurements are collected at different depths that are related to time (time series) and the problem is to find the 1D model (a function of depth or time) that predicts the data. Then, this model is used as a proxy to infer past climate events.

One might idealise paleoclimatic data as a succession of periods with internally homogeneous statistical properties, bounded by abrupt shifts to subsequent or antecedent regimes. This type of situation is refered to as a change point problem by statisticians. The objective being to estimate the time of each 'change point' (or abrupt shift) from noisy observations. Change point models have been previously used to localise regime changes in times series. However, these studies use optimisation methods where the fit between observed and predicted values is minimised and the number of change points in the model has to be chosen in advance. Furthermore, data uncertainties are often poorly constrained and hence it is not clear how well the data should be fitted.

We present a methodology called Hierarchical Bayes reversible jump where the data itself is used to infer the required level of data fit and also the number of change points in the model. The regression is carried out with a fully non-linear parameter search method based on Markov chain Monte Carlo formulated in a Bayesian framework. This enables the regression model to automatically detect the position and number of climate shifts within data that are statistically significant.

The algorithm is applied to geochemical measurements collected in a peat core from the Hongyuan region in China. The Hongyuan peat-land bog is located on the eastern Qinghai Tibetan plateau and has therefore directly been influenced by the South East Asian and the Indian Monsoon systems during the Holocene. We show that this method is an effective tool for identifying changes in the source regions for airborne material and to the study of climate change using such deposits.

Late Palaeoproterozoic palaeochannels of the Robinson River area, McArthur Basin, NT

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Large meandering conglomerate and sandstone filled palaeochannels of the Robinson River 1:250,000 Sheet Area have long been regarded as early Cambrian or Neoproterozoic; but they are late Palaeoproterozoic.

This is an area of near-horizontal sedimentary and igneous rocks of the eastern shelf (the Wearyan Shelf) of the Proterozoic McArthur Basin. A basal late Palaeoproterozoic unit of clastic and carbonate sediments and volcanics, the Tawallah Group, is overlain disconformably by a dominantly carbonate unit about 700 m thick, the late Palaeoproterozoic Karns Dolomite; and this is in turn overlain disconformably by the probable Mesoproterozoic clastic sediments of the Roper Group. The McArthur Basin rocks are overlain disconformably by the early Cambrian or Neoproterozoic Bukalara Sandstone. Further west, a much thicker section, 5.5 km, of carbonate and fine clastic sediments, the McArthur Group and the overlying Nathan Group, occur between the Tawallah Group and Roper Group.

The palaeochannels are incised into Tawallah Group sediments, a dolerite sill, and a lower part of the Karns Dolomite. 10 km north-east of Robinson River settlement, and either side of the Wollogorang Road, sediments of two of the palaeochannels are overlain by about 10 m of sandstone and siltstone with halite casts; and these in turn are overlain by stromatolitic dolomite of an upper part of the Karns Dolomite. Sediments of the palaeochannels were formerly correlated with the Bukalara Sandstone, but these observations show that the incision and filling of the palaeochannels interrupted the deposition of the Karns Dolomite.

The best exposed palaeochannel meanders past Robinson River settlement. It is 500 to 1000 km wide and about 60 m deep, with a meander wavelength of 3 to 4 km. The bottom half of the sediment fill is

conglomerate with chert and sandstone cobbles and pebbles. This fines upward to pebbly sandstone and coarse red-brown sandstone with large scale trough cross beds. Trough axes are parallel to the palaeochannel, and foreset dips are in one direction. The above observations indicate a fluvial, rather than tidal, origin for the palaeochannels. Around and east of Robinson River settlement the trough cross bedding and patterns of branching indicate a general northerly palaeodrainage with major tributaries from the west and east.

The Karns Dolomite has recently been correlated with the Nathan Group, but I suggest that it more closely resembles parts of the McArthur Group. The palaeochannel sediments and overlying fine clastic sediments with halite casts may correlate with the regressive Myrtle Shale; and the overlying stromatolitic dolomite closely resembles the Emmerugga Dolomite. 15 km north-west of Robinson River settlement similar stromatolitic dolomite, with *Conophyton,* is overlain by dolomite with small chert spherules and sandy and shaly dolomite resembling the Reward Dolomite and Batten Subgroup. Sandstone at the base of the Karns Dolomite was formerly, and probably correctly, correlated with the basal Masterton Sandstone of the McArthur Group.

Palaeofire records and sedimentation (pyrocolluviation) in the context of past and current climate change

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An understanding of past fire regimes can be gained from the study of appropriate Quaternary sedimentary environments such as upland peat bogs, water reservoirs and coastal lagoons. Fire history reconstructions can be correlated with past climatic variations and used to test the validity of models that predict more intense and regular fires associated with any future global warming.

Fire records can be obtained from a number of sources including historical fire records and dendrochronology but sedimentary records containing charcoal fragments are the only reliable long-term (thousands to tens of thousands of years) record of fire activity. Charcoal is an important palaeofire proxy. The relative abundance and morphology of charcoal in sedimentary deposits can give us information on the intensity and proximity respectively, of past fire events within a catchment and help to reconstruct palaeofire histories.

Research was undertaken during 2005 to 2007 at Wilson Bog, Mt Lofty Ranges, South Australia where contiguous 2cm interval sediment sampling of a ~ 4 m section was undertaken for quantative charcoal and sediment grain-size analysis. A simple charcoal extraction technique based on floatation and skimming was developed to extract coarse charcoal from coarse-grained gravels to determine the palaeofire record at a proximal site of sedimentation. Numerical dating of charcoal and sediment samples, using optically stimulated luminescence (OSL) and radiocarbon analyses yielded ages confirming that deposition occurred from about 8000 years ago to present. Three distinct charcoal peaks occur during the Holocene climatic optimum 8000–5000 years ago suggesting there were infrequent but intense fires associated with wetter conditions. The period from 4000 to 2000 cal. yr BP was characterised by more frequent charcoal peaks and higher background levels of charcoal, which is consistent with more regular but less intense fires during drier, cooler conditions. The sharp transition from siliciclastic sedimentation to peat formation began ~1200 cal. yr BP, which may relate to a return to wetter conditions. However, fire frequency appears to have increased in this time suggesting augmentation by anthropogenic or ENSO-related factors.

This project will follow on from the study at Wilson Bog and will initially aim to calibrate the depositional signals of past fire events through analysis of sediment cores within catchment reservoirs that have a well-established fire record. Catchment-scale remote sensing of fire severity can help distinguish catchments on the basis of size and severity of burning events and this can be correlated with post-fire sediment sedimentation in reservoirs. Calibration of this kind is largely lacking in Australia.

The study also aims to link palaeofire records of proximal upland sites with distal lagoonal sites in several catchments, with sediment cores taken at sites along the east coast of Australia. The study will focus on fire records during times of climatic change during the Holocene Climatic Optimum when temperatures and sea-levels rose a few degrees above present levels. This will provide valuable baseline data to test models of fire behaviour with the predicted future global warming and increased ENSO (el nino/la nina cycles) activity. Generally climates become wetter with increasing temperature but eastern Australia is strongly influenced by ENSO activity which if more intense during warmer conditions may result in more extreme fire events as seen

recently in Canberra and Victoria. Superimposed on this is the anthropogenic fire activity related to indigenous and more recent European burning practices.

The stromatolites of Hamelin Pool—Brian Logan's contribution re-assessed

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In 1954 the first modern analogues of the 'Stromatoliths' described by Kalkowsky (1908) from the Triassic Buntsandstein in Germany were recognised by Richard Chase fringing the shores of Hamelin Pool, Western Australia. Brian Logan (1961) described them as '*Cryptozoon* and associated stromatolites' and suggested that they formed only in the intertidal zone. By 1974 it was realised that stromatolites extended from the high intertidal zone to subtidal depths of about 2 metres in Hamelin Pool. Logan et al. (1974) attempted to relate variations in stromatolite structure to differences in microbial communities at different elevations relative to tidal inundation. Microbiologists found that benthic microbial communities varied depending on the degree of wetting in the peritidal zone. These variations were matched to different stromatolite structures in subtidal and intertidal zones. The resulting model of simultaneous stromatolite growth in subtidal and intertidal settings gained wide acceptance and underpinnned the majority of subsequent studies of Hamelin Pool stromatolites and microbial communities. Burne & James (1986) proposed an alternative model in which stromatolite growth initiates only in subtidal environments and the present intertidal distribution is a result of falling sea levels and modification of relict forms by intertidal microbial communities. Deiter Meischner (1994) agreed that Holocene stromatolites grow subtidally, but suggested that many of the stromatolites in the intertidal zone were of Pleistocene age. A careful review of the localities described by Meischner has found no evidence to support this conclusion and it seems that misinterpretation of complex field relationships led Meischer to misinterpret the age of the intertidal stromatolites. In this study we have precisely surveyed the elevation of stromatolites and related this to records of the short term sea level variations due to tidal, wind and other effects. Short term variations in sea-level in Hamelin Pool were analysed from a 19 month record from October 1983 to April 1985. This revealed several components of variation, with the tide being a minor one, probably accounting for 20 per cent or less of the variation in sea-level. The tide has a .4m frequency, and 90 peaks and troughs in 51 days. The dominant component of sea-level variation is a seasonal cycle peaking in May-June with troughs in October to December. The peak of sea level (May-June) precedes the June to August trough of solar radiation. The most likely cause is a seasonal wind from northern sectors. 43 per cent of the variation in the record is in this component, with a range from below 0.1m to 0.6m. A second component was an event in February 1985 with a peak of 0.6m. It occurred just after the seasonal trough in December 1984 but equalled the seasonal peak. Winds were from northern sectors with a sustained strength about 18 km/hr. We conclude that principal stromatolite growth occurs between mean sea level and a depth of 2 metres, growth rate is 5 mm/decade, growth commenced 1,500 years bp, and relative sea level has fallen by 2 metres in the past 4000 years.

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Cenozoic volcanism in the Capel-Faust Basins, northern Lord Howe Rise

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Geoscience Australia recently acquired new geophysical data (seismic, potential field and multibeam swath) and geological samples in the Capel and Faust basins of the northern Lord Howe Rise. Volcanic features identified in survey results include cones, flows and sill-related features that crop out on the seafloor or have seafloor expression. Based on analysis of seismic data and swath bathymetry in the region (s302), two distinct phases of seafloor volcanism are recognised; Miocene-Pliocene cones with a largely unmodified conical shape, and Eocene-Oligocene volcanic features. A blanket of marine ooze onlaps the older volcanic edifices and each cone is surrounded by a moat where currents have eroded sediment.

Previously identified Cenozoic volcanism in the region includes the north-south trending Miocene to Recent Lord Howe Seamount chain. A nearby expression of this hot spot chain, the Gifford Guyot (dated at approximately 18 Ma), was included in the survey area. Other volcanic features include a few small conical seamounts on the northern LHR identified by the French ZoNéCo 5 survey. These features are aligned roughly north-north-west and have been dated as Early Miocene. The younger Capel-Faust seamounts are aligned with these and the age relationships suggest they could be part of a single seamount chain. The older Eocene-Oligocene cones do not show any preferred alignment within the survey area and are too old to be related to the current hotspot activity identified in the region.

Samples are variably altered but trace element abundances in mafic rocks from the Late-Miocene-Pliocene cones and Gifford Guyot indicate they are alkalic basalt to basalt. SiO2 abundances vary from 43.7–50% and show an overall trend of increasing SiO2 with decreasing Mg#. All samples are enriched in light rare earth elements. REE profiles are parallel for all samples except those from the Gifford Guyot, which have flatter heavy rare earth elements. Samples from the younger cones can be differentiated from each other and from the Gifford Guyot on a plot of Ti, Sr and Tb/Yb reflecting different source depths or degrees of partial melting. Patterns on primitive mantle-normalised plots indicate they are similar to oceanic island basalts. A comparison of pyroxene from the older, more altered cones and the Late-Miocene-Pliocene cones shows that these most likely represent two distinct magmatic events and that the younger cones are similar to the basalt from the ZoNéCo 5 seamounts. All pyroxenes are augite or diopside and those from the older cones are more titanium-rich.

Miocene shelf-edge deltas and influence on slope morphology, Australian North West Shelf

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Shelf deltas and shelf-edge deltas, identified in the Neogene of the Northern Carnarvon Basin, North West Shelf of Australia, show distinct clinoform morphologies. In addition, along-strike variability of slope morphology and sediment transport occurs as a result of localised shelf-edge delta sedimentation. Key bounding stratigraphic surfaces were mapped using 3-D seismic data and horizontal and proportional slicing of seismic amplitude and coherency volumes used to interpret depositional systems and their architecture.

Late-middle Miocene siliciclastics in the Northern Carnarvon Basin (Bare Formation) are interpreted as shelf and shelf-edge deltas that prograded across a preexisting carbonate shelf. Mapping of these deltas reveals lobes that display distinct clinoform characteristics (e.g. heights of tens versus hundred meters) depending on their location with respect to the shelf break. There were distinct fluctuations between shelf and shelf-edge delta deposition within at least one interpreted delta lobe complex. Accordingly, some of the lobes within this complex deposited sediments at and beyond the shelf break forming shelf-edge deltas, whereas other lobes did not reach the shelf break before they retreated or were abandoned. Seismic stratigraphic analysis and mapping of individual lobes suggest that the stratigraphy was built by regressive pulses that cause a basinward shift of deltaic deposition (shelf-edge deltas) and transgressive pulses that pushed deposition landward (shelf deltas) within this lobe complex.

Deepwater slope morphology in plan view changes from linear to convex-outward where shelf-edge deltas were deposited. Incisions were already conspicuous on the slope even before deltas reached the shelf-break. Nevertheless, slope gullies immediately downdip of the shelf-edge deltas display greater erosion of underlying strata and are wider and deeper (>1 km wide, ~100 m deep) than incisions that are laterally displaced from the deltaic depocenter (~0.7 km wide, ~25 m deep). We interpret this change in slope gully morphology as the result of erosion by sediment gravity flows sourced from the delta itself. Furthermore, localised deposition of the shelf-edge deltas had significant impact on along-strike variability of margin progradation. Late-middle and late Miocene margin total progradation is ~26 km to the south where there are no shelf-edge deltas; whereas shelf-edge progradation is ~37 km to the north where the deltas were concentrated.

A palaeoenvironmental study in wetlands from semi-arid Australia: the Macquarie Marshes, NSW

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The Macquarie Marshes (MM) are one of the largest floodplain wetland areas in the Murray-Darling Basin, occupying ~220,000 ha in semi-arid central-western NSW. Distinguished as northern and southern marshes, they are a diverse set of lotic/lentic wetlands (river, channels, swamps, floodplains) developed over the last *c.* 6–10 ka years, in the permanent Macquarie River. Approximately 17% of the Macquarie Marshes (~ 21,645 ha) is a Ramsar site since 1986, in recognition of its aquatic biodiversity, mainly water birds, and productivity.

The understanding of the long-term history of semi-arid areas in Australia and how climate has affected them is important in order to recognise the effect of climatic shifts on biota and landscape and responses to these shifts, as well as to be able to recognise the overprint of anthropogenic changes (i.e. agriculture) in the last ~200 years.

Geomorphological aspects of the MM have been studied by Yonge & Hesse (2009) who identified two main processes involved in the formation and evolution of the marshes: channel breakdown and channel avulsion.

A detailed palaeoenvironmental project analysing diverse biological proxies (vegetation, aquatic plants, charophytes, diatoms, invertebrates, charcoal, diatoms), sedimentology and geochemistry from sediment cores from the northern and southern MM started few years ago in order to reconstruct the palaeo-ecologies of the marshes, and their response to climate change (i.e. warming, increasing droughts) and anthropogenic action (i.e. agriculture, clearing) following a 'pilot' study which analysed two cores from the southern marshes (Ralph et al., submitted).

We have studied in detail the last ~ 800 years represented in 4 cores from the southern MM and 3 cores from the northern MM, though some cores reached ~ 50 ka at ~ 2 m depth. Several general points:

- due to the depositional characteristics of the MM, lagoon and marsh areas were targeted as they accumulate water and sediment and retain these for longer periods of time, compared to the throughgoing fluvial facies. These lagoonal wetlands team with life (algae, charophytes, aquatic macrophytes, invertebrates, fish, birds, reptiles), and are areas where sedimentation is more continuous
- the cores show a continuous representation of the last ~800–1000 years (~70 cm core-depth), though below this the ages obtained are Pleistocene (> 30 ka)
- numerical dating has been performed and single-grain OSL has proven to be effective to date the very young upper strata (less than 80 years old)
- microfossil remains are represented by siliceous- and organic-walled organisms, although calcareous remains are found in surface sediments
- preliminary results indicate shifts in biota and sedimentation, especially at ~ 45 years ago, coinciding with the building of the Burrendong Dam in the 1960s.

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High resolution correlation of hydroclimatic change and an aerosol emission event, Upper Devonian Burdekin Basin, Queensland

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A Frasnian to Famennian sandstone unit with torrential cross bedding overlies playa red beds in a section across the Burdekin River, Queensland. The sandstone unit is followed by lithic sandstone with emission-milled pebbles, one of which returned a Famennian K-Ar age determined by the Radiometric Laboratory, Department of Earth Sciences, the University of Queensland. The sandstone unit is extensively anomalous in its geochemistry along with synsedimentary leaching indicative of acid-sulphate aerosol fallout. The modern implication is that aerosol emission can cause abrupt changes in rainfall patterns otherwise attributable in the longer term to emission of greenhouse gases.

Development of a geochemical toolbox to quantify groundwater dynamics in the semi-arid lower Murrumbidgee aquifer system, Australia

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This presentation will examine the development of a 'geochemical toolbox' for quantifying the rates and extents of various processes influencing groundwater composition in the semi-arid, siliceous Lower Murrumbidgee Aquifer System in the eastern Murray Basin, Australia.

The toolbox was populated with select physical and chemical parameters (i.e. environmental tracers) identified by graphical and chemometric review of analytical results from approximately 200 surface water and groundwater samples collected during the first year of the three-year project. The toolbox was developed to minimise the computational intensity of hydrological and hydrogeochemical models of the study area by identifying processes active in the aquifer system (i.e. evapotranspiration, ion exchange, fluid mixing, water/rock interaction) and by minimising the number of parameters required for detailed modelling of these processes.

Processes influencing groundwater composition in the catchment were identified via, for example, piper plots and cluster analysis. By reviewing the reduced geochemical data within the conceptual model developed for the study area, processes could be identified via their geochemical fingerprints. Minimising the number of parameters required to model each process was accomplished via principal component analysis and reaction path modelling, whereby parameters providing redundant data could be eliminated and parameters involved in multiple processes could be determined.

Following the review of the analytical results, parameters for the toolbox were selected such that each process is characterised by the minimum number of environmental tracers. To minimise the need to model concurrent reactions, preference was given to discrete tracers influenced by one specific process. However, given the complexity of natural groundwater systems, this was not possible for all processes.

Calcification and pH changes in corals from the southern Great Barrier Reef

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Rapid accumulation of anthropogenically produced carbon dioxide in the atmosphere over the last ~100 years is a key issue for carbonate secreting marine biota in two main aspects. Firstly the effect of increasing in sea

surface temperature from global warming and secondly the impact on calcification with ocean chemistry changing towards more acidic conditions due to increased absorption of carbon dioxide from the atmosphere. In sub-tropical coral reefs warmer sea surface temperatures would be expected to have a positive effect on coral calcification by increasing coral metabolism and enhancing photosynthesis of zooxanthellae which activates fixation of CO_2 and precipitation of $CaCO_3$, whereas ocean acidification hinders calcification of corals by decreasing of carbonate ion concentration in sea water and consequently causing a decline in aragonite saturation state. Concerns about climate and ocean chemistry changes have directed a lot of attention to the fates of tropical corals and coral reefs but much less attention has been given to calcifying organisms living in subtropical (20˚S to 35˚S) environment. In this environment, corals develop under more limiting conditions to compared to those at lower latitudes since solar radiation and ocean pH generally decrease toward high latitudes. Thus, it is of critical importance to investigate how sub-tropical corals are responding to the global environmental changes.

In order to constrain the impact of changes in ambient seawater and conditions for coral calcification we have determined geochemical proxies and calcification rates at high temporal resolution from *Porites* corals from the southern Great Barrier Reef (GBR). Annual calcification rate shows that extension rate is the main factor to control coral calcification rate in this region. Interdecadal changes in calcification rate from two cores from Pompey Complex (~20 to 21˚S 150˚E) were indentified with positive correlation to Pacific Decadal Oscillation (PDO) over the last century.In contrast, a major decline in calcification rate is shown in two coral cores from Lady Musgrave Island located in further southern GBR (~23.5˚S 152˚E) with the rate of coral extension declining by 50% since 1980 but still within the range of longer-term (centennial) variability. Whether these preliminary observations are typical remains to be verified by ongoing work. Boron isotope ratios ($\delta^{11}B$) were measured to investigate the effect of oceanic pH changes from Pompey Complex cores. The result also represents interdecadal variation of oceanic pH by following PDO cycles over the last 100 years, which may suggest that long-term pH changes in this region is generally controlled by atmospheric and oceanic anomalies in Pacific as shown in the previous studies (Pelejero et al., 2005; Wei et al., 2009). The measured pH derived from coral $\delta^{11}B$ record shows decrease of about 0.2 units since 1900 along with the long-term variation, whereas trace element ratios (Sr/Ca and Mg/Ca) estimated from coral skeleton represent increase in sea surface temperature in this region. These results suggest that increased anthropogenic CO_2 in the atmosphere contributed to both ocean acidification and increases in sea surface temperature, although how these counter mechanisms are affecting coral calcification rates is still uncertain.

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Getting seabed sediments right: application of a simulation experiment to predict seabed mud content on Australian margin

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Geoscience Australia is supporting the exploration and development of offshore oil and gas resources and establishment of Australia's national representative system of marine protected areas through provision of spatial information about the physical and biological character of the seabed. Central to this approach is prediction of Australia's seabed biodiversity from spatially continuous data of physical seabed properties. However, information for these properties is usually collected at sparsely-distributed discrete locations, particularly in the deep ocean. Thus, methods for generating spatially continuous information from point samples become essential tools. Such methods are, however, often data- or even variable-specific and it is difficult to select an appropriate method for any given dataset. Traditionally, simple interpolators like inverse distance squared (IDS) have been used. However, predictions using IDS are usually not satisfactory. Improving the accuracy of these physical data for biodiversity prediction, by searching for the most robust spatial interpolation methods to predict physical seabed properties, is essential to better inform resource management practises. In this regard, we conducted a simulation experiment to compare the performance of statistical and mathematical methods for spatial interpolation using samples of seabed mud content across the Australian margin. Five factors that affect the accuracy of spatial interpolation were considered: 1) region (N,

NE, SW); 2) statistical method: 14 statistical methods (37 sub-methods); 3) sample density: (20%, 40%, 60%, 80%, 100%); 4) searching neighbourhood (global, local); and 5) sample stratification by geomorphic provinces, (non-stratified, stratified). Bathymetry, distance-to-coast and slope were used as secondary variables. Mud content was chosen because it plays an important role in affecting the nature and composition of marine biodiversity.

In this study, we only report the results of the comparison of 14 methods (37 sub-methods) using samples of seabed mud content with five levels of sample density across the south-west Australian margin. Ten-fold cross validation with relative mean absolute error (RMAE) and visual examination were used to assess the performance of these methods. A total of 1,850 prediction datasets were produced and used to assess the performance of the methods. Considering both the accuracy and the visual examination of prediction maps, we found that a combined method of random forest and ordinary kriging (RKrf) achieved the most accurate representation of mud content for Australia's seabed. This combined method is novel, specifically developed for this experiment, with a relative mean absolute error (RMAE) up to 17% less than that of IDS. Moreover, the RMAE of RKrf is about 30% lower than that of the most accurate methods in previous publications, highlighting the robustness of the method selected in this study. No threshold in sample density was detected in relation to prediction accuracy; as sample density increases, the accuracy of the statistical methods for spatial interpolation also increases. The results of the simulation experiment can be applied to spatial data modelling of various physical parameters in different disciplines and have application to a variety of resource management applications for Australia's marine region.

Strontium isotope composition variations in the lower Murrumbidgee groundwater system, NSW, Australia

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Strontium isotopes are useful tracers of hydrological and hydrogeochemical processes, such as water-rock interaction and water mixing, and can be used to constrain ground- and surface-water sources, aquifer dissolution rates, and groundwater ages. $^{87}Sr/^{86}Sr$ ratios are modified by the decay of ^{87}Rb ($t_{1/2}$ = 49 Ga) to ^{87}Sr. Sr substitutes for Ca in minerals, and Rb for K and Na; hence K-rich minerals evolve to have higher $^{87}Sr/^{86}Sr$ ratios than Ca-rich minerals such as calcite. Sr isotopes are not significantly fractionated during mineral precipitation and dissolution, so groundwater $^{87}Sr/^{86}Sr$ ratios tend to reflect the composition of the rocks with which they have interacted. In this study, we use Sr isotope compositions measured in groundwater and surface water samples from the Lower Murrumbidgee Groundwater Management Area (LMGMA), in combination with major, minor, and trace element concentrations, to understand better the extent of water-rock interaction and water mixing in the area.

Groundwater usage in the LMGMA is approximately 300 GL/year, mostly pumped from the semi-confined Calivil and Renmark formations for irrigation of cropland and pasture. According to current hydrological understanding, the main source of recharge of these deeper aquifers is channel leakage from the Murrumbidgee River in the Darlington Point area; however, there is also evidence of leakage from the shallow unconfined Shepparton formation into the deeper aquifers through aquitard windows. The water quality in the Shepparton is often poor, and hence it is important to understand the groundwater dynamics and changes in water chemistry in greater detail.

Major and minor ion ratios (Cl/Br, Na/Cl) indicate that evapotranspiration is a major control on groundwater chemistry in the LMGMA, while changes in cation ratios also indicate a significant degree of water-rock interaction or water mixing. For example, Ca/Mg molar ratios vary from over 2 to under 0.5 and show a broad decreasing trend with increasing salinity. $^{87}Sr/^{86}Sr$ ratios vary from 0.711 to 0.716, and, in general, increase from east to west and with increasing depth, roughly following the groundwater age distribution based on previous radiocarbon dates. However, large local-scale variations in Sr isotopic composition also exist, suggesting the $^{87}Sr/^{86}Sr$ ratios are influenced by interaction with heterogeneously distributed minerals within the aquifer matrix. Samples with $^{87}Sr/^{86}Sr$ ratios above 0.715 are associated with high iron and low total Sr concentrations, suggesting dissolution of iron-rich, high $^{87}Sr/^{86}Sr$ material such as detrital biotite derived from weathering of the exposed bedrock upstream.

Many groundwater samples closer to the main recharge zones and irrigation areas display $^{87}Sr/^{86}Sr$ ratios below those of Murrumbidgee River surface water samples. This may indicate dissolution of low $^{87}Sr/^{86}Sr$

minerals such as calcite; Ca/Cl ratios are relatively high in many of these samples. However, carbonates are not widely present in this part of the Murray Basin. The low $^{87}Sr/^{86}Sr$ ratios may alternatively reflect evapo-concentrated rainwater with an $^{87}Sr/^{86}Sr$ ratio of ~0.710 leaking downward from the surface under the effect of irrigation pumping.

These initial results indicate that significant variations in Sr isotope ratios are present, and demonstrate their utility in tracing groundwater sources and the extent of water-rock interaction. Analysis of further samples for Sr isotope composition, and, in future, U-series isotopes, combined with our existing major, minor, and trace element data, will enable a better understanding of this important groundwater resource.

Acknowledgments

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Post-glacial development of the Black Sea: a problem of two radiocarbon-based chronologies

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The Black Sea Flood hypothesis (Ryan and Pitman, 1997) proposed a catastrophic early Holocene transgression of the Black Sea region by Mediterranean sourced water through the Bosphorus Strait, while outflow hypotheses argue the converse. This debate has been dependent on radiocarbon methods for numeric ages.

Here we present a new radiocarbon-based chronology based upon new accelerator mass spectrometry (AMS) ^{14}C ages on individual molluscs and peat samples, and a reassessment of previous AMS ^{14}C and conventional radiocarbon ages on peat and shells. These data, supported by the first amino acid racemisation dating of bivalve molluscs in the Black Sea, indicates prompt infilling of the Black Sea from an initial depth (c. -100m) below that of the Bosphorus Sill (-35 m).

Amino acid racemisation (AAR) and AMS ^{14}C methods were used for chronology on shells, and AMS ^{14}C was used on peat samples. Four peat and 56 shell samples were analysed from five cores, BS37-82, BS37A-82 (Odessa Bay, Ukrainian shelf, water depth -18 m), core 721 (Sukhumi Bay, Georgia, -14.9 m water depth) core 342 (western Ukrainian shelf, -30 m water depth) and core 45 (outer Ukrainian shelf, water depth -107 m). Four shell samples consisted of bulk samples of juvenile *Cardium*, and 52 were of individual valves. Samples of core material were selected at Odessa National University and analysed at the School of Earth and Environmental Sciences, University of Wollongong, for the extent of amino acid racemisation in molluscs. AMS was undertaken at the laboratories of the Australian Nuclear Science and Techonology Organisation using methods detailed in Hua *et al.,* (2001). Reverse-Phase High Performance Liquid Chromatography was used to examine the extent of AAR in the bivalve molluscs *Dreissena*, *Cardium edule, Chione gallina and Mytilus.* The AAR method used (Kaufman and Manley, 1998) was modified by strong bleaching (12.5% NaOCl) for one hour.

We have found that our AMS ^{14}C ages on peat in core 721, Sukhumi Bay, Georgia, are broadly comparable with earlier data (Apakidze, 1987; Yanko and Troitskaya, 1987) from the same core using β-counting radiocarbon methods. Thus, our results suggest that earlier ^{14}C data using β-counting (mostly from eastern European laboratories) are as valid as those from western laboratories. In light of these results we have integrated previously published ^{14}C ages on peat and bivalve molluscs to model the development of the early Holocene Black Sea.

A basinwide transgressive event is recorded in the sedimentary record on the shelves of the Black Sea. This signature is visible in each of the examined cores. In core 721 this transgressive event is dated to just after 8530 ^{14}C yr BP on peat but prior to 8210 ± 120 ^{14}C yr BP on marine molluscs. This is also recorded in core 45 (-107 m depth, outer Ukrainian shelf) after 8695 ± 50 ^{14}C yr BP (lacustrine phase) but prior to 6530 ± 45 ^{14}C yr BP (marine). Reworked shells in core 342 (-30 m water depth, inner Ukrainian shelf) testify to the change from alluvial and lagoonal (peat, and *Dreissena* and *Monodacna* bivalves) to marine conditions (indicated by the presence of the Mediterranean bivalve mollusc, *Mytilus*) after 9020 ^{14}C yr BP but prior to 6200 a BP (AAR). Integrating the data presented here with those of previously published ages on peat (Balabanov, 2007; Gorur

et al., 2001; Filipova-Marinova, 2007) and molluscs (Lericolais *et al.,* 2009) indicate a transgression into the Black Sea from 8760 ^{14}C yr BP, and a near-zero radiocarbon reservoir age in *Dreissena* shells (indicative of low to near-zero salinity) marking a rapidly transgressing coastline. This transgression took c. 300 yr to reach the level of the Bosphorus sill from an initial water depth of c. 100 m, occurring after drawdown of the pre-existing lake initiated at the beginning of the Younger Dryas. We conclude that two radiocarbon chronologies on shells have been used to debate the history of the Black Sea: AMS ages on single valves, and conventional ^{14}C ages on bulk shell samples. These do not appear equivalent because the AMS ^{14}C ages on single valves appear to give younger ages than the bulk samples, and many of the bulk shell samples dated by conventional ^{14}C methods consist of marine and non-marine shells which, based on stratigraphic relationships in cores, inhabited the Black Sea at different times. Thus the use of ^{14}C ages on bulk shell samples from the Black Sea has muddied the scientific waters in these investigations.

Facies analysis and depositional environment of the Oligocene-Miocene Qom formation in the central Iran (Semnan area)

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The Qom formation was formed in the Oligo-Miocene during the final sea transgression in Central Iran. This Formation in the Central Iran Basin Contains oil and gas. Organic geochemical analysis in previous studies indicated that the hydrocarbons migrated from deeper source rocks, likely of Jurassic age. In the Central Iran Basin, the Qom Formation is 1,200m thick and is abounded by the Oligocene Lower Red Formation and the middle Miocene Upper Red Formation. In previous studies, the Qom Formation was divided into nine members designated from oldest to youngest: a, b, c1 to c4, d, e, and f, of which 'e' is 300m thick and constitutes the main reservoir. Our study focused on a Qom Section located in the Arvaneh (Semnan) region of Central Iran that is 498m thick. The lower part of the formation was not deposited, and only the following four members of early Miocene age (Aquitanian-Burdigalian) was identified between the lower and upper Red Formation. The studied section mainly consist of limestone, marl, sandy limestone, sandy marl and argillaceous limestone. According to this study(field and laboratory investigations), 9 carbonate microfacies were recognised which are grouped into four facies associations (microfacies group). These facies associations present platform to basin depositional setting and are nominated as: A (Tidal-[U+FB02]at), B (Lagoon), C (Slope) and D (Open marine). Based on paleoecology and Petrographic analysis, it seems the Qom Formation was deposited in a Carbonate shelf setting. The Qom formation constitutes a regional transgressive-regressive sequence that is bounded by two continental units (Lower and Upper Red Formation).

Hydrogeochemistry and groundwater–surface water connectivity of the Broken River, Victoria, Australia

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Understanding groundwater-surface water exchange is critical for catchment hydrology studies and therefore water resource management. Failure to account for these fluxes can lead to problems concerning water quality degradation, misallocation of resources and incomplete understanding of catchment hydrodynamics.

Located in north-eastern Victoria, the Broken River is a major tributary of the Goulburn River and an important local resource for agricultural and domestic water storage. Previous work broadly characterised the physical hydrology of the Broken River (CSIRO 2008), and the hydrogeology of surrounding regions (e.g. Cartwright et al, 2005). Little information exists, however, for the Broken River catchment. This study uses major ions, environmental tracers and trace metals to determine the factors that control groundwater and surface water chemistry, and the extent of groundwater–surface water exchange on the Broken River.

Bores located within 1 km of the Broken River, Broken Creek or major tributaries were chosen from DPI and SKM networks, along with river water samples to represent the potential interface of groundwater and surface waters. All samples were analyzed for major and minor ions, hydrogen and oxygen isotopes, and trace metals. Major ion analysis indicates that Na^+ and Cl^- are the dominant ions (>75%) in all groundwater sites. Electrical conductivity in groundwaters ranges from <1,000 to >20,000 µS/cm, and may be strongly controlled by local

lithology. River water is relatively fresh (<250 µS/cm) and dominated by Na^+, HCO_3^-, and Cl^-. Na^+ and Cl^- concentrations increase downstream at the expense of Ca^+, HCO_3^- and H_2SiO_4. However, there is little downstream variation in EC. River water chemistry is relatively homogeneous throughout the length of the Broken River with exceptions occurring near the junctions of major tributaries, suggesting gaining stream behaviour in the upper catchment. Na/Cl ratios range in river water samples from 0.86–2.5, and are probably a result of water-rock interaction rather than halite dissolution. A consideration of the local geology suggests that silicate weathering may control water chemistry in upper catchment bores and river water. Further downstream, chemical signatures indicate a disconnected or losing stream, as both major and minor ion concentrations increase in near-river bores with little correlation to river water values. The increase in ion concentration is believed to be a function of increased residence time and evaporation as compared to upper catchment sites. $\delta^{18}O$ and $\delta^{2}H$ values of groundwater samples range from -6.1‰ to -4.2‰ and -39‰ to -28‰, respectively. A linear regression curve of these values deviates to the right of the GMWL. The slope of this trend is ~4.6, and is interpreted as an indication of evaporation during recharge, especially in groundwater from the alluvial plain of the Broken River. The $\delta^{18}O$ and $\delta^{2}H$ values of groundwater are similar to those of modern rainfall suggesting recent recharge.

The Broken River catchment is characterised by two provenances: an upper catchment with hydraulic connectivity where the Broken River is a gaining stream in some reaches. Chemical signatures from water-rock interaction are present in tributaries and upper reaches. The lower catchment is dominated by Na^+ and Cl^-, and the river does not receive significant groundwater input. Evaporation is a source of salinity and total ion concentration.

This study fills important gaps in characterising the hydrogeology of the Broken River region in north-eastern Victoria. It also provides high-resolution data on the chemistry of ground- and river waters, which may be used to model water flux across the groundwater-surface water boundary for the purpose of groundwater management.

References

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Geochronological study of a non-carbonate karstic system, middle Paraiba do Sul River valley, SE-Brazil

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A non-carbonate karstic system has been studied at Santana river basin (286 km^2) located at middle Paraíba do Sul river valley, SE-Brazil, that drains gneiss and quartzites in a humid-tropical area. Karst features in meta-sedimentary rocks in this area were previously described (Avelar, 2006), but not studied in detail. In a 42 Km^2 mapping area (1:10.000) variable karst and erosional features are found, including 42 caves, 23 collapse dolines, 209 solution dolines and areas of scars, fans and valley deposits, with paleosols (Uagoda, 2006).

In other basins of SE Brazil, even if they are not karst, some authors use paleosol chronologies to discuss if erosion and depositional features are controlled by climatic or adjustment level variations (Coelho Netto, 1999). Our study aims to determine ages of paleosols in fans and in deposits under solution dolines, in order to identify possible climatic or adjustment level controls. We collected samples in two adjacent sub-basins: Luiza basin (gneiss) and Lourenço basin (quartzite) which drain into sinks and knick points in different portions of the Santana basin.

In Luiza basin, the results show ages between 4.690 Y/B.P (top) and 8.830 Y/B.P (bottom) for a depositional fan, and between 8.800 Y/B.P (top) and 9.230 Y/B.P (bottom) for deposits within a solution doline. In the Lourenço Basin, the results show ages between 9.750 Y/B.P (top) and 11.740 Y/B.P (bottom) for a depositional fan. Although the results of the Lourenço doline are not yet available, there is a difference of around 3.000 years between the basal paleosols of the two fans, suggesting different controls for two adjacent basins. Surprisingly, the deposition rates of the various deposits are very similar -. 0.027cm/year for the Luiza fan,

0.046cm/year for the Luiza doline and 0.025cm/year for the Lourenço fan respectively. This suggests similar rates of deposition for different lithologies and types of deposits.

We are currently processing a new set of samples in the Research School of Earth Sciences at the Australian National University. These new samples including Lourenço doline may show if the paleosols are related to a single humid period or to different lithologically controlled adjustment levels.

ANDRILL targets Coulman High, Ross Sea, Antarctica to recover history of the west Antarctic ice sheet

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The international Antarctic Geological Drilling (ANDRILL) Program, which recently recovered long (> 1000 m) rock and sediment cores from two sites in McMurdo Sound, aims to recover new stratigraphic sections from sites beneath the Ross Ice Shelf east of Ross Island on the Coulman structural High. ANDRILL will utilise new drilling capabilities to operate from a fast moving ice shelf platform (~700 m/year northward) and complete two deep holes. The drilling target for the Coulman High Project is a Cretaceous (?) to lower Miocene section. Recovery of these strata will allow our team to investigate: (1) the behaviour of ice sheets in West Antarctica during periods of moderate to high greenhouse gas levels; (2) the Antarctic environment in warm greenhouse periods; and (3) tectonic processes within the West Antarctic Rift System.

In 2003 and 2004 a marine multichannel seismic grid was completed across Coulman High as close as 500 m from the front of the Ross Ice Shelf. The ice shelf has advanced 4 km north and now sits over several seismic lines providing a platform from which to drill into sites located on those lines. Selected drill sites target ~600 m of laterally continuous sediments underlain by a major regional unconformity and 350–850 m of faulted sediments and basement beneath the unconformity. Acoustic basement is interpreted to be from 700 to >1500 m below the sea floor. Seismic correlation from Deep Sea Drilling Project Sites 272 and 273 to the Coulman High sites implies that the section proposed to be drilled predates 19 Ma.

Several new operational challenges exist at the Coulman High sites and work is under way to modify existing technology and develop new approaches to accommodate these challenges. Access to the sea-floor requires melting through 250 meters of ice shelf using the ANDRILL hot water drill, which has previously be used to maintain an open hole through 80 meters of ice. The amount of lateral deflection that ANDRILL's sea-riser can accommodate is limited by water column thickness and amount of ice shelf movement. These parameters constrain drilling depth to a maximum of ~500 m at the Coulman High sites if existing technology were utilised. To reach targets at > 1000 m below sea floor, two drilling options are being considered: pull out at ~500 m, move the rig back over the drill hole, re-occupy the hole via a re-entry cone, and commence coring; or pull out, allow the string to swing back to vertical, wash drill to ~500 m at the new offset site and commence coring below that depth.

An airborne radar survey has recently been completed over the Coulman High sites and will be augmented by satellite data and a ground-based radar survey to examine the ice shelf for basal and surface crevasses and identify brine-rich zones. Oceanographic moorings will be deployed in 2010/11 to obtain water current data from beneath the ice shelf to model deflection of the riser. In addition, the hot water drilling system will be used to make a series of 40 cm holes through the ice shelf. These holes will be used to deploy a remotely operated vehicle beneath the ice shelf and to obtain short sediment cores. Plans are being developed to acquire additional seismic data to improve seismic velocity control and enhance drilling depth estimates. Drilling is planned for 2012–14, depending on the commitment of funds by international Antarctic Programs.

Results from the Coulman High Project will compliment anticipated outcomes from the Integrated Ocean Drilling Program (IODP) expedition 318 to offshore Wilkes Land, Antarctica and will broaden our understanding of the evolution of the East and West Antarctic ice sheets. These efforts fit within a community-based strategy to acquire records of ice sheet behaviour from the Antarctic margin, which was submitted to the recent INVEST workshop. These new stratigraphic archives from the Antarctic continental margin will provide direct records of ice volume variability to augment high resolution isotope stratigraphies and sea-level records recovered by IODP from the deep ocean basins.

Canberra landscapes shaped by geology—the centenary of Pittman's 1910 geological map that helped shape the design for Australia's capital city

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Walter Burley-Griffin and his wife Marion fully recognised the potential for a truly beautiful city landscape when they submitted their design for the capital of Australia. Their urban design took full advantage of the local topography and drainage system when they developed their city axis and associated triangular urban development corridors. The architectural scheme for the capital of Australia, including a central parliament building and associated administrative departments, was designed to be enhanced by the landscape of the Molonglo River basin and the surrounding hills, at that time known as the Limestone Plains.

The landscapes of the Limestone Plains region are the product of a long geological evolutionary process that began about 490 million years ago during the Ordovician geological period. Edward Fisher Pittman, Government Geologist and Under Secretary for Mines in the State of New South Wales, mapped the central area for the national capital and produced his 1910 geological map that formed an important component of the brief for the competitors in the competition for the design of the city. Prior to this mapping assignment, Pittman had contributed to the 1883 Geological Map of New South Wales compiled by C. S. Wilkinson (Government Geologist) based on the earlier work of the Rev. W. B. Clarke (1798–1878), the 'father' of Australian Geology.

At this Australian Earth Science Convention 2010 we celebrate the contribution Edward Pittman made to Canberra regional geological mapping on the centenary of the publication of his map 'Geological Survey of the Site of the Federal Capital of Australia' dated 14 December, 1910; scale 800 feet to 1 inch (1:9600); based on Charles Robert Scrivener's contour map of the area chosen for the federal capital.

Some geological features of the Canberra area were recognised from the very first days of European reconnaissance visits to the region in December 1820. Limestone outcrops on the banks of the Molonglo River were identified as being a possible source rock for manufacturing building mortar and the region became known as Limestone Plains. During the 1840s the Reverend William B. Clarke visited the Limestone Plains and discovered the Silurian brachiopods within mudstones in the bed of the Woolshed Creek, now not far from Canberra Airport. The 1893 general geological map of New South Wales indicated widespread Silurian sequences throughout the Limestone Plains region with associated limestone and granite outcrops.

However, the 1910 Pittman geological map for the site of the national capital was the first to indicate some detail of the geology of the Limestone Plains region. Significant comments in Pittman's report 'Geology of the Federal Capital Site' issued in 1911 by the Commonwealth Government Minister of Home Affairs included:

- the suitability of Black Mountain Sandstone for building purposes
- the suitability of various shales for the manufacture of bricks
- the supply of Mugga Mugga Porphyry for engineering purposes and as an ornamental stone
- the profusion of Silurian, corals, brachiopods, trilobites and crinoids within some sedimentary sequences
- the lack of suitable slate for roof tiles
- the availability of limestone for the manufacture of mortar and hydraulic cement
- the possible establishment of a Portland cement factory in the capital
- no insuperable difficulties with the construction of sewer tunnels and surface reservoirs
- weir sites were available for the construction of an ornamental lake in the centre of the city

- granite outcrops at Tharwa were identified as being of considerable value for architectural and engineering purposes

- the Cotter River system was identified as being 'the most impressive feature of the whole territory' and 'it will form a magnificent water supply for a large population'.

Most of Pittman's observations and comments on the geology and landscape in the Canberra Federal City site have stood 100 years of scrutiny and testing. He should be congratulated. His lasting reward is the naming of the Pittman Formation within the Adaminaby Group of Ordovician deep-marine inter-bedded sandstones, siltstones and shales across a wide area around Canberra. Motorists can see them readily in road cuttings along the freeway routes from Canberra to Sydney, Batemans Bay and into the city from Gungahlin as they cross the Lake George Fault, the Queanbeyan Fault and the Deakin Hill Fault respectively on their busy daily commutes to and from work.

Interpretation of field portable XRF test results

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Field portable XRF devices have been on the mining/exploration scene for several years now. In my perception they are often used for menial though necessary tasks, but often their full potential does not appear to be appreciated.

Barriers between instrument and sample

Any barrier between instrument and sample will affect the magnitude of the result reported. Barriers may be water (or other liquids), plastics, sample bags (plastic or cotton), lacquers or air. These affects are not fully appreciated, and in some cases they negatively affect operator safety.

When the samples being tested are powdered, it is desirable to insert something between the Kapton Window and the powdered sample so that the window does not become contaminated. This might be particularly so in exploration areas where the sample is fine bull dust such as at Tennant Creek, NT or with powdered metallurgical products that might contain 60% Cu. In either case, one does not want the powdered material to contaminate the window. So some sort of protection is desirable.

It is not desirable though to place adhesive tape like Sellotape over the window because:

- it presents a barrier between the instrument and the sample, which will absorb a substantial amount of the X-rays

- it is likely to disable the automatic safety cut-out feature that the instrument has. With a naked X-ray window, when one does a fresh-air shot, the instrument will cut-out after ~0.4 seconds. So if it was pointed in someone's direction, which it should not be, it will promptly disable itself. Apart from the obvious safety implications, to disable a safety feature is illegal.

The paper will discuss what happens when several media are inserted between instrument and sample, and one will be recommended where the diminution of element values is minimal. In one case this will include data on prepared standards.

Element readings

The author has conducted a considerable number of orientation studies over a wide range of ores and minerals from many mines and exploration areas. From this he has concluded that it is essential such studies be done by FPXRF operators commencing data collection in new areas or environments.

For example it is generally said that these instruments do not measure gold. Certainly with an XL3t-500, the instrument used by most mining and exploration companies, gold is not one of the thirty odd elements routinely reported digitally on the screen when one makes a reading. That is still the case if a scan of a gold ring or broach, or any other object that is known to be mainly made of gold. But an examination of the spectra will soon show that that the principal peaks are labelled, and in this case they are labelled 'Au'. So the spectra indicates the gold even if the digital read-out doesn't acknowledge it. However if the gold levels are much

lower, the peaks would be correspondingly lower, and if the real grades were 1–2 g/t Au then positive Au readings may not be discernable. Other elements though, perhaps ones that are not there, might indicate positive results that could be a reflection of the gold. This will be explored in the presentation.

Still other elements that traditionally have very low values in assay like 1–4 ppm, sometimes digitally report as 250–400 ppm on the FPXRF. Logically that is not reasonable. But maybe the data should not be junked. Maybe the high numbers are indicating that element, but in much lower quantities. This will be explored further if time permits.

These are wonderful instruments and in the near future they will become necessary accessories to the exploration and mining geology departments of every ambitious mining company. Without them those departments will become lame, and fall behind the pack.

A new Master of Natural Hazards Program at The Australian National University

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The new Master of Natural Hazards program at The Australian National University provides a multi-disciplinary approach to the study and monitoring of geophysical processes that can lead to the recognition of hazards and a consequent reduction of their impacts through emergency measures, disaster plans, and relief and rehabilitation. The program provides people with an understanding of the most up-to-date scientific understanding on the causes of natural hazards, their effects on human societies, and ways to mitigate their impacts and reduce their losses by focusing on Australia and the Asia-Pacific case studies.

The Master of Natural Hazards program brings together the expertise of researchers across the university to provide an opportunity for students to do coursework and research projects that will provide them with extensive knowledge of the natural hazards that occur and pose the greatest risks on human communities in the Asia-Pacific, and an understanding of the human dimensions of the natural hazards occurrences.

The program consists of two compulsory courses each in the Earth Sciences and in the Social Sciences that are designed to provide a complementary and comprehensive overview of natural hazards issues. Elective courses can be of a general grouping, or students may choose one of four Focus Streams: Environmental and Geographic Studies; Climate Change; Earth Structure and Imaging; or Socio-economic, Development and Policy Studies. A special case study project will involve writing a thesis on a topic to be approved by the Program Conveners and will comprise a body of work on an approved topic in natural hazards in the Asia-Pacific region.

Students in this program will gain a broad scientific knowledge and methodological skills to understand the physical causes and frequency of the most important natural hazards in the Asia-Pacific region, as well as the latest scientific methods and best practices of monitoring them for hazard mapping and disaster reduction purposes. Furthermore, students will learn to apply critical thinking in studying the involvement of societies' social systems in framing and influencing the severity of impacts and destructions that are brought about by different physical events.

The academic training in hazards and disaster research that the program offers will enable students to get actively involved in the preparation of short- and long-term disaster mitigation programs that can help members of communities in Australia and the Asia-Pacific region who, without sufficient knowledge on hazards and skills on disaster management, would be left vulnerable against the adversities that can be brought about by natural hazards.

Cooling and solidification of channelised viscoplastic lava flows

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Lava flow dynamics are characterised by a complex set of thermal and mechanical interactions between the flow and its environment. Factors which can strongly affect (and be affected by) these interactions include solidification, shearing, internal convection, stirring and the rapidly changing physical properties of the lava. A clear understanding of the controls on lava rheology and its interactions with flow dynamics forms a crucial

basis for the interpretation of lava flow morphology, the design of predictive models for lava flow emplacement and the development of mitigation strategies to minimise flow hazards to people or property. At a purely volcanological level such an understanding can come from phenomenological rheological models deduced from direct measurements of stress and strain rates, and also from micro-physical investigation of flow textures. However, these studies cannot explain lava flow dynamics on their own. Laboratory experiments aid these investigations by providing physical insight and intuition about the often complex nature of these flows.

Many lavas contain crystal fractions sufficient to generate a significant yield strength. These viscoplastic rheologies are typical of distal Hawaiian flows and most Mt Etna flows. We report the results of a series of analogue laboratory experiments designed to investigate the effects of this viscoplastic rheology on cooling, convection and solidification within a channelised lava flow. Viscoplastic slurries, comprised of polyethylene glycol (a wax which freezes at 20°C) and kaolin, were used as an analogue to a crystal-rich lava. In the experiments these slurries flowed with a constant flux down an inclined channel under cold water, allowing us to study the internal convection patterns and quasi-steady-state crust distribution at the flow surface.

Experiments with cooling but no solidification at the flow surface show thermal convection occurs in organised rolls aligned with the shear flow driven by downwelling plumes near the channel walls. The cooling viscoplastic experiments were compared to viscous flows at the same Rayleigh number. Dye trails show that, unlike the viscous flows, the downwelling plumes in the viscoplastic flows do not fall the full depth of the flow before moving into the interior, however the plug in the centre of the channel does not appear to have a significant effect on the convective flow.

In the experiments with solidifying flows, two crust cover regimes were identified: (a) a 'mobile crust' regime in which a mobile raft of crust formed in the centre of the channel, separated from the channel walls by open shear zones, and (b) a 'tube' regime, in which the surface crust covered the entire channel and jammed against the channel wall. The degree of surface crust coverage and the transition between these regimes were quantified in terms of a single dimensionless parameter. The transitional value of the dimensionless parameter between the tube and mobile crust regimes was found to vary with Bingham number. The results of these experiments are compared to analogous viscous experiments involving pure polyethylene glycol.

Towards automated seismic moment tensor inversion in Australia using 3D structural model

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The seismic activity in the seismogenic zones around Australia, largely due to the plate boundaries to the north and to the east of the mainland poses serious hazard in a wider region, and risk to coastal areas of Australia. This is monitored by Geoscience Australia (GA), which operates a network of permanent broadband seismometers within Australia. Earthquake and tsunami warning systems were established by the Australian Government and have been using the waveforms from the GA seismological network. The permanent instruments are augmented by non-GA seismic stations based both within and outside of Australia.

Seismic moment tensor (MT) solutions for events around Australia and local distances are useful for both warning systems and geophysical studies in general. These monitoring systems, however, currently use only one dimensional, spherically-symmetric models of the Earth for source parameter determination. Recently, a novel 3D model of Australia and the surrounding area has been developed from spectral element simulations, taking into account not only velocity heterogeneities, but also radial anisotropy and seismic attenuation. This development, *inter alia*, introduces the potential of providing significant improvements in MT solution accuracy. Allowing reliable MT solutions with reduced dependence on non-GA stations is a secondary advantage.

We studied the feasibility of using 1D versus 3D structural models. The accuracy of the 3D model has been investigated, confirming that these models are in most cases superior to the 1D models. A full MT inversion method using a point source approximation was developed as the first step, keeping in mind that for more complex source time functions, a finite source inversion will be needed. Synthetic experiments have been performed with random noise added to the signal to test the code in the both 1D and 3D setting, using a

precomputed library of structural Green's functions. Implementation of this 3D model will improve warning systems, and we present results that are an important step towards automated MT inversion in Australia.

LIFE AND THE SOLAR SYSTEM

The geochemistry of volcanic and impact glasses from the Taurus-Littrow Valley on the Moon

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The petrography and geochemistry of glass particles from the lunar regolith at the Apollo 17 site have been investigated. A principal challenge in this type of study is distinguishing volcanic from impact-produced glasses, and relating these glasses to parent rocks and magmas.

Spherules are tiny (25 µm -25 mm) particles of glass formed by rapid quenching of silicate melt produced during meteorite impacts or volcanic eruptions. On the Earth, tektites are silicate glasses survive for tens of millions of years at the surface of the Earth. On the anhydrous Moon, however, these glasses can be preserved for billions of years. Impact spherules can record the compositions of the target rocks, even when transported over distances of 10s or 100s of km. This makes them useful for obtaining a representative overview of the lithological diversity surrounding the immediate sampling region, possibly including rock types that were not collected during the Apollo expedition.

A number of physical and chemical differences help to distinguish impact-produced spherules from volcanic glasses. Volcanic glasses may show dendritic crystals that grew during quenching after eruption in a homogeneous matrix with no vesicles or metal blebs. Impact-produced melt droplets can be internally heterogeneous, with fractured and partially melted mineral grain remnants, and their major element compositions reflect mixtures of the target rocks rather than primary igneous compositions.

About 300 spherules were separated from a 1g sample of lunar soil that was collected from the Sculptured Hills, Taurus-Littrow region by the Apollo 17 astronauts. These spherules have been subdivided into 18 groups by size, density, magnetic properties, colour and shape. Major element analyses of impact spherules have shown distinct end-member characteristics of highland samples (high Ca and Al), mare compositions and intermediate compositions reflecting mixtures of highland and mare materials. Highland mixing components were dominantly troctolite and norite, suggesting that anorthosite is genuinely uncommon in the Taurus-Littrow area. Major and trace element compositions of volcanic spherules were used to investigate the petrogenesis of mare magmas erupted in this region of the Moon, and indicate that some melts may have been derived from previously unreported mantle cumulate types.

A search for evidence of volcano–ice interactions in Amenthes, eastern hemisphere, Mars

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Sub-ice volcanic activity is common in high-latitude geologically active regions. Iceland, Antarctica (e.g., Corr and Vaughan, 2008) and British Columbia have many instances of current and past sub-ice volcanic activity. Typical morphologies and lithologies produced by volcano-ice interaction are: tuyas, volcanic constructs characterised by flat tops and steep flanks; moberg ridges, formed by fissural sub-ice volcanism; tindars, tephra piles deposited when the heat from the volcanic activity melts the ice, and fragments of lava are extruded in the resulting melt-water lake. These provide evidence of past sub-ice volcanic processes after volcanic activity ceases and ice sheets or glaciers retreat.

Morphological and lithological evidence is particularly important in the study of past Martian environments and geological processes. Apart from selected and areally limited locations directly studied by landers, the geologic, volcanic, tectonic and environmental evolution of Mars can be investigated only by remote sensing

data collected from orbiters. High-resolution imagery and digital terrain models are particularly suited for the description and analysis of surface features. Of critical importance are the description, analysis, and interpretation of the morphologies of the sub-equatorial regions north of the crustal dichotomy. The northern hemisphere has been postulated to have hosted an ancient ocean (Baker, 2001, and refs. therein), possibly frozen totally or in part. In this scenario the crustal dichotomy scarp represents the boundary of the ocean. Accordingly, evidence of coastline environments, such as shores, lagoons, erosional and depositional features, should be found along the northern boundary of the dichotomy. The data currently available are not sufficiently unequivocal to reach such a conclusion. In the absence of direct evidence for coastlines or lake-shores, the identification of morphologies typical of volcanic activity in water or under ice informs research on the locations of martian paleolakes or of the putative northern hemisphere paleo-ocean (e.g., Chapman, 1994, 2002; Chapman et al., 2003; Chapman and Tanaka, 2001).

Here we present the preliminary results of our investigation of the area of coordinates: 110–121˚E; 0–13˚N where we are searching for morphological evidence of sub-ice volcanism. The study area is in Amenthes, a sub-equatorial region in the eastern hemisphere, immediately west of Nepenthes, where a comprehensive geological study has already identified morphologies typical of volcano-ice interaction (de Pablo and Caprarelli, 2010), and is located north of the Amenthes – Tyrrhena Terra region, already investigated by this group (Caprarelli et al., 2007). We collected and processed: (1) Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) Mission Experiment Gridded Data Record (MEGDR)—resolution 128 pixel/deg (463 m/pixel); (2) MGS Mars Orbiter Camera narrow angle (MOC-NA) imagery—resolution 1–5 m/pixel; (3) Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS) daytime infrared BTR (band 9) and night-time infrared data—resolution 100 m/pixel; (4) Mars Express (MEX) High Resolution Stereo Camera (HRSC) imagery—resolution 10–25 m/pixel, and altimetry—resolution 100 m/pixel. We used ArcGIS to map and analyse the datasets.

The area is highly eroded, and this makes unequivocal identification of geological features very difficult based on morphology alone. However some enigmatic forms appear similar to the moberg ridges already identified in Nepenthes (de Pablo and Caprarelli, 2010), and some resemble tindars. We continue our investigation of the study area, and plan to further our understanding of putative volcano-ice interaction processes on Mars by conducting a detailed geological study that will set the context for unambiguous interpretation of enigmatic morphologies.

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Evolution of the stoichiometry of the essential elements of life

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One way of answering the question ‘What is life?’ is to consider the ingredients of life in terms of chemical elements. We present abundances in life (as represented by humans and bacteria) for 25 of the most abundant stable elements in nature, including major elements such as carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus and trace elements such as sodium, potassium, calcium, magnesium, iron and copper.

Life may have begun with a basic set of elements and then progressively increased its elemental ‘toolkit’. Initially, life may have been based on abundant elements like carbon, hydrogen and oxygen and ions like calcium or magnesium to stabilise its structures, and catalytic metals like iron.

Significant changes in the bioavailability of elements such as iron, copper and zinc in environments such as the oceans were linked to the rise in atmospheric O_2 concentration. If the concentration or bioavailability of a metal used by life decreased in the environment such that an alternative metal became more competitive in terms of bioavailability, reaction rate or reaction efficiency, then life may have co-opted the alternative metal in a modified metabolic pathway.

These changes may have triggered the development of new metabolic pathways which harnessed copper and zinc for roles previously performed by iron, and over time led to increased elemental diversity in the composition of life.

Genetic and proteomic conservation translates to conservation of metabolic pathways to varying degrees across taxa. It follows that the stoichiometry of elements that make up proteins in metabolic pathways will be conserved to varying degrees across taxa such as Bacteria and Eukarya. It may be possible to use stoichiometric and phylogenetic relationships between taxa to investigate how changes in the distribution of elements in environments such as the oceans, may have affected the evolution of life over the past ~4 billion years.

Solar wind exposure effects on lunar metal grains

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The lunar surface is continually bombarded by solar wind. The velocity of the solar wind is typically 400 km/s and so atoms from the Sun are implanted below the sample surface. Lunar soil is a valuable resource for attempting to understand isotopic compositions of elements in the Sun. The issue is to obtain mineralogical samples free of the elements of interest. Our main focus is on the isotope signature of implanted oxygen ions in the surface of lunar grains, predominantly metal spherules. While silicates can be used to constrain C and N isotopic compositions, metals have been used to look for solar oxygen because of the low inherent oxygen content of metal. The surface of lunar soil grains can be analysed in SHRIMP to determine the distribution and isotopic composition of included oxygen. Oxygen isotopic compositions in the solar system are highly variable. The rocky planetary bodies (including Earth, Mars, and asteroidal parent bodies) lie within 5‰ of the terrestrial fractionation line (-5‰ < $\Delta^{17}O$ < +5‰ where $\Delta^{17}O = \delta^{17}O - 0.52 * \delta^{18}O$). However refractory inclusions, often inferred to represent solar condensates, have ^{16}O excesses up to +60‰. At the other extreme, matrix oxides in Acfer 094 show ^{17}O and ^{18}O excesses of up to +180‰.

Previous analyses on solar wind implantation show very different results and interpretations. Hashizume and Chaussidon (2005) analysed metals and sulphides from an ancient (2Ga) regolith breccia (79035). The composition of oxygen deepest in the grains appears enriched in ^{16}O ($\Delta^{17}O$ < -20±4‰; $\delta^{17}O \approx \delta^{18}O \leq$ -40±8‰) and on the basis of the concentration they proposed that this was solar-wind oxygen. Ireland et al. (2006) on the other hand also found anomalous oxygen (in a recent regolith soil 10084), but found a composition strongly enriched in ^{17}O and ^{18}O with $\Delta^{17}O$ = +25.6±3.2‰ ($\delta^{17}O = \delta^{18}O$ = +50‰). Recently, Hashizume and Chaussidon (2009) also found the heavy component implanted in metal grains from a young soil (71501). Preliminary results from the Genesis mission now indicate that the Sun is enriched in ^{16}O (McKeegan et al., 2008) with $\delta^{17}O \approx \delta^{18}O \approx$ -60‰. However this specific composition has not been detected in any samples from the Moon so far. The question is therefore why this component is not observed on the Moon despite the continuous bombardment of the solar wind.

While lunar soils are a valuable source of information on solar wind implantation processes, there are, however, several fundamental questions still unsolved and various processes still insufficiently understood. The wide range of isotopic compositions of some elements in individual soils, specifically for oxygen and nitrogen, reinforces the need for more analyses on individual lunar grains but with measuring a combination of elements to individually correlate the data for each grain. A new generation of SHRIMP, optimised for stable light isotopes (SHRIMP SI), will be used to characterise the isotopic composition of oxygen, nitrogen and carbon implanted on the surfaces of individual grains. These will be coupled with He and Ne isotope analyses by Noble Gas Mass Spectrometry at RSES to provide data on single grains for correlation of measured abundances and isotopes to characterise the composition of the solar wind.

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Provenance and age distribution of lunar impact spherules from Apollo 16: integration of major and trace element chemistry and $^{40}Ar/^{39}Ar$ ages

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Lunar Impact Spherules are micron to centimetre glass particles formed during impact events where shock induced melting of the lunar regolith and impactor produce melt splashes that can be deposited locally or be ejected far beyond the point of impact. The chemical characteristics of impact spherules are extensively studied and are known to predominantly represent the bulk regolith from which they were formed. These spherules are common in the lunar regolith making them ideal recorders of particle transport and impact history. However, their small size limits our ability to analyse and evaluate any biases in the impact history as recorded by the impact spherules. This study aims to address these issues by integrating major and trace element chemistry and radioisotopic ages on individual impact spherules.

We separated and described 272 spherules >75µm in diameter from an Apollo 16 soil (66031,65). Using a new mounting technique we described the petrography and collected major element chemistry using electron microprobe. Trace element compositions of a subset of 134 lunar impact spherules were collected using laser ablation-ICPMS. From this population, a further thirty spherules were selected for $^{40}Ar/^{39}Ar$ dating. Twenty-seven of the dated spherules are derived from local soil based on the major and trace element compositions and the remainder have compositions exotic to the Apollo 16 landing site. Twenty-two of the dated spherules gave statistically acceptable $^{40}Ar/^{39}Ar$ isochrons and plateaus. One spherule only gave a single fusion age, two others contain very low amounts of radiogenic $^{40}Ar^*$ and are inferred to be young. This data has allowed us to develop the first age distribution for local impact spherules at the Apollo 16 site complementing previous work at Apollo 12 and 14. The lunar impact spherule age distribution shows a peak in impact spherule formation in the 0–400Ma bin, consistent with the distribution at Apollo 12. An older peak in activity is seen between 3.2Ga and 4.4Ga consistent with the Apollo 14 record. In general the age distributions from Apollo 12, 14 and 16 show a ‘U’ shaped distribution for impact spherule production broadly similar to H-chondrite age distribution. However, the magnitude and peak locations in the impact spherule records can vary due to various collection and sampling biases unique to the site. Cosmic exposure ages obtained on 13 impact spherules indicate that spherules <500Ma old have spent most of their time within the top metre of regolith. Older impact spherules, however, have spent less than 25% of their time exposed. Since the older spherules were collected from the near surface, they must either have been evacuated and undisturbed until collection or undergone rapid overturning to depths greater than a metre.

To address potential biases we have developed our method to allow us to link the major and trace element chemistry directly to the age of individual impact spherules. In the previous Apollo 12 and 14 studies, major element compositions were only used to identify and remove any non-impact (i.e. volcanic) glasses. The major elements could also be used to determine the provenance of impact spherules though was neglected in the previous studies. As such the contribution of local vs. exotic impact spherules in the Apollo 12 and 14 impact age distribution is unknown. Later studies on impact spherules recovered at, but exotic to, Apollo 16 have integrated the major element compositions though determination of spherule provenance is limited to the broadly defined major element compositions of the various lunar terrains (highlands, mare and, KREEP) or compositional groupings. The addition of trace element compositions in our approach allows for more confident determination of impact spherule provenance. More importantly, our approach allows the recognition of impact spherules that may have been produced from the same impact. A multi-spherule impact event can produce a number of impact spherules with identical chemistry that if counted twice could

artificially inflate the age distribution. Our results indicate that the 25 spherules dated may only record 13–17 unique impact events depending on our use of major or trace element indices and on how conservative we are with error estimates. Although we can identify potentially duplicate impact spherules, we caution against removing them as closely spaced impact events in a region with soils similar in major and trace element chemistry can produce spherules that cluster like multi-spherule events.

Identification of carotenoid breakdown products in the 1.64 Ga Barney Creek formation, McArthur Basin, northern Australia

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Microbial communities are often highly pigmented due to organic compounds known as carotenoids. All photosynthesising organisms utilise carotenoids as accessory pigments in various stages of photosynthesis. In order to study the occurrence of carotenoids in the geological record as molecular fossils (biomarkers), the effect of burial and heat on their molecular structure must first be determined. Burial diagenesis reduces functionalised and unsaturated organic molecules to their saturated hydrocarbon equivalents. However, compounds that undergo diagenesis often retain structural information about their biological precursors and may contain information about depositional environment and biological communities. Biomarkers are ideal for the investigation of life in the Precambrian where body fossils are often poorly preserved and not informative.

Carotenoids are often difficult to study in the geological record because of their low preservation potential. Preservation of the hydrocarbon equivalents of carotenoid molecules is rare due to their tendency to break into smaller units or undergo complex aromatisation and rearrangement reactions, e.g. [1]. Generally, biomarkers are only preserved under specific conditions, for instance in reducing, low energy environments where oxidation and recycling by microorganisms is less severe. In rare instances where intact C_{40} carotenoid hydrocarbons are preserved by suitable diagenetic conditions, they are often subsequently cleaved into smaller fragments by increasing temperatures during burial of the host sediment (catagenesis). Catagenesis can be simulated in the laboratory using a method called hydrous pyrolysis [2], which involves heating organic matter submerged in water in a sealed vessel for several days.

The aim of this study was to synthesise a standard to investigate the thermal breakdown of the C_{40} carotenoid hydrocarbon, β-carotane from precursor β-carotene, as it would occur in nature. This experimental investigation involved pyrolysing β-carotane in a sealed quartz vessel under a cold-seal pressure apparatus. The ideal conditions that generated systematic cleavage products of β-carotane were determined to be heating β-carotane for 1 day at 360°C under hydrous conditions.

To validate the standard that we synthesised, we looked for the occurrence of these β-carotane breakdown products in the 1.64 billion-year-old (Ga) shales from the Glyde River (GR-7) drill core of the Barney Creek Formation (BCF) in the McArthur Basin, Northern Australia. β-Carotane had previously been reported from the BCF [3], and a comparison of BCF mass chromatograms with the pyrolysis standard demonstrated that a full series of β-carotane breakdown products are also present. These results confirm that our pyrolysis experiments adequately simulate the breakdown of carotenoids under geological conditions.

To apply the carotenoid breakdown products standard to a new system, we analysed yet older and more mature samples from the BCF where intact β-carotane was not present. We were able to detect a partial series of β-carotane breakdown products representing the oldest evidence for saturated carotenoids in the geological record.

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Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) mapping of olivine trace element distribution in the pallasite meteorite Brahin

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Pallasites are stony-iron meteorites derived from proto-planetary or asteroidal sources. They are predominantly composed of large olivine xenocrysts (100*Mg/[Mg+Fe] = 80–89) in a groundmass of Fe, Ni metal. Their dual mineralogy represents two geochemical reservoirs: that of a silicate mantle and a metallic core, possibly formed during magmatic intrusion or a violent event such as a collision between two proto-planets. Oxygen isotopes and trace element systematics reveal that pallasites come from at least three different parent bodies, implying that their formation is reasonably common and may have some consequences for the evolution of larger terrestrial-style rocky planets.

Unfortunately the mineralogy provides a challenge to analytical techniques; the nearly sole silicate mineral, olivine, does not readily accommodate much in the way of diagnostic trace, radioactive or rare earth elements, making it difficult to derive information about the silicate portions of pallasite parent bodies. Nevertheless, considerable effort has been made to determine the abundances and spatial distributions of trace elements in pallasite olivine, with many (Al, Ca, Ti, V, Cr, Co, Ni) found to show decreasing abundances within 100 microns of crystal rims. This feature is commonly interpreted as a diffusion profile formed during cooling, consistent with the morphologies of pallasite olivine which indicate that annealing occurred. Al, Ti and Cr have previously been found to have correlated abundances in the interiors of pallasite olivine; diffusion profiles are apparently superimposed on these structures.

To improve the understanding of the spatial distribution of trace elements in pallasites, we have developed a LA-ICP-MS routine to analyse materials across a surface, allowing maps of elemental distribution at the sub-1 part per million level. Regions (~200 x 200 microns) of olivine xenocrysts in the Brahin main-group pallasite have been mapped using this approach. We have successfully imaged the diffusion profiles near the rims and the correlated structure in Al, Ti and Cr, which is anti-correlated (though poorly) with P. These structures are not parallel to crystal margins and are not linear; rather they are sub-circular in shape and are unlikely to represent igneous zoning or microfractures.

Pyrite-munching microbes in the Early Archean

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The earliest stages in the evolution of iron- and sulphur-oxidising microorganisms are not well understood but are important because of the key role such microbes play in the cycling of two of Earth's most important elements.

Iron and sulphur are two of the most prevalent redox-active elements in the biosphere, and their reactions are often coupled to the cycling of carbon, nitrogen and oxygen. A diverse group of microbial metabolisms are associated with iron and sulphur redox reactions in modern environments. However, only a limited amount of information is currently available regarding when these metabolisms first arose on Earth, and their subsequent effects on the evolution of early Earth environments.

Sedimentary pyrite (FeS_2) grains are ubiquitous throughout geological time and thus provide a potential mechanism to trace the evolution of iron- and sulphur-oxidising microbes. In natural environments on the modern Earth, pyrite oxidation results from exposure to oxygen, ferric ions and water, catalysed by iron- and sulphur-oxidising microorganisms, and commonly has the unfortunate consequence of producing acid mine drainage. In the early Archean, where oxygen levels are thought to have been less than ~10^{-5} of the present atmospheric level, biology may have been the essential driving force for pyrite oxidation.

Here, we use a combination of high-resolution instrumentation (NanoSIMS, Laser Raman, Focused Ion Beam sample preparation and TEM) to show that detrital sedimentary pyrite grains in a 3.4 billion-year-old sandstone from Western Australia were colonised by microbial communities.

The pyrite grains exhibit carbonaceous coatings with localised nitrogen, which we interpret as the *in situ* remains of biofilms growing on these nutrient-rich minerals. Microbial trace-fossils demonstrate the attachment of bacteria to the pyrite surfaces. These are widespread, have a clustered distribution typical of microbial colonisation, and are comparable to microstructures in the younger rock record and those created by extant iron- and sulphur-oxidising microbes. Nano-grains of iron oxide are abundant within the biofilms and are interpreted as the fossilised mineral products of the iron-oxidising metabolism. A UV-protection mechanism for these microbes, analogous to that employed by some modern bacteria, is suggested by the presence of thin iron-silicate coatings around the microbes. These data provide evidence for reduced forms of iron and sulphur acting as electron donors for microbial reactions on the early Earth.

SIMS and TEM: complementary techniques to study stromatolites and early life on Earth

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Evidence for early life on Earth is extremely difficult to constrain. We now know that while morphology and geological context are vitally important tools, they are not always sufficient to establish biogenicity because many inorganic processes can give rise to similar features. Geochemical data [e.g., micro- to nano-scale elemental distributions, elemental ratios, carbon- and sulphur-isotopes], provide an extra level of information that may indicate specific biological metabolisms on the early Earth. Until recently, however, a major stumbling block was the inability to obtain the spatial resolution required to accurately characterise individual micron-sized features.

Here we demonstrate the use of two complementary techniques [Nano-scale secondary ion mass spectrometry (NanoSIMS) and Transmission electron microscopy (TEM)] for investigating the biogenicity of Precambrian micro-fossils, trace fossils, putative biominerals and stromatolites ranging in age from <600 Ma to almost 3,500 Ma. With respect to stromatolites, we will also present data from modern analogues from Western Australia that help to constrain the preservation potential of biosignals in these structures.

NanoSIMS data includes chemical maps and carbon and sulphur isotopic analyses measured *in situ* at the sub-micron scale, and we discuss the protocol for obtaining SIMS elemental ratios (e.g., N/C). TEM imaging and spectroscopy (EELS and EDS) data helps to elucidate the structure of carbonaceous material, in terms of aliphaticity and aromaticity, the functional groups present, and degree of ordering. TEM data also includes elemental distributions on the nano-scale across boundaries between the putative biological structures and their mineral hosts, and oxidation and co-ordination states of e.g. iron in the vicinity of these structures.

RESOURCE SECURITY: SUPPORTING THE NATION

Will my hydrangeas be pink or blue? Field pH and soil colour results from the National Geochemical Survey of Australia

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National geochemical surveys have been carried out in many countries around the world to provide important information on the natural concentration of chemical elements and compounds in the near-surface regolith. In 2007, following on from the success of several regional geochemical pilot projects, Geoscience Australia established Australia's first nation-wide geochemical survey, the National Geochemical Survey of Australia (NGSA). The primary aim of the NGSA is to provide pre-competitive data and knowledge to support exploration for energy resources in Australia. In particular, it will improve the existing knowledge of the concentrations and distributions of energy-related elements such as uranium and thorium at the national scale. Resultant data and information layers will also potentially be used to identify targets for mineral exploration, improve land-use management and environmental policy development, and provide information for studies into the health and well-being of humans, animals and plants.

Working in collaboration with State and Territory geoscience agencies, ultra low-density sampling of catchment outlet (overbank) sediments was carried out from mid-2007 to late 2009. Two samples were collected at each site: a near-surface sample (Top Outlet Sediment, TOS, from 0–10 cm) and a deeper sample (Bottom Outlet Sediment, BOS, from a ~10 cm interval approximately 60–90 cm below the surface). At each locality a detailed site description, field pH, and dry and moist Munsell® soil colours were recorded for bulk samples and several digital photographs were taken. At the completion of the sampling period 1314 sites, or 86% of the 1530 target sites, had been sampled.

Sent back to Geoscience Australia for processing, all samples were dried and a portion of the bulk sample was archived. Samples were then riffle split and dry sieved into <2 mm and <75 µm fractions before being analysed using a wide range of analytical techniques including XRF and ICP-MS. Samples are also currently being analysed for electrical conductivity (EC) of 1:5 (soil:water) slurries, pH 1:5; and the colour will again be recorded while bulk samples are subjected to laser particle size analysis. Sample analysis will conclude in mid-2010; to date over 50% of samples have been completely analysed.

Sampling error is commonly the largest source of uncertainty in any geochemical survey. Ten per cent (10%) of all sites were sampled twice, providing field duplicates. Duplicates samples were collected approximately 100 metres up the catchment from the first sample and were re-sampled using exactly the same procedures.

Using the first complete datasets available for the NGSA, those of field pH and soil colour, maps of point data along with mosaic maps of soil pH and colour have been created. Sample sites were selected to be near outlets or spill points of large catchments, so that overbank sediments there could reasonably be assumed to represent well-mixed, fine-grained composite samples of all major rock and soil types present in the catchment. This allows for the reasonable extrapolation of point data to the catchment scale when the data is mapped.

Mosaic maps demonstrate the variety of soil colours in Australia from the dark brown soils of the mountain ranges of eastern Australia, potentially rich in organic material, to the classic red soils of central Australia. While soils across Australia range from strongly alkaline (pH 10.5) to very strongly acid (pH 4), maps of soil pH highlight the strongly alkaline soils of eastern South Australia and illustrate that in many parts of Australia BOS samples are often more alkaline than TOS samples. This trend may reflect the removal of elements from surface soil either by biological uptake or leaching into deeper soil horizons.

National maps of TOS and BOS soil pH will be the first in a series of geochemical maps that will be released by the NGSA. These maps are a precursor for the National Geochemical Atlas of Australia that will be generated by the NGSA and released along with the geochemical dataset in June 2011.

Data acquisition, processing, interpretation and data delivery from the Pine Creek airborne electromagnetic survey, Northern Territory

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The Pine Creek AEM survey was flown over the Pine Creek Orogen in the Northern Territory during 2008 and 2009 as part of the Australian Government's Onshore Energy Security Program at Geoscience Australia (GA). The survey provides pre-competitive data for enhancing uranium and other mineral exploration. Flight lines were spaced at 1666 m and 5000 m covering an area of 74,000 km^2 (roughly the size of Tasmania) which hosts several uranium deposits, including the Ranger Uranium Mine, Rum Jungle and Nabarlek. The region is also prospective for metals including copper, lead, zinc, gold, tin, rare earths, tantalum, tungsten, molybdenum and nickel.

The Pine Creek AEM survey comprises three areas: Kombolgie to the east of Kakadu National Park; Woolner Granite near Darwin; and, Rum Jungle to the west of Kakadu National Park. Collaboration with the National Water Commission and eight private infill companies brought an additional investment of approximately $1 million into the survey, with follow-up exploration equal to or exceeding this amount.

Data in the Woolner Granite and Rum Jungle survey areas were acquired using the TEMPEST fixed wing AEM system. The acquisition and processing were carried out by Fugro Airborne Surveys Pty. Ltd., under contract to

GA. The Woolner Granite and Rum Jungle surveys were flown between August 2008 and May 2009 and the data were publicly released by GA in July and September 2009, respectively.

In the Kombolgie survey area, the data were acquired by Geotech Airborne Pty. Ltd. using the VTEM helicopter AEM system. The survey was flown between August and November of 2008, and additional calibration flights relating to the survey were flown in April 2009. The Kombolgie data were publicly released by GA in December 2009.

The main aims of the Pine Creek AEM survey were to assess the potential for uranium mineralisation by mapping geological features including: the thickness of regolith and Paleozoic-Mesozoic-Cenozoic cover, the thickness of the Kombolgie subgroup cover, discrete EM conductors within the Pine Creek Orogen basement, faults and other fluid pathways in both the cover and Pine Creek Orogen sequences and sea water incursion into coastal aquifers. Preliminary interpretation results have improved mapping of geological units under-cover, and thus the understanding of the regional- and tenement-scale geology and prospectivity.

Potential uranium systems and their associated key geological units identified within the Pine Creek AEM survey area include:

- sandstone-hosted: roll-front or paleochannel styles within Permian, Mesozoic or Cenozoic sediments in paleovalleys or sediment sheets adjacent to U-rich granitoids for example the Waterhouse granites
- Proterozoic unconformity sedimentary-related: volcanic rock units forming the north-west edge of the Mesoproterozoic McArthur Basin unconformably overly the Pine Creek Orogen basement units
- Westmoreland-type: Oenpelli Dolerite dykes and sills intrude both the Pine Creek and McArthur Basin sequences; and
- vein-type: within the Palaeoproterozoic rocks of the Pine Creek Orogen.

Geoscience Australia's interpretation products will include sample-by-sample layered earth inversion products comprising located data, geo-located conductivity depth sections, depth slice grids, elevation slice grids and an inversion report. GA will also release an interpretation report highlighting the impact of the new data for uranium prospectivity and the use of regional AEM surveying to decrease exploration risk in the Pine Creek area.

SHRIMP U-Pb detrital zircon provenance of Cretaceous and Cenozoic sediments in the Lake Frome region: constraints on the architecture of sandstone-uranium systems

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Cenozoic basins in the Lake Frome region of South Australia host some of the largest sandstone-hosted uranium deposits in Australia. Mineralisation occurs in sediments of different ages: Four Mile East, Honeymoon and Goulds Dam in the Paleogene Eyre Formation; and Beverley in the Neogene Namba Formation. The possible poly-chronoic introduction of uranium-rich ground waters into sandy aquifers requires a favourable basin architecture permitting a fertile hydrodynamic regime. One of the critical elements of this architecture is the nature and location of the uplifted highland area which not only provided the necessary hydrostatic head to drive the fluids but may also have served as the uranium source (Skirrow, 2009).

Uranium in the paleochannel-hosted uranium systems of the southern Lake Frome region (e.g. Honeymoon, Goulds Dam, Oban), is interpreted to have been sourced from uranium-rich felsic rocks in the Curnamona Province. These sources may have also provided sediments to the extensive system of northward running paleochannels in the region. The situation in the northern Lake Frome region is less clear. Quigley et al. (2007) suggested that the present-day rugged relief of the northern Flinders Ranges formed in the last four million years, providing an important constraint on the age of the uranium systems in the northern Lake Frome region. However, paleo-landscape reconstruction undertaken by Dubieniecki and Hill (2007) showed that the area presently occupied by the northern Flinders Ranges supported moderate relief during deposition of Cretaceous and Paleogene sediments.

To better understand the tectonic development of the basin, SHRIMP U-Pb detrital zircon analyses were undertaken on the principal sedimentary units of the northern Lake Frome region. Results show that zircons analysed from a basal Cretaceous unit, the Eyre Formation and the lower Namba Formation are mostly ~1.58 Ga in age, similar to the ages of some igneous rocks in the nearby Mount Painter Inlier and Curnamona Province. These samples were collected from an exposed section along Four Mile Creek. In contrast the zircons obtained from drill-hole WC2 from the Beverley Sands (upper Namba Formation) range in age from ~2.70 Ga to ~100 Ma and are broadly similar to the LA-ICPMS U-Pb zircon results obtained by Wülser (2008). This sample lacks the conspicuous ~1.58 Ga population present in the older units investigated and is mostly comprised of Phanerozoic zircons ranging from ~470 to 100 Ma in age.

The zircons from the basal Cretaceous unit and the Eyre Formation are dominated (~85%) by euhedral ~1.58 Ga zircons, indicating that these units were probably deposited proximal to their likely Mount Painter Inlier or Curnamona Province source rocks. The zircons from the lower Namba Formation are sub-rounded to well rounded and although dominated by ~1.58 Ga zircons (~60%), also contain a wide range of Paleoproterozoic as well as late Archean grains, demonstrating a much wider range of sources. Given the long time period between deposition of the basal Cretaceous unit and the Eyre Formation, euhedral ~1.58 Ga zircons in these units probably represent first-cycle sediments derived from separate uplift and erosion events in the Mount Painter Inlier and/or Curnamona Province. If this is the case, the uplifted rocks of the northern Flinders Ranges could have served as sources of uranium as early as the Cretaceous, and later during other uplift events for example during the early Palaeogene when the Eyre Formation was deposited.

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Pyrite variation and radiogenic isotope geochemistry of datable minerals at Coronation Hill deposit, Northern Territory

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Coronation Hill is a rich multi-element deposit with U-Au and Pt/Pd hosted by the strike-slip South Alligator Fault system in the Northern Territory. It is near the margin of the McArthur Basin and shares similarities to unconformity U deposits found further north in the Alligator River area, including Ranger, Narbalek, Jabiluka and Koongarra. U-Pb and Sm-Nd geochronology of samples from these deposits indicates that U mineralisation post-dated the host basement succession as well as the overlying Kombolgie Sandstone. Although some geochronology was undertaken at prospects within the South Alligator Valley close to Coronation Hill none has been carried out on samples from Coronation Hill.

As part of this study Zircon Laser ICPMS U-Pb geochronology was performed on samples from with the deposit but the ages scattered widely due to extensive Pb loss in metamict zircons. The best result was obtained from low U zircons in the overlying Capping Sandstone. Most of the analyses plotted close to concordia although some seem to be slightly reversely discordant. This meant that the 207Pb/206Pb ages of the youngest 22 zircons (1853±16Ma) were slightly younger than the 206Pb/238U ages (1869±13).

In a high Au, PGE and uranium zone within the deposit, breccia fragments are surrounded by successive zones of illite, uraninite, quartz and infilled by late pyrite. Element mapping of these pyrite crystals by laser ICP-MS indicates that growth zones with elevated Ni and Co occur in these crystals. The zones elevated in Ni and Co are also elevated in Ag, As, Au, Bi, Cu, Hg, Pb, Sb and Se. Late galena post-dates the pyrite. Pb isotope ratios from these minerals indicate the presence of radiogenic Pb. Direct Pb isotope dating of the uraninite gave young 207Pb/206Pb ages of 1261±20 Ma assuming extensive Pb loss continuing to recent times. If we assume that this Pb was lost at some time in the past this age would increase considerably. The radiogenic Pb loss from uraninite is accompanied by the incorporation of radiogenic Pb in the later sulphides. Some uraninite with

textures suggesting late stage recrystalisation returned more concordant data with 207Pb/206Pb at 446±42 Ma.

Elsewhere in this deposit altered diorite contains pyrite with non radiogenic Pb with high 206Pb/204Pb ratios suggesting formation around 1800 Ma. The rims and a network of fractures in this pyrite crystal contains much more radiogenic Pb suggesting extensive remobilisation of radiogenic Pb by late stage thermal or tectonic events. Areas containing the late radiogenic Pb also contain elevated Au, Ag, Bi, Co, Cu, Hg, Mn, Ni, U and Zn.

Deep in the deposit, gold is associated with clausthalite (PbSe) and isomertiete (PdAsSb). The Pb isotope in the clausthalite is highly radiogenic (207Pb/206Pb=0.4) suggesting a mixture between 40% common Pb and 60% radiogenic Pb. The 207Pb/206Pb ratio of the radiogenic component after correcting for common Pb (204Pb method) indicates that the Pb evolved at some time between 1400–2000 Ma.

Conclusions

A protracted paragenesis is apparent at Coronation Hill with early pyrite forming after the intrusion of diorites in the area. The U mineralisation is older than the 1200–900 Ma suggested in the past and similar to the uraninite at El Sherana and the age of Umineralisation at Narbalek and Jabiluka. Once uranium entered the system it provided radiogenic Pb which was incorporated into many later minerals including pyrite, Ni-Co pyrite, galena and the selenide clausthalite associated with platinum minerals and gold. New uraninite crystals formed within the deposit in response to overprinting events.

Mineral potential mapping in a frontier region—a case study from Mongolia

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GIS-based mineral potential mapping permits fast and efficient evaluation of spatial geoscience data and allows delineation of areas which may be prospective for hosting mineral deposits. However, target generation in frontier regions using GIS-based mineral potential mapping introduces many challenges. Data tends to be of poor or questionable quality, is often not digitised, may exhibit incomplete coverage, or may be unavailable entirely. Additionally, a lack of knowledge about known deposits in the literature with which to derive models or train data sets may further hinder any analysis. Such issues are not limited to frontier regions, but they are compounded by having multiple flaws within an individual dataset (something less common in well-explored, data-rich areas), which can permeate though the analysis.

Both data-driven and knowledge-driven mineral potential mapping techniques have been used to overcome these challenges in order to produce country-scale mineral potential maps for orogenic gold deposit target generation in Mongolia. The success of these mineral potential maps is measured by their ability to predict known deposits, which allows for validation of the results. Commonly applied methods for mineral potential mapping include weights of evidence, fuzzy logic and probabilistic neural networks. This study was focused on the use of weights of evidence due to its effectiveness in dealing with incomplete datasets.

Weights of evidence is a data-driven method that requires training data (mineral deposits) and evidential layers (geological features) to produce mineral potential maps. The presence of logical inconsistencies in the data, which may be due to inaccurate training data or inaccurate data in the evidential layer, can be verified using statistical measures. Using an iterative weights of evidence process, expert geological knowledge can be used to exclude or modify datasets in further analysis which show such inconsistencies. Evidential layers which demonstrate strong spatial relationships with the training data, and which don't show inconsistencies, are then integrated into a mineral potential map using weights of evidence, which can then be verified by its ability to predict the location of known mineral deposits.

The mineral potential maps generated in this study were able to successfully predict the location of known orogenic gold deposits in Mongolia using an iterative weights of evidence method. However, the process highlights the need for good-quality, publicly available digital geoscience datasets, and access to such data in the future will allow for improved mineral potential maps and target generation.

The COGENT II Project: making precompetitive geoscience data accessible across New South Wales

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The Geological Survey of NSW (part of Industry and Investment NSW) manages government-acquired and exploration industry geoscience data. The COGENT II data management project will provide easy discovery and download of the best available geoscience data for New South Wales. This will aid our clients and staff to further understand the state's geological history, assess mineral and energy resource potential (minerals, coal, petroleum and geothermal), and aid decision making in land use planning. The COGENT II project commenced in late 2008 and will run through to June 2011. COGENT II is building on the original COGENT database project implemented in 2000. (COGENT is an acronym for COmmon Geoscientific EnvironmeNT).

The key aspects of the project are to: (1) consolidate our data holdings (minerals, coal and petroleum) to ensure up-to-date, consistent, quality assured records; (2) design work flows to ensure these data holdings are maintained at a high standard in the future; (3) redesign our data systems to improve our relational database management system to minimise data redundancy; and (4) provide our clients with a variety of options for data discovery and download from easily accessible platforms.

Data to be incorporated into the COGENT II environment includes mineral occurrence data, geological field observations and measurements, collar and down hole drilling data, geophysical data, and specialist analytical data such as isotopes, geochemistry and palaeontology. Geological vector data (e.g. geological unit boundaries, faults) will be stored in a revamped statewide geodatabase, allowing seamless coverage and derived layers for NSW. Common look up tables, complying with GeoSciML standards where appropriate, will be implemented across the COGENT II system.

Careful design of data discovery, access and download functionality will embrace new as well as existing technologies. Data from a SQL database and documents from the existing DIGS (digital imaging) system will be spatially locatable through an interactive web map similar to the existing MinView system, and non-spatial criteria entered on textual web-pages will allow further refinement of searches for data and documents. Data download functionality will also be incorporated into the internet access system. In addition, web delivery formats such as Web Feature Service and KML (Google Earth) will allow discovery of data in GIS and other client environments, as well as in non-proprietary applications such as Google Earth and via geoscience data portals (e.g. Geoscience Australia, AuScope).

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Carbon dioxide geological storage opportunities of the Gunnedah, Bowen, and Surat Basin areas in NSW—regional mapping

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Regional mapping is an essential component to determining the suitability of potential sites for geological storage of carbon dioxide (CO_2). As part of a larger project to evaluate the CO_2 storage potential of eastern Australian sedimentary basins, the Carbon-Dioxide Geological Storage Atlas of the Gunnedah Region in New South Wales (NSW), Australia has been developed using the ArcInfo Geographical Information System (GIS) and 3-D visualisation packages. The geological setting of the study area is dominated by two sedimentary basin provinces ie, the Permo-Triassic Gunnedah-Bowen Basin and the Jurassic-Cretaceous Surat Basin. The study area also includes parts of two major fold belt provinces, the Lachlan Fold Belt to the west and the New England Fold Belt to the east. These four provinces are intruded by younger igneous rocks and overlain by younger volcanic rocks, sedimentary rocks and unconsolidated alluvium.

The Atlas provides a graphic and mapping display that can assist in analysing the spatial characteristics of key geologic, physiographic, and anthropogenic factors affecting CO_2 storage opportunities in the study area. The aim of the Atlas is to build confidence with the data and to map, visualise and understand uncertainties and the potential risk associated with CO_2 storage and resource estimates. The Atlas also assesses the potential

impacts of CO_2 storage on land usage, distance to emission sources, interference with other resources (e.g. groundwater, hydrocarbon exploration, geothermal resources and coal mining, and potential social, technical and environmental risks, and does not assess economic suitability of potential storage sites.

The key layers mapped include: CO_2 industrial and natural sources, regional geology and depositional environment, existing energy resources, geothermal conditions, the CO_2 spatial density profile, hydrogeology, infrastructure and socio-economic factors. A series of maps were created to make a high level, qualitative, and illustrative attempt to identify those areas where there are social and environmental sensitivities that may affect the approvals process for carbon storage projects.

An impact of surface geology, sediments thickness and geothermal conditions in the basin has been mapped and analysed in terms of its impact on CO_2 storage Performance and Risk. The map shows very large variations in the geothermal gradient from less than 25°C/km to local anomalies over 50°C/km. The significance of this is that temperature affects CO_2 density distribution in the basin and hence storage capacity. Limitations with the dataset, however, may affect the uncertainty of the interpretations.

Avoidance of high concentrations of carbon dioxide is a priority in delineating petroleum exploration and CO_2 storage targets. However, coal seams and natural gas accumulations in conventional reservoirs of the Gunnedah-Bowen Basin contain elevated levels of CO_2. The CO_2 concentrations are highly variable, ranging from pure methane to pure CO_2 over short distances. The high accumulation of CO_2 mapped in several exploration well testing in the study area provides some evidence that CO_2 has remained in place for thousands to millions of years with no evidence of leakage. The presence of naturally occurring CO_2 in the Gunnedah Basin demonstrates the efficacy of this basin for long-term storage of CO_2 but also indicates a decrease in the total pore volume of the basin, because some pores are already occupied by CO_2.

Finally, map layers were developed to show areas with potential for chemical reaction of CO_2 with minerals in mafic (basalt) and ultramafic (serpentinite) rocks. Mafic and ultramafic volcanic formations are a distinguishing feature of the region's geology, including large Early Permian basalt flows that form the basement to the sedimentary sequence and Tertiary volcanic rocks which form three spectacular mountain ranges. However, a systematic and quantitative evaluation of basalts as a potential geologic storage option has not yet been developed in Australia.

Data from the deep: new geological results from Geoscience Australia's marine survey of frontier basins, south-west Australian margin

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Under the Australian Government's Offshore Energy Security Program, Geoscience Australia conducted a marine reconnaissance survey (GA2476) from October 2008 to January 2009 using the German research vessel RV Sonne. The 90-day survey acquired geological and geophysical data over poorly known areas of the Zeewyck and Houtman sub-basins (Perth Basin), the southern Exmouth Sub-basin and Bernier Platform (southern parts of the Carnarvon Basin) and the Cuvier Plateau (also referred to as the Wallaby Plateau). Over the duration of the survey, a total of 229,000 km^2 of multi-beam sonar data and almost 25,000 line kilometres of gravity, magnetic and sub-bottom profiler data was collected. Sixty-eight sampling operations recovered rocks during the survey: 19 from the Zeewyck Sub-basin; 19 from the Houtman Sub-basin; 15 from the southern Exmouth Sub-basin; 13 over the Cuvier Plateau; and two from the Bernier Platform. Geological sampling operations were undertaken in water depths ranging from 1,000 to 5,000 m. Sites were selected mainly to recover rocks from the pre-breakup succession (Valanginian and older) in order to determine the synrift sedimentary rocks and to identify any potential source rocks. A number of dredges were also acquired to sample the post-breakup succession.

Geological targets were identified using a combination of pre-existing seismic lines, concurrently acquired seismic lines (Geoscience Australia survey 310) and simultaneously acquired swath bathymetry, sub-bottom profiler records and camera tows. In general, submarine canyons provided the best opportunity for sampling the pre-breakup sedimentary strata as they were deeply incised and had steep slopes. Other steep slopes were identified in scarps, ridges and peak features. Fifty-one dredge, 13 grab, three benthic sled and one box core haul/s recovered several hundred individual rock samples. These samples represent the first successful

recovery of rock dredges from the Houtman Sub-basin and supplement previous sparsely sampled rocks from the frontier Zeewyck Sub-basin, southern Exmouth Sub-basin, Bernier Platform and Cuvier Plateau. The rock hauls yielded a diverse range of rock lithologies including sandstone, claystone, siltstone, mudstones, limestone and minor basalt. Samples containing plant material and/or fossils were selected for biostratigraphic analysis (palynology, nannofossil, foraminiferal and macrofossil analyses). Potentially organic-rich samples were selected for geochemical analyses.

Initial micropalaeontological analyses of rock samples from the Houtman, Zeewyck and Exmouth sub-basins and the Bernier Platform have shown that most samples fall within two broad stratigraphic intervals: Lower Cretaceous strata and Middle Paleocene to Upper Eocene strata. Depositional environments derived from these analyses indicate a progression from terrestrial and restricted marine facies (Berriasian-Valanginian) to proximal shallow marine (Late Valanginian-Barremian) to open marine (Aptian-Albian) and distal open marine facies (Paleogene). Source rock assessment of 85 rock samples using Rock-Eval pyrolysis reveals that most are organically lean with three quarters showing Total Organic Carbon (TOC) below 1%. The hydrocarbon-generating potential of the samples with TOC > 1% is mostly for gas with only a few samples having limited liquids potential. The best potential source rocks are seen in five rock samples from the Exmouth Sub-basin, which are immature and show mixed oil and gas potential. The rock samples have been tied via seismic lines into the tectonostratigraphic framework for the frontier depocentres to help assess potential petroleum system elements. Basaltic rocks recovered from peak-shaped bathymetric features in the Houtman Sub-basin indicate that volcanism took place on this part of the Perth margin in the recent geological past. Several sampling stations indicate that the basinal succession of the Zeewyck, Houtman and Exmouth sub-basins extend further seaward than previously mapped.

The bulk of rock samples recovered across the Cuvier Plateau contain volcanic rocks that are consistent with the known extensive volcanism across this area. For the first time, terrestrial marine sedimentary rocks have been recovered from the south-western escarpment. These rocks, deposited in relatively shallow water environments, include fossiliferous claystones, quartz-dominated sandstones and siltstones. Preliminary palaeontological analyses have shown at least one sample is likely to be Upper Jurassic, making it the oldest known sedimentary sample from the Cuvier Plateau. Further analyses of the sedimentary rock samples from the Cuvier Plateau may provide evidence to support the presence of continental depocentres beneath parts of the Cuvier Plateau, whereas analysis of the various volcanic rocks are expected to yield further insights into the breakup, thermal and subsidence history of the south-west Australian margin.

Noble gases and halogens in metamorphic ore-forming environments

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Fluid inclusions sample crustal fluids from greater depths than can be achieved directly, and provide new information about the behaviour of noble gases in the crust. However, as few prior studies have reported the full suite of noble gases (He, Ne, Ar, Kr and Xe) in metamorphic fluids, an interpretive framework for understanding their behaviour in ~6–10 km deep ore-forming environments typical of gold-only and iron-oxide-copper-gold deposits is still being developed. Our work shows combined analysis of all the noble gases plus halogens (Cl, Br, I) provides information on all stages of the fluids history.

Noble gas isotopic ratios ($^{3}He/^{4}He$, $^{20}Ne/^{22}Ne$, $^{21}Ne/^{22}Ne$, $^{40}Ar/^{36}Ar$, $^{136}Xe/^{130}Xe$) and the halogens (Br/Cl, I/Cl) distinguish mantle, crust and hydrospheric fluid reservoirs and sources of salinity. The relative abundance of non-radiogenic isotopes (^{20}Ne, ^{36}Ar, ^{84}Kr, ^{130}Xe) together with their fluid concentration and $Cl/^{36}Ar$ ratios help constrain the extent of fluid-rock interaction. Despite partial rock-buffering, fluids commonly preserve noble gas mixing lines that are correlated with $Cl/^{36}Ar$ and noble gas concentration. This can allow the noble gas signature of the fluids source reservoir to be constrained even after significant overprinting. Radiogenic isotopes (^{4}He, $^{21}Ne^{*}$, $^{40}Ar^{*}$, $^{136}Xe^{*}$) have predictable relative abundances related to the crustal U, Th and K abundance, as a result, fractionation of these isotopes provides information on H_2O-CO_2 phase separation or fluid exsolution from silicate melts.

Regionally extensive late-orogenic Na-Ca alteration and related iron-oxide-copper-gold mineralisation in the northern part of the Eastern Fold Belt (Mt Isa Inlier) involved two fluid reservoirs: 1) basinal—metamorphic fluids and 2) magmatic fluids with variable XCO_2 and salinity. Magmatic fluids (H_2O and CO_2) contain a mixture of mantle and crustal Ne giving signatures that are comparable with Nd-model ages of ~2200 Ma obtained for

the ~1500–1550 Ma Williams-Naraku Batholiths. Therefore, CO_2 could have been introduced by mantle melts, if they first mixed with crustal melts older than ~2200 Ma. The CO_2 $^{21}Ne^*/^{136}Xe^*$ value is close to the production ratio suggesting that much of the CO_2 was introduced independently of H_2O. Fluid inclusion density variations suggest pressure fluctuations of ~2 Kbar related to magmatic first boiling and regional brecciation. Brecciation generated pathways for basinal- metamorphic fluids to penetrate to depths of ~10 km and the highest salinity fluids were generated by scapolite breakdown. In contrast, deposits in the southern part of the Fold Belt (e.g. Osborne) are dominated by basinal—metamorphic fluid inclusions only and predate magmatism.

Gold-related H_2O-CO_2 and CH_4 fluid inclusions in the Yilgarn Terrane have distinct isotope signatures that require independent sources. H_2O-CO_2 fluids are characterised by mixed air-crust-mantle neon and crustal $^3He/^4He$ of <0.01 Ra. The CH_4 has an unusually radiogenic noble gas signature ($^3He/^4He$ <0.02 Ra; $^{40}Ar/^{36}Ar$ = 50,000 and $^{21}Ne/^{22}Ne$ = 0.55) and a mantle-like halogen signature diagnostic of ultramafic crustal rocks. The H_2O-CO_2 and CH_4 fluids are depleted in ^4He relative to $^{21}Ne^*$ demonstrating He-Ne decoupling which could be explained if the fluids were exsolved from variably differentiated silicate melts. A magmatic CH_4 source is also suggested by its high $Cl/^{36}Ar$ ratio and low ^{36}Ar concentration. H_2O-CO_2 fluids are enriched in $^{21}Ne^* > ^{40}Ar^* > ^{136}Xe^*$ by a greater extent than CH_4 which indicates preferential trapping of the volatile phase and suggests limited interaction of CH_4 and H_2O during fluid migration. The fluids acquired atmospheric noble gases by interaction with the greenstone host rocks, however, a basinal component could also be present.

The data from both Mt Isa and the Yilgarn provide evidence for involvement of magmatic heat and/or volatiles during regional scale metamorphic processes. However, the noble gas data do not favour the direct involvement of mantle volatiles in hydrothermal mineralisation.

The use of water bore cuttings in phosphate exploration, Georgina, Wiso and Daly basins, Northern Territory, Australia

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Middle Cambrian shallow-marine sedimentary rocks include a significant phosphogenic interval that hosts all the major phosphate deposits of Australia, including Duchess, Phosphate Hill, Lady Annie and D Tree in Queensland, and Wonarah, Alexandria, Alroy and Highland Plains in the Northern Territory. In the central Northern Territory, these rocks extend over about 360 000 km^2 of the Georgina, Wiso and Daly basins. Most phosphate accumulations are located along basement highs and palaeoshorelines relative to the deeper parts of the basins. In the last decade, the Northern Territory Geological Survey (NTGS) has flown high-definition magnetic and radiometric surveys over the Georgina and Wiso basins, and has also conducted a helicopter-borne regional gravity survey of the central Georgina Basin. Data from these surveys can be modelled to configure the basement architecture, so as to better define phosphate-prospective terranes.

More than 4000 reverse circulation (RC) water bores have been drilled in these basins and rock chip samples from about a third of these holes are stored at NTGS. An NTGS study (Khan *et al* 2007) conducted relatively inexpensive, qualitative phosphate testing on rock chip samples from water bores in the Georgina, Wiso and Daly basins. The work program targeted holes located within 100 km of the Alice Springs–Darwin railway line, together with selected holes from further afield. Cuttings from 214 water bores were logged and tested for phosphate, using an ammonium molybdate reagent. In all, a total of 5350 samples, each denoting a 3 m depth interval, were subjected to qualitative testing followed by quantitative analysis. Some 2500 m of core from 16 stratigraphic and engineering drillholes was also tested.

Six areas were highlighted for further investigation. The area to the west of the Warrego mine is probably the most significant among these, because it is located only about 22 km from the Alice Springs–Darwin railway line. Furthermore, waterbores in this area were apparently terminated in a phosphatic interval.

In the Lady Judith area, located along the western margin of the Wiso Basin, waterbore RN020989 returned an assay of 28.2% P_2O_5 over 3 m from a depth of 15 m within the Hooker Creek Formation.

In the Ammaroo area, waterbore RN013015 intersected a 12 m-thick zone averaging 12.8% P_2O_5 within the Arthur Creek Formation. Follow-up drilling by Aragon Resources Ltd in 2009 intersected significant phosphate

mineralisation at shallow depths. The highest assays were reported to be 16.7% P_2O_5over 20 m from 34 m below surface.

In the vicinity of Morginie Waterhole, located about 38 km east-north-east of Tennant Creek, waterbore RN016928, provided an upper 3 m intercept from a depth of 24 m that assayed 2.7% P_2O_5, and a lower 3 m interval returned 1.1% P_2O_5 from 51 m depth. Two other waterbores, located 18 km south-east of Tennant Creek, averaged 1.7% P_2O_5 over 43–52 m depth. Waterbore RN016930, located about 25 km west of the Warrego mine, intersected a 15 m-thick phosphatic zone within cherty mudstone of the Montejinni Limestone from 27 m depth. A second bore (RN010533), located about 6 km along strike, intersected 3 m at 3.2% P_2O_5 from 40 m depth. Both holes were terminated within the phosphatic interval. Waterbore RN011609 is located about 52 km south-west of Tennant Creek, in the vicinity of Kunayangku outstation. This bore intersected 3 m at 2.4% P_2O_5 from 84 m depth within dolostone of the Montejinni Limestone.

The location of anomalous phosphate occurrences surrounding the Tennant Region indicates that this area formed an island high during the Cambrian and possibly throughout the Phanerozoic. Most phosphatic intervals are in fine silty material which is easily washed away during RC drilling. Rock chip sampling may consequently yield relatively poor results and careful follow up is therefore required to verify anomalous results.

Reference

Khan M, Ferenczi PA, Ahmad M and Kruse PD, 2007. Phosphate testing of waterbores and diamond drillcore in the Georgina, Wiso and Daly basins, Northern Territory. *Northern Territory Geological Survey, Record* 2007-003.

Platinum group element mineralisation in the Papuan Ultramafic Belt, south-eastern Papua

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Recent exploration in the Papuan Ultramafic Belt (PUB) has focused on the SE (Mt Suckling) and NW (Waria River) extremities of the 400 km long, 12–18 km thick sequence. Four distinctive mineralisation styles containing PGE have been discovered, with Pt-Pd dominating PGE assemblages.

- Doriri Creek hydrothermal Pd-Pt-Ni lode (Mt Suckling) is characterised by relative enrichment of more mobile PGE, typically with Pd:Pt ratio >8. PGE-Ni mineralisation occurs in a tabular and vertical zone with a strike length in excess of 520m. Mineralisation occurs in massive mica-magnetite rock. Widths and grades at the surface average 10–15 m @ 1.3% Ni, 1–2 g/t 2PGE. Wholesale hydration of gabbro wallrock, coarse mica books, vein/breccia textures and the presence of trace marcasite indicate migration of large volumes of low temperature hydrothermal fluid along a relatively narrow, near vertical structure.

- Urua Creek porphyry Au-Cu (Pt-Pd-Ni) prospect (Mt Suckling) is a porphyry system hosted in a series of sub-parallel eruption breccias. Eruption breccias contain carbonised wood fragments suggestive of maar-type eruptions, possibly of Early Pliocene age. Breccias are hosted in a pervasively argillised and limonite stockworked Late Oligocene-Middle Miocene pillow basalt sequence. Mobile elements Au-Cu-Pd form a strong and coincident soil anomaly measuring 800m x 500m in the centre of the prospect. Interestingly, Pt is decoupled from Pd and with Ni forms a coincident anomaly at the eastern end of the prospect, where soils are developed on ultramafic bedrock. The presence of PGE in porphyry copper systems is not unusual, and in the western Pacific has been noted in trace amounts from Ok Tedi and Panguna, PNG; Santo Tomas II, Philippines; Grasberg, West Papua; Mamut, Sabah, Malaysia; Cadia Hill, Cadia East and Goonumbla, eastern Australia.

- Goroa Creek cumulate-layered Pt-Pd prospect (Waria River) consists of three Pt-Pd bearing ‘reefs’ hosted at ‘critical’ levels in a 500m thick layered gabbro. The lowermost reef occurs within sulphide- and plagioclase-rich gabbro, immediately above its contact with ultramafics. Pt grades range to 244 ppb. A second reef straddles the transition zone from plagioclase- and sulphide-rich to plagioclase-poor gabbro, with Pt grades to 114 ppb. The uppermost reef occurs in the upper part of a sequence of weakly layered plagioclase-poor gabbro, immediately below its transition with overlying diorite. Pt:Pd ratios at Goroa Creek are >1, similar to Bushveld-type cumulate-layered mineralisation.

- A narrow, platiniferous pegmatoidal anorthosite dyke at Duna Creek (Mt Suckling) is hosted in the ultramafic zone of the Mt Suckling complex. The Duna Creek occurrence is the first example of an ultramafic rock containing PGE mineralisation in the PUB.

The PUB is widely regarded as an ophiolite, a slice of oceanic crust and upper mantle that was thrust along a low-angle fault plane onto continental rocks of the Australian plate. PGE mineralisation found in ophiolite rocks worldwide is distinctly enriched in Ir-Os-Ru, with a marked depletion of Pt-Pd-Rh. By contrast, the Bushveld Complex and many other cumulate-layered complexes around the world are enriched in Pt-Pd-Rh relative to Ir-Os-Ru. Mineralisation in the Bushveld Complex is hosted in a large ultramafic-mafic complex emplaced into a region of thick continental crust. The thick crust played a key role in facilitating enrichment of Pt-Pd-Rh. The limited crustal thickness available in ophiolite sections is insufficient to allow enrichment of Pt-Pd-Rh.

Pt-Pd mineralisation at the SE and NW extremities of the PUB 'ophiolite' is anomalous. Exploration work at Mt Suckling has also indicated that the mafic/ultramafic sequence is Pt-Pd fertile, with 258 unmineralised rocks having an average content of 21 ppb Pt+Pd compared with a global average of 10 ppb Pt+Pd. By contrast, previous mineragraphic studies have shown that alluvial platinoids from the central section of the PUB (Aikora-Gira, Yodda-Kokoda areas) consist only of alloys of Ir-Os-Ru. This section of the PUB conforms with the ophiolite mineralisation model.

In the Mt Suckling district the Keveri Fault Zone, the bounding structure to the PUB, has facilitated uplift in excess of 8 km over the past few million years. This wide zone of vertical faulting represents the margin between continental rocks of the Australian plate and rocks of an island arc affinity of the Pacific plate. The Timeno Fault in the Waria River district is another vertical structure bounding the PUB.

PGE geochemical and structural heterogeneities of the PUB suggest that geological histories and geological processes have varied throughout the complex.

Uranium mineral systems in the Paterson region, WA: constraints from regional AEM survey data

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The Paterson region is one of the most highly prospective areas for uranium in Australia. It hosts a number of known unconformity-related uranium deposits and prospects including the Kintyre deposit, which is the 5th largest in Australia in terms of contained U_3O_8 (36,000 tonnes U_3O_8). GA is currently assessing the potential for several types of basinal fluid-related uranium mineral systems in the region, including unconformity-related, sandstone-hosted, and calcrete-hosted. A key dataset in this assessment process is the regional-scale airborne electromagnetic (AEM) data recently acquired and released by Geoscience Australia.

Surface and solid geology mapping depicts an arcuate belt of highly deformed rocks including the Paleoproterozoic Rudall Complex and the eastern margin of the Archean Pilbara Craton. These rocks are unconformably overlain by Neoproterozoic sediments of the Yeneena Basin mostly north of the Rudall Complex and the Officer Basin south of the complex. These in turn are overlain by Permian glacial sediments including fluvioglacial and glacial-lacustrine deposits of the Paterson Formation near the base of the Canning Basin. Mesozoic sediments of the Canning Basin unconformably overlie the Permian sediments. Much of the Mesozoic sediments and older rocks have been eroded by a complex system of paleovalleys.

The regional AEM data provide valuable pre-competitive information for up to the top 500 m of the crust by effectively mapping altered or weathered unconformity surfaces buried by more recent cover, identifying regional geological trends that are less evident in other regional-scale datasets, and mapping buried paleochannels and paleotopography (Roach et al., 2010). The AEM data are also particularly useful for mapping the depth to mineralised basement, reducing exploration risk in cover-dominated terrains.

For unconformity-related uranium systems critical ingredients include: shape and depth of the unconformity surface between oxidised and reduced rocks, proximity to Archean Pilbara Craton and/or Paleoproterozoic Rudall Complex felsic rocks, graphitic zones in the reduced rocks below the unconformity and dilatational structures in rocks below and above the unconformity. The essential ingredients of sandstone-hosted uranium

systems (paleochannel and roll front types) are: basins rimmed by uranium rich felsic rocks with leachable uranium, sequences of permeable fluvial sands, *in situ* or introduced reductants and systems of braided and/or meandering paleochannels filled with organic-rich sands and conglomerate. Calcrete uranium systems (paleochannel and deltaic type) require the presence of: calcrete (in the paleochannels and/or near deltaic regions of lakes); source-rocks of uranium and vanadium (mafic rock or iron formations) and shallow ground water systems draining towards a regional discharge zone (such as a lake). These ingredients are being assessed for each uranium mineral system to produce a set of prospectivity maps showing levels of mineral potential and certainty for the basinal fluid-related uranium mineral systems.

In relation to uranium mineral systems in the Paterson region, preliminary interpretations of the AEM data have identified paleovalleys filled with Permian and younger sediments and fluid pathways that are less evident in other geoscience datasets. Aquifers are identified in on-lapping Permian sediments adjacent to fluid pathways through Rudall Complex and Pilbara Craton. The unconformities of Mesozoic over Permian and Permian over Neoproterozoic Yeneena and Officer Basins or Mesoproterozoic Rudall Complex are mappable in some places, although the unconformity of Neoproterozoic over Rudall Complex or Pilbara Craton appears poorly defined in the data, probably due to low conductivity contrast between the units across the unconformity, and/or structural complexity, or below a conductive layer thus difficult to detect by AEM or at depth beyond AEM detection. In addition, the AEM data can also assist mapping the locations of some faults, that are poorly defined or not evident in other datasets. These results form part of a holistic interpretation of the AEM data interpreted with information from a database of historical drilling, regional mapping and electrical conductivity logging of drill holes to assess the potential of all uranium mineral systems in the Paterson region.

Reference

Roach IC, Whitaker AJ, Costelloe MT, Hutchinson D and Liu SF 2010. The Paterson AEM survey, Western Australia: Enhancing prospectivity using regional AEM data to image paleotopography (this volume).

Time-temperature history of the Permian Tinowon Formation coal seam gas reservoir revealed by integrated U-Th-Pb-He and fission track techniques

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A tephra unit of the Wallabella Coal Member (Tinowon Formation), recovered from a cored section of a well east of Roma, on the edge of the Roma shelf, Bowen Basin (27°04'10.673"S, 149°12'57.590"E, -2070 m depth) was investigated using integrated geo-thermochronology techniques. The objective of the study was to: (i) determine a stratigraphic age for the Wallabella Coal using SHRIMP zircon U-Pb geochronology and (ii) to determine the post-depositional thermal history of the Tinowon Formation using complementary fission track and (U-Th)/He thermochronometers.

Zircon separated from the ~1 m thick Wallabella Coal tephra unit (WCTU) consisted of a homogenous population of clear, prismatic crystals ranging from 80–100 µm in diameter. Cathodoluminescence images showed simple, concentric zoning consistent with magmatic crystallisation and very few inherited cores. Similarly, apatite grains were subhedral to euhedral and averaged 90–100 µm in diameter.

A total of 37 concordant SHRIMP II analyses of igneous zircon gave the same radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 257.0 ± 1.5 Ma (95% confidence). Given that zircon commonly crystallises in magmas prior to eruption, this is interpreted as a maximum age for the eruption of the tephra unit within the Wallabella Coal Member. The WCTU is the same age (within error) as the Platypus Tuff (SHRIMP zircon U/Pb age of 258.9 ± 2.7 Ma; Michaelsen et al., 2001, AJES 48: 183–192), a chronostratigraphic marker horizon in the Moranbah Coal Measures in the northern Bowen Basin.

Zircon (U-Th)/He, apatite fission track and apatite (U-Th)/He thermochronometers are sensitive to geological events at temperature intervals of ~190–130°C, ~120–60°C and ~85–40°C respectively, and can be used to constrain the post-depositional thermal history of the WCTU. Zircon (U-Th)/He and apatite fission track ages are partially reset indicating that the tephra unit was located within both the zircon He partial retention zone

(~190–130°C) and apatite fission track partial annealing zone (~120–60°C) for a prolonged period. In contrast, apatite (U-Th)/He ages have been completely reset and return Miocene ages.

We used the HeFTy modelling program (Ketcham, 2005, Rev Mineral Geochem, 58: 275–314) to integrate this geo-thermochronology data with other measured thermal parameters (borehole T = 84±3°C and vitrinite R_0 = 0.93 ± 0.1 at ~2070 m depth) for the Tinowon Formation. An internally consistent thermal history model, based on 'steady-state' basin formation and inversion processes and a constant continental geothermal gradient (e.g., 30°C/km) produces several plausible scenarios. By application of *Occam's Razor,* the following geological interpretation is preferred:

- deposition of the WCTU ~257 million years (Myr) ago
- post-depositional burial heating and coalification of the Wallabella Coal via passive thermal subsidence to T_{max}=160°C at basinal depths equivalent to ~5,000 m by the Late Jurassic, equivalent to an average depositional rate of ~50m/Myr
- basin inversion led to cooling of the WCTU to 60°C by ~90 Ma, and it remained at this relatively constant temperature throughout the Tertiary
- a thermal re-heating event in the Late Neogene (~5 Ma) accounts for Miocene apatite (U-Th)/He ages and present-day borehole temperatures of 84±3°C.

Palaeozoic palaeontology and geochemistry of Windjana-1 Well, south-eastern Bonaparte Basin, Australia

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Windjana-1 is a petroleum exploration well drilled during 2009 in the south-eastern offshore Bonaparte Basin of northern Australia. The well was drilled to test for the presence of hydrocarbons in a seismically-defined closure below the mid Carboniferous (top Visean) unconformity, specifically in a section thought to be of Early Carboniferous to Late Devonian age based on off-set exploration wells and long distance seismic correlation to onshore seismic profiles. The well reached a total depth of 2033 m in a series of siliciclastics and carbonates dated as Frasnian to Givetian, the first offshore intersection of rock of this age in the Bonaparte Basin. Detailed palynological, micropaleontological and geochemical sampling was undertaken. Unfortunately, no hydrocarbons were encountered.

Regional 3D modelling of the Latrobe Valley coal resource

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Introduction

Clean Coal Victoria (CCV) is a new body set up by the Victorian Government dedicated to maximising the value of Victoria's coal resource in order to best deliver the economic, social and environmental objectives for local communities and Victoria. These coal reserves are Victoria's largest natural resource asset and currently supply fuel for 90 per cent of Victoria's power generation utilising coal from the Loy Yang, Hazelwood and Yallourn mines. The coal lies in the Latrobe Valley Depression that contains coal resources of 129 000 million tonnes and is one of the world's largest, and lowest cost, energy sources. The ability to be able to manage this asset effectively relies on accurate and detailed modelling of the resource. Modelling in the Latrobe Valley region in the past has been undertaken under contract by 3rd parties for DPI, but now as GeoScience Victoria has expanded into the 3rd dimension and with improvements in skills, software and computing power this modelling can be done more effectively within the department.

Modelling

In the past GeoScience Victoria has relied on products such as GeoModeller, used in conjunction with GoCad, to produce 3D models. This has been an effective method were data has been relatively sparse and based on regional scale interpretations. In contrast, modelling of the Latrobe Valley coal resource is based on around ten

thousand drillholes covering an area of just over 2000 square kilometres. The stratigraphy within the Latrobe Valley is very well understood and documented by a number of previous workers. This rich dataset was in part developed by the (now privatised) State Electricity Commission of Victoria who over a period of approximately 70 years carried out a very thorough drilling program. Although it may seem great to have such a rich data source it also produces issues when it comes to effectively modelling them.

CCV and GeoScience Victoria have recently modified their modelling workflow to include SKUA, a companion product to GoCad. SKUA is different from GoCad in that it allows you to define known stratigraphic relationships and known fault relationships within the application. In the Latrobe Valley the stratigraphic sequence and fault architecture are well defined and documented and within SKUA you are able to define these geological rules through a stratigraphic column defining conformable, unconformable, baselaps, onlaps etc.

The modeller is no longer required to model each lithology in isolation, with SKUA all horizons are modelled in one implicit modelling process to ensure consistency between horizons and faulting during the same process. The process ensures no cross-overs and that all measured data which provides geometric and thickness information is utilised to model the entire sequence, not just a single horizon. Finally, additional data can be added to the model and the model regenerated to account for this data at any time. This is of great importance in projects such as this where data is continually becoming available from miners, explorers and our own drilling programs and the complex models must be updated regularly to reflect this.

Once the coal horizons are modelled they can form the basis for a fully attributed 3D volume that can then be interrogated at a range of scales for around 25 different properties such as moisture, ash, sulphur and energy content (NWSE) as well as contained volumes. These are the main attributes that are required when managing the coal resource.

Conclusions

This latest modelling technique has provided CCV with the most accurate 3D model of the Latrobe Valley coal resource possible with the available data. It provides a 3D model in which we can have a high degree of confidence knowing that it is consistent with all the available data and the well understood stratigraphic sequence within the Latrobe Valley. The model forms the foundation for resource utilisation planning and land use. Because it is such a rapid modelling process the whole model is easily updated with the addition of new data. This is important because CCV is currently undertaking new drilling in under explored areas as well as validating and reinterpreting existing drill hole data.

What do we know about that geological unit?

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If you are studying the geology of an area, how do you find out what has been published about it? How do you find out who else has worked in the area and how nomenclature has evolved? How do you register a new geological unit resulting from your study?

The Australian Stratigraphic Units Database (ASUD) can provide you with answers to these questions. It is freely accessible online via Geoscience Australia's website at www.ga.gov.au/oracle/stratnames/index.jsp.

This national database was started in 1949 by agreement between the universities, the State and Territory Geological Surveys and the Bureau of Mineral Resources (now Geoscience Australia). All Australian stratigraphic unit names and their usage in literature are recorded in this centralised reference point. The database is also a handy tool for authors and reviewers to check the names to be used in forthcoming publications or products. The ASUD can be used to determine which version of a name is currently accepted. The database also stores approved unit definitions.

The search page and the results reports from the ASUD have recently been upgraded. As well as the existing searches for stratigraphic names and geological provinces, it is now possible to search for units within an age range, such as Devonian to Carboniferous, and in a particular State as well, if that is appropriate.

The first page of the report gives summary information on the unit names that satisfy your query, including a unique number for each unit, the State or Territory they are found in, the currency of the name, and if we hold

any definition information. When you select a particular unit, the hyperlink will take you to the detailed report that gives all the information available on this unit, and lists all the publications the data has come from.

The detailed report tells you how much information has been published, ranging from definitions down to mentions. It usually includes the unit age and some hierarchy information, such as which Group a unit belongs to and what other units are in the same Group. For example, the Delegate River Mudstone is part of the Bredbo Group, and there are 5 other units listed in this Group as well. For igneous units such as granites or volcanics a Suite or Supersuite may be shown in the Chemical Hierarchy section. For instance, the database shows the Kallanda Granite has been included in the Oweenee Supersuite.

The next section is Related Units, which used to list just overlying and underlying units, but the database structure was modified last year to allow other relationships to be recorded such as 'intrudes' and 'is intruded by'. This data will be added progressively, from existing comments fields and new references. As an example of the new options, Corunna Conglomerate is shown to be intruded by the Charleston Granite, and is correlated with the Blue Range beds.

In the reference section of the report, as well as listing the First Reference and the Definition Reference, a new section has been included to list all the map sheets that have used the unit, as a convenient guide to its general location and extent. In the Full Bibliographic Details section, those references with the most information are shown at the top of the list. Usage of the stratigraphic name, its age and other comments are given for each reference, as well as the full reference details.

If your research shows that you need to modify existing geological units, or create new ones, the same Geoscience Australia web page also has guidelines and contacts for help. There are also various forms for submitting unit definitions (or redefinitions), reserving new names, making special enquiries, letting us know about references we have overlooked, or any problems you find in the database.

Try us out! We think you will be glad you did.

Information models for the Australian geoscience community: GeoSciML, EarthResourceML and GroundwaterML

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[1]Geoscience Australia, [2]Geoscience Victoria, [3]Geological Survey of Canada

Open Geospatial Consortium (OGC) web services offer a cost efficient technology that permits transfer of standardised data from distributed sources, removing the need for data to be regularly uploaded to a centralised database. When combined with community defined exchange standards, OGC services offer the ability to access the latest data from the originating agency and return the data in a consistent format. Interchange and mark-up languages such as the Geography Markup Language (GML) provide standard structures for transferring geospatial information over the web. The IUGS Commission for the Management and Application of Geoscience Information (CGI) has an on-going collaborative project to develop a data model and exchange language based on GML for geological map and borehole data, the GeoScience Mark-up Language (GeoSciML). The Australian Government Geoscience Information Committee (GGIC) has used the GeoSciML model as a basis to cover mineral resources (EarthResourceML), and the Canadian Groundwater Information Network (GIN) has extended GeoSciML into the groundwater domain (GWML). The focus of these activities is to develop geoscience community schema that use globally accepted geospatial web service data exchange standards.

GeoSciML draws from many geoscience data modelling efforts to establish a common suite of feature types to represent information associated with geologic maps and observations. After extensive testing and use case analysis, in December 2008 the CGI Interoperability Working Group (IWG) released GeoSciML 2.0 as an application schema for basic geological information. The release included a schema representation in UML and XML formats, text descriptions of schema components, and example data files. GeoSciML 2.0 is the format used by the OneGeology portal to deliver global geology data (http://portal.onegeology.org/).

Forthcoming changes to the OGC Web Feature Service specifications have required some modification and updating of GeoSciML to version 3.0. These changes will make it easier for web clients to support complex web-based queries, as well as data providers to link to standard vocabulary and registry services. The depth

and breadth of GeoSciML remains largely unchanged, covering the representation of geologic units, earth materials and geologic structures. Geologic structures include shear displacement structures (brittle faults and ductile shears), contacts, folds, foliations, lineations and structures with no preferred orientation (e.g. 'miarolitic cavities'). The earth material package allows for the description of both individual components, such as minerals, and compound materials, such as rocks or unconsolidated materials, and includes the relationships between the components. Provision is made for alteration, weathering, metamorphism, particle geometry, fabric, and petrophysical descriptions. Mapped features describe the shape of the geological features using standard GML geometries, such as polygons, lines, points or 3D volumes. Geological events provide the age, process and environment of formation of geological features.

Testing of the changes is currently being undertaken with the aim to release GeoSciML 3.0 later in 2010.

The EarthResourceML model is an extension of the GeoSciML data exchange standard designed to facilitate mineral resource data transfer between government, industry and other organisations. Without a standard data transfer format like EarthResourceML, there is no easy way to share this data because each State and Territory Geological Survey has its own database with its own structure and vocabularies for storing information on mineral occurrences, mines, commodities, production, reserves and resources. EarthResourceML also provides a formal structure for reporting resources and reserves that can comply with national and internationally accepted reporting codes. EarthResourceML describes earth resources and associated human activities independently. It caters for the description of the earth resources using mineral deposit models, and describes mines as made up of a number of mining activities, each producing some commodity.

The Geological Survey of Canada (GSC) has developed the Groundwater Markup Language (GWML) as a common format for exchanging groundwater data. It extends two advanced GML standards, GeoSciML and Observations and Measurements, by adding entities such as hydrogeological units (e.g. aquifers), properties (e.g. storativity), water wells, and water budget entities. Due to its firm grounding in OGC standards, GWML can be used with OGC services, such as Web Feature Services, to enable exchange of a wide spectrum of groundwater data.

Mineralogical and spatial validation of hyperspectral indices: a coordinated approach towards exploration uptake

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Spectroscopic methods for determining mineralogy are increasingly being taken-up by the mineral exploration industry with the aim of adding another layer of information in their search for the next ore body. Although companies are actively collecting spectral data from their drilling, as well as acquiring remotely-sensed data, there is need for a structured approach to handling such data—including the necessary geological context—that can only come from a coordinated research effort. This concern is echoed within industry ranks, where company geologists call for spectrally-derived mineralogical indices, algorithms and strategies that can be easily applied within their daily routines to differentiate different lithologies and alteration assemblages. A way forward in developing such mineral mapping tools lies in the creation of a suite of mineral and mineral assemblage indices, easily-followed procedures and locally-relevant mineral libraries. The object of this paper is to demonstrate the value of pursuing the systematic development of spectral indices for gold mineralising systems and application in exploration.

The proposed methodology evolved from characterising mineralisation-associated alteration from seven gold deposits within the Archean Yilgarn Craton, which found that each deposit contained a common set of spectrally-measurable alteration minerals. The approach involves a four-stage process (1. Identification of alteration assemblages; 2. Spectral characterisation; 3. Spatial analysis; 4. Transfer of outcomes to client/integration into client database) that progresses knowledge from raw spectra to mineralogically- and spatially-validated hyperspectral indices for use by exploration geologists. The four-stage process is summarised in the following paragraphs.

Stage 1 encompasses mineralogical characterisation of alteration assemblages that involves initial spectral assessment and identification of mineralogical gradients, incorporated with the sampling of key textural and paragenetic relationships in drill core. The way forward is to integrate the collection of basic geological

analyses, including thin sections, XRD and multi-element/stable isotope geochemistry, across different sites with the intention of comparing geology/alteration to create more holistic spectro-mineralogical indices for exploration.

Stage 2 involves the selection of minerals for spectral characterisation. Minerals will be selected from the identification of key alteration mineral assemblages developed in Stage 1. Diagnostic absorption features and/or compound signatures of selected minerals and assemblages are targeted in the visible infrared (VNIR), short-wave infrared (SWIR) or thermal infrared (TIR). Output is in the form of a series of spectral indices, scalars or classifications.

Stage 3 is the spatial validation of the newly-created scalars or classifications. The 3D software package Leapfrog™ is used to add the numerical scalar data to East Yilgarn Au chemical-architectural models, and assess the value of the scalar in a spatial sense.

Stage 4 packages the newly interpreted scalars into tutorial form that will detail how each scalar or classification was created, its significance in terms of the mineral system understanding, and practical applications for the mineral industry.

The combination of hyperspectral indices and 2D/3D maps that are the key deliverables from this style of research approach is a way of testing the spatial and genetic significance of the hyperspectrally-characterised minerals, and if the indices are successful in delineating validated near mine alteration anomalies, it will enable a confident transferral for use within brown/greenfields exploration. Furthermore, hyperspectral indices that are proxies for minerals commonly associated with hydrothermal mineralisation have the potential to be universally transferable to other non-Archean mineral provinces.

Short wavelength infrared reflectance spectroscopy: a new tool in very low grade petrology

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In sub-greenschist facies pelitic rocks, powder X-ray diffraction (XRD) derived Kübler Index (KI; Kübler, 1967) is a standard method for estimation of very low metamorphic grade, and is widely applied in sedimentary basins and other very low-grade terrains (Merriman and Frey, 1999). Few attempts have been made to quantitatively apply spectroscopy methods in the field of very low-grade petrology. These have focused on the infrared wavelength area ('Flehmig index'; Flehmig, 1973) and have gained little application. In terms of Short Wave InfraRed (SWIR) reflectance spectroscopy (wavelengths between 1000 and 2500 nm) attempts have been driven mainly towards applicability as a monitor of mineral chemistry, structural ordering (Hauff et al., 1991) or polytype evolution of K-white mica (KWM) in hydrothermal systems for field, laboratory and remote sensing studies (e.g. Cudahy et al., 2008). We investigated the ability of SWIR reflectance spectroscopy to track changes in metamorphic grade and geothermal gradients in low and very low-grade pelites through comparison with standard XRD analytical measures KI and KWM *b* cell dimension.

SWIR measurements were carried out with the CSIRO-developed HyChips 6-4, semi-automated chip-logging instrument, with a nominal spectral range of 350–2500 nm and a spectral resolution of ~8 nm. The spectra measured were processed with CSIRO-developed software—The Spectral Geologist (TSG™). The KI was measured on textured (KWM *b* cell dimension on untextured), air-dried preparates (<2μm fraction), and values were calibrated using a correlation with the standard samples of Warr and Rice (1994).

Doublier et al. (2010) introduced the term 'illite spectral maturity' (ISM) for SWIR reflectance spectroscopy methods which measure KWM mineral physicochemistry as a sensitive indicator of changes in metamorphic grade. Three ISM measures have been found potentially valuable in correlation studies with XRD derived KI data (e.g. Hauff et al., 1991; Cudahy et al., 2008; Doublier et al., 2010). They are based on two vibrational absorption features at 2200 nm (main feature for KWM in this spectral range) and at approximately 1900 nm (relates to the overtones of water), which are parameterised according to their asymmetry (as), area (A) and depth (D). The ISM measures are reflectance 2200as index (ISM(as)), reflectance 2200A/2200D index (ISM(A/D)) and reflectance 2200D/1900D index (ISM(H_2O)). All show a good correlation with KI, with correlation coefficients ranging between R^2=0.61–0.70. For all ISM measures, it has been possible to define

boundary values which allow distinguishing anchizonal from diagenetic samples, and mapping metamorphic zones in a regional example.

Another parameter tested is the wavelength of the 2200 nm feature (2200wvl), which shows an inverse relationship with octahedral Al^{3+} (Post and Noble, 1993). These Al^{3+} contents are controlled by the celadonite substitution (Guidotti, 1984) and form the petrological basis for the KWM *b* cell dimension method, which is a parameter for the geothermal gradient (Sassi and Scolari, 1974). Both parameters show a very good linear correlation with R^2=0.85, suggesting that the 2200wvl is a suitable parameter for the estimation of geothermal gradients in very low-grade pelites.

The present study demonstrates that SWIR spectroscopy can be used to assign metamorphic grades and geothermal gradients in low- and very low-grade metamorphic environments. The diagenetic zone/anchizone boundary is important, particularly in the evolution of organic material, and therefore for hydrocarbon and coal industries. It grossly coincides with the catagenesis-metagenesis boundary (maturation stage), the end of the wet gas hydrocarbon zone, and the boundary between bituminous and semi-anthracite coal (Merriman and Frey, 1999). The main advantages of SWIR spectroscopy include: rapid analysis (minutes); low-cost; application to remote sensing as well as proximal spectral data.

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It's easy to distinguish the type of hydrothermal ore deposit based only on trace elements in hydrothermal vein quartz

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We analysed trace elements in over forty hydrothermal vein quartz samples from porphyry copper, IOCG, intrusion-related Au, Mississippi Valley type, epithermal, and orogenic Au deposits using laser ablation inductively coupled plasma mass spectrometry (LAICPMS). We found that each type of ore deposit can be distinguished from the others type based on the concentrations of trace elements in the quartz. This technique for discriminating the origin of the quartz has important implications for mineral genesis and mineral exploration models.

We analysed quartz for the following trace elements (approximate limits of detection are given in parentheses): Li (100 ppb), Be (50 ppb), Na (5 ppm), Mg (200 ppb), Al (1 ppm), P (5 ppm), Ca (40 ppm), K (2 ppm), Ti (250 ppb) Fe (6 ppm), Cu (250 ppb), Zn (150 ppb), Ga (40 ppb), Ge (250 ppb), As (1.4 ppm), Rb (10 ppb), Sr (4 ppb), Zr (14 ppb), Mo (15 ppb), Sn (120 ppb), Sb (12 ppb), Cs (2 ppb), Ba (6 ppb), La (1 ppb), Ce (1 ppb), W (4 ppb), and Pb (3 ppb). The most abundant trace element in most hydrothermal quartz is Al. In addition, Ti, Li, and K, are present in the range of 1s to 10s of ppm and Ge, As, and Sn are detectable in most samples in the range of 10s of ppb to 1s of ppm. Surprisingly, Sb varies significantly among quartz samples from less than detection up to a few tens of ppm. Heavy REEs are detectable only in porphyry copper quartz in the range of a few tens of ppb. Beryllium, Mg, Ca, Fe, Cu, Zn, Ga, Rb, Sr, Zr, Mo, Cs, Ba, W, and REEs are typically present in hydrothermal quartz in quantities less than the detection limits shown above.

Trace element concentrations in quartz vary slightly amongst samples of each individual deposit type. However the trace element variation amongst quartz from different deposit types is much larger than the variation within a single deposit type. Therefore quartz trace elements in a sample of unknown affinity can be used to fingerprint the type of deposit from which the hydrothermal quartz was likely derived. Quartz trace element composition could be a useful indicator to fingerprint potential ore deposits in stream and soil samples, drill cuttings, or in rocks where the geology of the deposit is not well constrained.

In all samples from all deposit types, there is a strong correlation between Al and Li concentration. A correlation between Al and K also exists, however it is more difficult to quantify due to the higher detection limits of K and the presence of K-rich fluid and mineral inclusions. These correlations strongly suggest the co-substitution of Al^{3+} and either Li^{+} or K^{+} for Si^{4+} within the quartz structure. Antimony correlates closely with aluminium in some quartz, but not in others. No other trace elements consistently correlate positively with one another in quartz from all deposit types.

Porphyry copper quartz contains 10s to 100s of ppm Al, 10s to a few hundreds of ppm Ti, and also contains Li and K in the 1s to 10s of ppm range. Epithermal and MVT quartz is euhedrally growth zoned with quartz that shows bimodal trace element distribution. Some zones are trace element-rich containing up to 3500 ppm Al, hundreds of ppm Li, and tens of ppm K. Other zones within the same quartz grains contain <100 ppm Al and <10 ppm Li and K. Quartz from these deposits always contains less than 2 ppm Ti. Quartz from orogenic Au deposits and IOCG deposits have the most similar trace element signatures, however they are still distinguishable from one another. The signature is characterised by overall low trace element abundance, with less than 10 ppm Ti and most with less than 100 ppm Al and less than a few ppm Li. These deposits can narrowly be differentiated based on their Ti to Al ratios which differ slightly. A few orogenic Au samples also had higher Al concentrations than were found in any IOCG deposit.

Texture, paragenesis and trace element concentration of quartz in gold mineralised veins from Warrior Mine, Charters Towers, Queensland

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Charters Towers Goldfield extends over 500 km^2 and contains mineralisation within quartz/carbonate-dominated veins (0.1–1 m wide) hosted in intrusions of the Ravenswood Batholith. It is historically one of Australia's largest goldfields with production of 6Moz Au and a high average grade of 34g/t Au. The purpose of this study is to constrain the physical and chemical conditions of vein formation and the mechanisms of gold precipitation, in an effort to aid in vectoring towards undiscovered resources. We have applied fluid inclusion petrography, scanning electron microscope–cathodoluminescence (SEM-CL), back scattered electron (BSE) imaging and laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) to numerous samples from the Warrior Mine vein system.

CL images reveal several distinct generations of quartz growth within mineralised and unmineralised intersections of the Warrior vein. The earliest generation of quartz (Q1) is recognised as CL-bright quartz in the inner core of most quartz crystals. These bright cores are always overprinted by a cobweb-like CL-dark fracture network which corresponds to abundant mineral and fluid inclusions within the quartz. Most fluid inclusions lack daughter minerals and contain liquid and a vapour bubble that occupies about 10–20% of the inclusion volume (B15s). No halite-saturated brines were identified. In addition to B15 inclusions, Q1 also contains liquid-rich inclusions with no vapour bubbles. The composition of these fluids is yet to be determined, but it is possible that they contain liquid CO_2 or liquid methane. Q1 is commonly overgrown by quartz with euhedral and oscillatory growth zones (Q2) that contain less mineral and fluid inclusions. Although Q1 quartz is not present in the core of every quartz grain in the Warrior vein, most contain Q2 which is nearly always overgrown by a narrow (~10–300 μm) series of CL-dark growth bands (Q3) that truncate growth bands of Q2. Q4 is a distinct CL-dark quartz with no alternating luminescence that is volumetrically minor and locally present in contact with sphalerite. Q4 contains only liquid fluid inclusions with no vapour bubble. More commonly, the final generation of quartz recognised (Q5) is a microbreccia that consists of fragments of Q2 quartz and sulphides (sphalerite and pyrite) and a finer matrix of quartz. Q5 quartz textures cross cut and fracture earlier quartz.

Trace element variations among the various quartz generations were determined by LA-ICPMS. The trace elements that varied among quartz generations are Li, Al, B, Sb, Ti and Al. Titanium concentrations vary slightly and consistently across all generations of quartz and are correlated with CL intensity. Early CL-bright Q1 contains ~4ppm Ti, whereas slightly less luminescent Q2 contains ~2.5ppm Ti. The CL-dark overgrowths of Q3 contains about 1ppm Ti, and the CL dark quartz of Q4 contains less than detectable Ti (<0.1ppm).

Based on the TitaniQ geothermometer, which employs the Ti content of quartz, (see Wark and Watson, 2006) the earliest vein quartz (Q1) quartz formed at temperatures of around 450°C, while successive quartz

generations formed at progressively lower temperatures. CL-dark Q4 quartz that formed with sphalerite suggests temperatures of precipitation below 350°C.

In contrast to the Warrior vein, quartz from unaltered and unminerlised granites that host the vein contain halite-saturated brine fluid inclusions typical of granitic systems. The quartz also contains up to 125ppm Ti indicating typical granitic crystallisation temperatures of up to 750°C.

This work shows that fluids that formed the Au-rich Warrior vein in the Charter's Towers district is not likely to be directly sourced from the host granite. The vein formed at temperatures several hundred degrees less than the crystallisation temperatures of the granites and did not obviously form from high salinity brines which characterise magmatic-hydrothermal systems. CL textures and trace elements suggest that mineralisation occurred in a brittle environment from hydrothermal fluids cooling below about 400°C.

As of yet, the composition and origin of the mineralising fluid is not well constrained. Further work will include microthermometry and LA-ICPMS of fluid inclusions in the various quartz generations. This work will elucidate the source of hydrothermal fluids and the Au precipitation mechanisms, which will help define future exploration targets in the region.

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A new reference library of thermal infrared reflectance spectra of minerals and rocks derived from CSIRO'S TIR-HyLogger

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CSIRO have developed a variety of HyLogging systems to acquire voluminous hyperspectral reflectance spectra of drill core and drill chips to identify and quantify the mineralogical composition of host rocks and mineralised systems. The HyChips and HyLogger instruments acquire reflectance spectra from the visible and near infrared (VNIR) to the shortwave infrared (SWIR) between 400 and 2500 nm suitable for OH-bearing silicates, oxides and carbonates. The latest development is the TIR-HyLogger which covers the thermal infrared wavelength range from 5 to 14 um (5,000 to 14,000 nm) discriminating non-OH-bearing silicates such as quartz, feldspars, garnets and pyroxenes.

A rock's reflectance spectrum can be considered as a mixed spectrum of the constituent weighted single spectra of the individual mineral crystals as a function of their fractional area of the scanned surface. These fractions can be estimated, e.g. using spectral unmixing approaches, from spectral libraries of pure reference materials. There are several existing overseas spectral libraries of reference minerals described in the literature; however, all have been measured with different instruments and using different measurement methods and geometries. To ensure a high accuracy of the mineralogical results from the operational TIR-HyLogger a new library of reference minerals, measured with the same system to be later used operational, is considered an important requirement. Particularly of it is representative of Australian terrains and Australian user requirements.

The heart of the TIR HyLogger is a Fast Fourier Transform spectrometer which scans bi-directionally the drill core mounted on a computer controlled x/y table moving the core in the x direction or to move a sample to a specific defined place on the table for static library measurements. Two heat bars are used as the light source. The spatial resolution is nominal 10 by 10 mm but smeared to 10 x 14 mm due to the table movement in core scanning mode. The spectral resolution is 20 nm at 5,000 nm and 170 nm at 14,000 nm. The signal-to-noise ratio (SNR) for a 100% reflecting target is averages 850:1 between 9,000 and 12,000 nm. The wavelength calibration is achieved by comparison with the known and well described quartz feature at 8,625 nm and the well known absorption feature of a polystyrene plastic film. Additionally a line scan camera simultaneously acquires imagery of the scanned core.

To develop the TIR-HyLogger's reference library, pure and solid samples (as opposed to particulate samples) of representative mineral and rock specimens were collected to be representative of the target samples (solid core samples). The samples have been described macroscopic, microscopic and/or by geochemical analyses for validation purposes. All spectra have been acquired in radiance and have been calibrated to absolute radiance

which has been required to remove the increase of the baseline towards the longer wavelengths due to sample heating during spectral acquisition. The conversion to reflectance data was performed by dividing the sample reflectance by the reflectance of a 100% diffuse reflecting gold standard.

Research has shown that for a given mineral a large amount of spectral variation can occur. This variation is thought to be due to surface roughness, crystal or sample anisotropy, relative to the bi-directional measurement geometry, and to natural chemical variation. The first two subjects have a large influence on the thermal infrared signal and can cause a change in spectral features. For example the surface roughness can cause volume scattering to become dominant, instead of surface scattering which causes a decrease in spectral contrast (low magnitude), or to a dramatically change from a reflectance peak to a reflectance minimum. Additionally crystal orientation effects can result in a wavelength shifts of significant mineral spectral feature positions (e.g. reflectance peaks). As with surface roughness effects a crystal surface oriented at a certain angle can also lead to an increase or decrease in the absolute magnitude of the spectrum. In this case a 'specular' reflectance occurs. To deal with natural variations in spectral signature resulting from chemical variations in different species a large number of different mineral samples is required to ensure covering the maximum range of naturally occurring spectra.

So far more than 200 different mineral specimens (feldspars, pyroxenes, carbonates, amphiboles) and different sheet silicates have been measured resulting in more than 850 single reference spectra. Many of these have been generously loaned by Australian museums, universities and Geological Surveys.

HyLogging systems produce very large datasets so new methods and algorithms are being developed to provide qualitative and quantitative analyses capable of representing with all these natural variations and to ensure reliable automated mineral interpretation results. The library is continuously growing as new material comes to hand and is available on request and the geoscience community is invited to submit characterised samples for expansion of the library.

PGE, Au, Ni, Cr and Cu variations in the Komatiites from the Mahakoshal Greenstone Belt, central India

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Komatiites are rare ultramafic volcanic rocks containing more than 18 wt % MgO (Arndt and Niusbet, 1982) that erupted mainly during the Archean and Early Proterozoic and less frequently in the Phanerozoic. The more recent examples tend to have lower MgO content than their Archean equivalents. Komatiites are also characterised by their low incompatiable element content which is consistent with their generation by high degrees of partial melting (30–50%). Komatiites are the hottest lavas erupted on earth (eruption temperatures 1400–1600°C), and therefore they provide important constraints on the composition and thermal structure of the Archean mantle (Sproule et al., 2002). The economic importance of komatiites was first widely recognised in the early 1960s with the discovery of massive nickel sulphide mineralisation at Kambalda, western Australia. Komatiite hosted nickel-copper sulphide mineralisation today accounts for about 14% of world's nickel production, mostly from Australia, Canada and South Africa.

The Late Archean Mahakoshal greenstone belt (MGB) in central India is an intracontinental rift (~ 500 km long) filled with a thick metavolcano-sedimentary sequence. The rocks have undergone greenschist facies metamorphism and polyphase deformation. Komatiites occur in the central part of the MGB near Katni. They are cumulate rocks and are composed mainly of olivine associated with clinopyroxene and orthopyroxene. Chrome spinel is a minor phase. These komatiites have between 35 and 39 wt % MgO and are Al-depleted with Al_2O_3 contents of 2.51–3.20 wt % and Al_2O_3/TiO_2 ratios of 5–10 significantly below the primitive mantle value of 20. Also they are depleted in TiO_2, V, Sc and HREE. Katni komatiites appear to be uncontaminated by continental crustal rocks, on the basis of various ratios of strongly to moderately incompatible low mobility trace elements.

Disseminated and locally coarse-grained sulphides occur in the Katni komatiites. The sulphides consist mainly of pentlandite and pyrrhotite associated with chalcopyrite. The sulphides have a distinctly intercumulus character, which is interpreted to reflect a primary magmatic origin. The sulphides and silicates exhibit sharp boundaries and there is no petrographic evidence of replacement of silicates by sulphides. Metal values range up to 2500 ppm Ni, 4600 ppm Cr, 150 ppm Co, 45 ppm Cu, 10 ppb Au, 22 ppb Pt and 12 ppb Pd. Komatiitic

magmas are S-undersaturated because they are high temperature magmas produced by large degrees of partial melting of upper mantle. Katni komatiites have high Ni contents and low Cu, Au and PPGE (Pt, Pd) contents, consistent with their having formed by high-degree melting that left no sulphide in the source. These komatiites that remained S-undersaturated during ascent and emplacement may preserve most of their original PGE concentration patterns and thereby provide insights into the PGE systematics of the Archean mantle.

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Encouraging exploration for the long-term sustainability of Western Australia's resources sector: the WA Government's royalties for regions exploration incentive scheme

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In April 2009 the Western Australian Government announced Royalties for Regions funding for the five-year $80 million Exploration Incentive Scheme (EIS) to encourage exploration in Western Australia for the long-term sustainability of the State's resources sector. The expanded GSWA work program will be dominated by pre-competitive geoscience programs, including a co-funded Government–industry drilling program. The scheme will allow GSWA to collect, interpret and distribute up-to-date, relevant, high-quality pre-competitive geoscience datasets, and introduce emerging geoscience concepts and skills.

A focus will be the completion of the airborne magnetic and radiometric coverage of WA at 400 m line-spacing or better. This is long overdue, and equivalent data is generally available for other jurisdictions in Australia. A program of deep crustal seismic traverses will include the frontier Kidson Sub-basin of the Canning Basin, jointly funded with Geoscience Australia as part of their Onshore Energy Security Program. Two further lines will cross the Capricorn Orogen between the Archean Pilbara and Yilgarn Cratons as part of a traverse co-funded by AuScope, and the Narryer and Youanmi Terranes of the Yilgarn Craton. A magnetotelluric survey collected in collaboration with the Centre for Exploration Targeting (CET), crossed the southern part of the Southern Cross Domain and imaged the boundary of with the Kalgoorlie Terrane. Further surveys are planned in the Musgrave Province and in conjunction with the planned deep seismic traverses.

Ground gravity surveys at 2 km and 2.5 km spacing have been carried out around Cunderdin, including the Kauring Airborne Gravity Test Range, and at the south-east margin of the Yilgarn Craton, and are planned for the Southern Cross and Lake Johnson areas in the Yilgarn Craton, and for the Gascoyne Province. There will also be expansion of other datasets with improved coverage of geology and regolith map layers planned in the Capricorn Orogen and in the Kimberley region. Soil geochemistry surveys will target the northern and eastern margins of the Yilgarn Craton where deep weathering, regolith cover and thin sedimentary basins obscure prospective Archean and Proterozoic bedrock.

GSWA will improve understanding of very low- to moderate-temperature events, including hydrothermal fluid flow and mineralisation, using SHRIMP phosphate geochronology in collaboration with Curtin University and UWA. In addition there will be expanded programs for whole rock Sm-Nd analyses and Lu-Hf in zircon already dated using SHRIMP U-Pb geochronology. Both datasets are important for regional-scale targeting linking large-scale mineralisation to relatively juvenile magmas derived from underlying fertile, metasomatised upper mantle.

Modernisation, expansion and integration of our systems will allow our geoscience databases to be accessed and interrogated online, and for our customers to be able create their own, customised geoscience reports and maps. Upgrading of the petroleum and geothermal and mineral databases will streamline exploration reporting and information release. Of particular importance will be access to mineral drill hole information, and to related geochemistry, which will include the entire TerraSearch surface and down hole geochemistry database for WA.

There will be an expansion of cooperative projects between GSWA and other government geoscience organisations, including Geoscience Australia and CSIRO, and with university earth science departments and research centres of excellence These projects will focus on the provision of strategically important information on mineral and petroleum systems, particularly for exploration targeting in under-explored greenfields regions, and in emerging areas such as tight gas, geothermal energy, and carbon dioxide geosequestration, where skills are in short supply.

Our overall aim is to develop an integrated approach to the delivery of the new and expanded datasets and their interpretation based on the development of the capability to model and visualise geological and geophysical data in 3D. Integration of the modelling of crustal architecture with geochronology, isotopic signatures, an understanding of geodynamic setting, and of the mineral and petroleum systems present in an area will act as a powerful guide to exploration potential. The challenge is to ensure that the datasets and products generated under EIS are effective in generating new exploration targets, particularly under thin soil and sedimentary basin cover, which may then qualify for funding under the Government co-funded drilling scheme component of EIS.

Thinking out cloud: the need for increasing virtualisation of Australian geoscience data to underpin cost-effective deep exploration

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The Geological Surveys of Australia have amassed substantial volumes of geophysical, geological and geochemical data from both open file company data and from their own geophysical, geological and geochemical acquisition programs. Currently, all surveys have a policy of open access to data and significant volumes of precompetitive data are available either free via the internet or at the nominal cost of transfer.

Access to such ever increasing volumes of precompetitive data should make Australia an attractive place to explore. Yet open access to these data does not seem to have made a significant impact on discovery rates in Australia, which continue to decline. Exploration in Australia is seen as too hard and there is an increasing shift in emphasis to deep exploration which is orders of magnitude more expensive.

Cost effective deep exploration will require a greater emphasis on new targeting strategies based on robust and testable 3D models that are produced by integration of fairly large volume digital data sets. Generating such 3D models in house requires a sizeable investment by individual organisations in computational infrastructure, in particular High Performance Computing (HPC).

However, the volumes of geophysical data are growing exponentially as improvements in the capacity of instruments have resulted in data being gathered at a greater rate and at higher resolution. This data deluge has been impacting on Geological Surveys and the Minerals Industry for some time, with the resolution and size of some digital data sets now reaching the point where they are exceeding the computational infrastructure of any organisation to:

- store and dynamically access the data sets internally
- internally process and analyse them to their full resolution
- deliver them online to clients, partners and stakeholders.

The standard way of dealing with a lack of computational power has been to approximate or sub-optimise HPC tasks by

- dividing tasks into smaller units and then stitching the individual units together
- degrading the data to larger cell sizes
- introducing simplifying approximations

To develop robust and testable 3D models to underpin cost effective deep exploration, more precise solutions are required.

The Cloud Computing paradigm, an adaptation of the Grid computing model, offers the Minerals Industry online access to the required HPC to generate high resolution 3D models. Cloud computing is a delivery model for IT services based on the Internet. Computational power, data and processing software are no longer required to be hosted within a single organisation. Users no longer need knowledge of, expertise in, or control over the technology infrastructure 'in the cloud': such services are virtualised and mostly available on demand.

A proposition is to develop a National Virtual Geophysical Laboratory similar to the Virtual Core Library being developed by AuScope as part of the National Collaborative Research Infrastructure Strategy (NCRIS). Standardised geophysical data sets would be either localised next to HPC Facilities or connected to them by high speed networks. Processing software would be available as online services. Open source software could be modified to operate as online services whilst commercial software would require a shift from a business model of one licence per seat per organisation to that of software being accessed either as a fee for time used or as a subscription service. A user would remotely log on, do the required processing online and then download the result: where 'in the cloud' the actual data, HPC and software are geographically located is irrelevant.

Other thematic virtual laboratories could be built (geochemistry, geology, satellite data, etc). By using agreed national profiles of relevant international standards data could be seamlessly integrated over the internet.

Utilising more powerful compute facilities will vastly improve the quality and resolution of our 3D models. More particularly, enhanced computer capacity and storage volumes will also allow uncertainties to be expressed in 3D models, so that the user will know how many points were used in the definition of each particular surface and what the uncertainties are for each measurement. Quantification and visualisation of uncertainties would also enable companies to know that when a deep drill target is identified in a 3D model, they would also know exactly which data were used to generate a particular target and just how reliable each data point is.

TOPICAL

Cassiterite—the zircon of mineral systems? A scoping study

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Cassiterites (SnO_2) from a variety of deposit settings in New South Wales were examined using LA-ICPMS to evaluate their usefulness for U-Pb dating and trace element chemistry. Cassiterite is a common mineral in granite-related ore deposits, but can also be found in some other mineral systems. It is chemically and mechanically stable and capable of long distance transport and deposition in placer deposits. Metals such as Nb, Ta, Ti, W and In can occur as substitutions into the cassiterite lattice, occasionally in economically viable abundances. While many other elements are also claimed as crystallographic substitutions (Ge, Sc, Zr, Be, Pb, Ag, Mo, Zn, V), most existing data is based on 1970s era literature using poor resolution analytical techniques involving mineral concentrates and whole crystal digestion techniques. The similarity of cassiterite to rutile in its ability to sequester U while excluding Pb, then retaining both subsequent to crystallisation, suggests that cassiterite should also be ideal for obtaining direct ages on mineralisation events (Gulson and Jones, 1992, Geology 20, 355–358).

For this scoping study we analysed cassiterite from the following deposits: Mole Granite (Yankee Lodes, Wallaroo Mine, Emmaville deep leads), Gundle and Elsmore (all from the New England Orogen); the Gibsonvale deep leads (shed from the Kikoira S-type Granite, Lachlan Orogen); and the Euriowie pegmatite (Curnamona Province). Cassiterite from Ardlethan was also examined. Trace element analysis indicates that Nb, Ta, W, Ti, Sc, Zr, Hf, U, Y and In among others form crystallographic substitutions, some of them in significant quantities. Large variations in concentrations of these elements and in the Ta/Nb ratio are also apparent between cassiterites sourced from I- and S-type granites.

Age determinations on cassiterites from Wallaroo, Yankee, Gibsonvale, and Gundle using NIST 612 glass as a U-Pb isotopic standard were calibrated against the known ages for these deposits. The results showed a simple linear trend with $r^2 = 0.9998$ for cassiterites over the age range from ~221 to ~432 Ma (all ages corrected for common Pb). Using this correction, cassiterites from a quartz-feldspar- muscovite pegmatite at Euriowie

yielded an age of 1506 ± 52 Ma (error does not include error propagation from age correction) broadly consistent with the inferred, but undated, timing of pegmatite formation based on deformation timing. Subsequent analyses yielded ages directly comparable with known age constraints established previously using Ar-Ar, U-Pb zircon and Rb-Sr mineral-whole rock techniques. For example, stockwork vein-hosted cassiterite from the Great Britain Mine and Taronga deposit, and deep lead alluvial tin from the Endeavour mill at Emmaville yielded 242 ± 3 Ma, 245 ± 3 Ma and 245 ± 3 Ma respectively, consistent with the 243 ± 1 Ma Rb-Sr mineral whole-rock isochron for the Mole Granite and related mineral deposits (Kleeman et al., 1997, Geol. Soc. Aust. Spec. Pub.19, 254–265). Previous studies on REE and trace element data on cassiterites deposited in the contact rocks around the Mole Granite have suggested that significant trace element exchange has taken place between the wallrocks to the granite and the Sn-bearing hydrothermal fluids prior to precipitation of the cassiterites in sheeted vein systems (Plimer et al., 1991, Mineral. Deposita 26, 267–274). These processes have not affected the U-Pb ages of cassiterites deposited either in volcanics at the Great Britain mine or in sediments as at Taronga. Results for the detrital cassiterites from the Emmaville and the Gibsonvale deep leads demonstrate the ability of cassiterite to maintain its geochemical integrity during erosion, transport and deposition.

Interestingly, cassiterite from the Elsmore greisen east of Inverell yielded an age of 242 ± 2 Ma, identical to that of the Mole Granite and its related deposits rather to that of the adjacent Gilgai Granite which has been dated at ~253 Ma. Cassiterite from the problematic Ardlethan tourmaline-rich breccia hosted deposit in the Lachlan Orogen yielded an age of 402 ± 2 Ma, much younger than previous dating, but close to the Pb model age for the deposit. U-Pb zircon dating using SHRIMP will confirm the ages for both Ardlethan and Elsmore.

The application of isotopic dating and trace element analyses of cassiterites will aid in provenance identification, age dating of mineral systems, and measuring and quantifying the role of wall rock in determining ore mineral assemblages, stabilities and zoning in wallrock hosted Sn deposits.

Australia's IMS 1280 large-radius ion microprobe

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The large-radius Cameca IMS 1280 Ion Probe Facility represents substantial investment from the Federal Government, the State Government of Western Australia, and The University of Western Australia to produce a truly world-class Secondary Ion Mass Spectrometry (SIMS) facility. NCRIS funding, through AUSCOPE and the Australian Microscopy and Microanalysis Research Facility (AMMRF), ensures that the Facility is available to all publicly-funded Australian researchers, international researchers, and industry. The IMS 1280 was installed in April 2009, and although the instrument has suffered typical first year 'hiccups', facility staff have been successful in developing and benchmarking a variety of measurement protocols. Sub per-mil external precision has been demonstrated for a variety of isotope systems including B, C, O, N, Si, S, Fe, and Sr in various matrices, and acceptable results have additionally been demonstrated for H and U for specific applications. Due to the matrix-dependent nature of SIMS analyses, well-characterised matrix-matched standards are mandatory to achieve accurate results. The development of high-quality standards will continue to make up a large percentage of analytical efforts for the foreseeable future. The status of these developments will be presented, and the geochemistry community is invited to treat this communication as a forum to discuss analytical requirements and requests.

Applications of mico-Raman spectroscopy for the identification of minerals and their polymorphs

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Micro-Raman spectroscopy has become an important, versatile, non-destructive technique that is well-suited to the study of minerals and the inclusions they may contain. This technique is particularly useful in cases where more common techniques (e.g. electron microprobe or X-ray diffraction analysis) cannot be used, for example, because of the difficulties in separating or preparing the sample to be studied. Another advantage of micro-Raman spectroscopy is that polymorphs with the same chemical composition can be easily distinguished. Furthermore, the Raman mapping technique can be used to generate a spectroscopic map of

the sample. The wealth of detailed spectral information produced during Raman mapping has made this an extremely valuable technique for detailed studies of internally heterogeneous minerals.

Because of the ability to perform analyses non-destructively, the micro-Raman technique has become an extremely valuable tool in the study of gemstones, including the identification of inclusions, and the detection of potential treatments done to enhance their colour and clarity. For example Millsteed et al. (2005) used micro-Raman spectroscopy for the characterisation of rhodonite from Broken Hill and the solid and fluid inclusions trapped therein. Raman analysis has also been applied to the study of minerals that have been fully or partially amorphised due to the effects of radioactivity, for example in radiation-damaged zircon, monazite and biotite. The Raman spectra provide information on the degree of short-range order and crystallinity, respectively. Another application based on crystallinity has been the characterisation of carbonaceous materials ranging from kerogens to granulite-facies graphite. This has led to the development of new geothermometers based on the Raman spectra of carbonaceous materials in metasediments (e.g. Beyssac et al., 2002).

Micro-Raman spectroscopy has been particularly useful for the rapid identification of polymorphs such as kyanite, andalusite and sillimanite. The difference between the Raman spectrum of α-quartz and moganite has allowed Raman mapping of rhythmic growth banding of moganite-bearing chalcedony. Micro-Raman spectroscopy has also been used for the identification of coesite (and other) inclusions in diamonds and also for determining the confining pressure on these coesite inclusions based on systematic shifts in the spectral bands. The Raman spectrum of diamond also changes with pressure and this has been used to map the strain around inclusions in diamond (Barron et al., 2008).

Semi-quantitative chemical analysis can also be carried out using micro-Raman spectroscopy. Mernagh and Hoatson (1997) used micro-Raman spectroscopy to identify different pyroxene solid solution compositions from the Munni-Munni layered intrusion in Western Australia. In another study, this technique has been used for the calibration of the Raman spectra of the forsterite—fayalite series (Mouri and Enami, 2008). A statistical method for determining the composition of an unknown sample in *n*-dimensional chemical space has also been developed by Smith (2005) and it is also possible to study the isotopic composition of minerals and included phases (e.g. Irmer and Graupner, 2002).

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HyLogger alteration fingerprints of NSW type deposits and their regional application

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This paper discusses the integration of HyLogger data into pre-existing geological and petrological frameworks and the regional application of spectral downhole data. Examples will be drawn from the alteration fingerprints generated for NSW deposits.

Hyperspectral logging (HyLogging) capabilities have recently been made available to the Geological Survey of New South Wales as research infrastructure delivered through the AuScope National Virtual Core Library. The HyLogger identifies spectrally responsive minerals in the visible-near infrared and shortwave infrared spectrum (600–2500nm) with an 8mm pixel resolution. An upgrade to thermal spectral capabilities will facilitate detection of non-hydrous silicates.

An initial HyLogging program conducted by the Geological Survey of New South Wales has focused on 'type deposits' from premiere mineral districts around New South Wales. The deposits represent several diverse mineral systems in NSW (Lewis and Downes 2008). Deposits scanned include Woodlawn and Captains Flat (VHMS), Dargues Reef (granite-related gold), Peak and Thackaringa-type (hydrothermal-metamorphic base metal), Dome 5 (carbonate hosted), and Doradilla (skarn).

The spectral data generated by HyLogger is efficient in identifying broad alteration related to mineralisation, particularly when used in conjunction with similar resolution datasets—logs, assays and petrophysics (Mauger et al 2007, Reid 2009, Clissold and Reid 2009). The system commonly identifies previously unrecognised minerals in the drillcore or increased differentiation of known minerals by their spectral variability. However, best constraints on the alteration assemblages of mineral systems are achieved by integration of ancillary paragenetic controls—thin sections, isotope data, structural interpretation, etc. The Dargues Reef deposit is a good example, with isotope data indicating an open, single phase alteration system (McQueen and Perkins 1995) These data accommodate the resolution gap (and the resulting ambiguities) delivered by the HyLogger and permit accurate interpretation of the alteration system.

Identified alteration data generated from scanned drillholes can be extrapolated to regional prospectivity and exploration, by generating spectral (or mineralogical) vectors towards unrecognised mineralisation and reducing exploration risk. Three themes to achieve this are considered:

- regression to satellite or airborne multi- and hyper-spectral datasets (e.g. Mauger et al 2007). In Broken Hill, Thackaringa-type galena-siderite-quartz veins have been targeted with both HyLogger and HyMap (Mauger and Clissold 2009, Clissold and Reid 2009, Cudahy et al. 2009)

- spectral logging of bottom-of-hole reconnaissance drilling in Cobar-Girilambone—Chan et al 2001, Reid 2009)

- spectral analysis of samples collected in GSNSW regional mapping campaigns (eg. Braidwood 100k).

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