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Dr Gavin Young with the life-sized model of the giant Devonian lobe-finned fish *Edenopteron* built by Baz Waterhouse. Photo: Belinda Pratten, courtesy ANU Media Office. Hear Dr Gavin Young deliver the Mawson Lecture, Tuesday, 8 July 2014.

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MONDAY 7 JULY

PLENARY

PLEN1-01. BETWEEN A ROCK AND A HARD PLACE: COMMUNICATING CONTESTED GEOSCIENCE

Iain Stewart

Plymouth University, Drake Circus, Plymouth PL4 8AA, United Kingdom

Geological issues are increasingly intruding into ordinary people's lives. Whether it be onshore exploration and extraction of oil and gas, deep injection of waters for geothermal power, or underground storage of carbon dioxide and radioactive waste, many communities are having to confront the ramifications of geological interventions beneath their backyard. In turn, professional geologists are increasingly being encouraged to communicate what they do and what they know to the public, and even to advocate more directly policy dimensions with stake holders and decision makers. Yet how can we do that when, for most people, geology is about 'stones' and stones are 'boring'! It is a problem compounded by the fact that many of our most acute geo-issues pertain to the unfamiliar realm of the deep subsurface. The result is that geology is largely out of sight and out of mind. To counter this, this talk will use a decade of experience in popularising geoscience for mainstream television programmes to explore ways in which geologists can make our subject connect better with the dissonant public, and in doing so forge more effective strategies for meaningful public engagement.

ENVIRONMENT

01EVA – HYDROGEOLOGY, THE WATER WITHIN

01EVA-01. NEOGENE-TO-RECENT TECTONICS: A KEYSTONE ELEMENT OF MANY HYDROLOGICAL/ GROUNDWATER SYSTEMS IN AUSTRALIA

K C Lawrie, Ross S Brodie, J Magee & L Halas

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Climate and paleoclimate processes, together with surface topography, drainage and river flow characteristics, soils, vegetation, land use, geomorphology and underlying geology, are key variables that dictate surface–groundwater interaction and groundwater distribution and sustainability. However, the role of geodynamics/tectonics in determining hydrological and groundwater processes as well as the 3D hydrogeological architecture of basins and catchments, have often been overlooked or under-estimated in Australia. This paper will demonstrate the importance of Neogene-to-recent tectonics for understanding hydrological systems across the continent generally, using regional examples including the Ord Valley (East Kimberley, WA), the Burdekin Delta (North Queensland), and the Murray and Darling Rivers (New South Wales/Victoria).

At long wavelengths (>10^3 km), dynamic topographic effects (influenced by plate stresses and Cenozoic volcanism in Eastern Australia) have controlled the tilting of the continent, while dynamic uplift has produced a relatively small topography range and low hydraulic heads to drive slow-moving groundwater flow systems. At intermediate (10^2–10^3 km) wavelengths, tectonics, through large-scale undulations and regional dynamic topography effects, has played a significant role in the development of major drainage basins, valley and river morphology, and consequently the character and distribution of aquifers and aquitards within these catchments/basins. Intermediate scale tectonics also influences the development of regional to intermediate scale groundwater flow systems. At short wavelengths (<10^2 km), tectonics is locally manifested by the development of fault systems and associated tilting, and discrete faults that modify local landscapes including valley and river morphology, and local aquifer and aquitard character and distribution. Neogene-to-recent tectonics at short and intermediate wavelengths has also been linked to the control and avulsion of major river systems (e.g. Edwards–Murray; Keep–Ord and Talyawalka Creek–Darling River) thereby influencing surface–groundwater interaction, inter-aquifer leakage and local to intermediate groundwater flow.

In the Broken Hill Managed Aquifer Recharge (BHMAR) Project, previously unidentified deformation of Murray Geological Basin unconsolidated sediments has been recognised beneath the Darling Floodplain, N.S.W. Deformation is manifested as discrete faults, tilting and warping within discrete, complex strike-slip fault zones. These fault zones control the major drainage features, inter-aquifer leakage, paleohydrology and recharge of the underlying Pliocene aquifers. Tectonics therefore plays a vital role in the viability of MAR and groundwater extraction options in the area, although the key tectonic elements were only revealed upon the acquisition of high-resolution airborne electromagnetics (AEM) and LiDAR datasets, validated by drilling, and ground and borehole geophysics.

In summary, recent studies have demonstrated that Neogene-to-recent intraplate tectonics play an important role, at a range of scales, in determining the location, nature and duration of surface hydrological processes including surface–groundwater interactions, and the distribution and quality of groundwater resources. Many of these features have only been mapped using high resolution geophysical and geospatial datasets, combined with novel basin and landscape mapping, modelling and assessment approaches. Geodynamics/tectonics can therefore be considered a 'keystone' element of many Australian hydrological and groundwater systems, often disproportionately important to the workings of these systems relative to the size, abundance and/or distribution of the tectonic elements that control or impact these systems.

01EVA-02. RAINFALL ISOTOPE (^{3}H, δ^2H and δ^{18}O) INPUT TO GROUNDWATER IN AUSTRALIA

Cath Hughes, Carol Tadros, Suzanne Hollins, Jagoda Crawford, Dioni Cendón & Karina Meredith

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The stable isotopes of water, δ^2H and δ^{18}O, are conservative tracers available for studying mixing of water in the hydrosphere. Radioactive tritium (^{2}H, half-life = 12.3 years), derived from both cosmogenic and anthropogenic sources (nuclear testing), is an important tracer for dating of young groundwater. Measurements of stable water isotopes and tritium in Australian rainfall have been made monthly at six coastal sites and Alice Springs since 1962 as part of the Global Network of Isotopes in Precipitation (GNIP).

Since 2006 this network has been expanded to include seven inland sites in New South Wales, Queensland, South Australia and Western Australia (δ^2H and δ^{18}O analysed only). In addition, event-based studies of stable water isotopes have been conducted at four locations in the Sydney region since 2005. These data have been analysed to determine local meteoric water lines, weighted averages and to investigate the relationships between rainfall isotopic composition, temperature and precipitation amount. Stable water isotopes are not completely conservative as they undergo fractionation as a result of hydrological processes such as evaporation, precipitation, ice and snow formation and melting, and geothermal activity. The fractionation can be used to understand the provenance and history of groundwater and to define end members for mixing studies.

For age dating of groundwater using tritium the rainfall tritium composition is required. In addition to the 50-year tritium record available from GNIP for six sites, data for an additional eleven locations throughout eastern Australia were compiled for varying periods mainly between 1970 and 1991, thereby improving the spatial resolution of the tritium time series in Australia. Unlike δ^2H and δ^{18}O, the spatial distribution and seasonal variation of tritium in rainfall is largely controlled by the stratosphere to troposphere exchange of anthropogenic tritium from nuclear testing, with the highest concentrations occurring at Adelaide and Melbourne during the early spring. Modern concentrations appear to be stabilising with average annual concentrations in the range 1–3 TU increasing with latitude. These data have also been used to estimate the tritium composition of rainfall resulting in the January 1974 Queensland floods, which are believed to have resulted in significant recharge to aquifers in Queensland and northern NSW.

01EVA-03. GROUNDWATER SYSTEMS IN NORTHERN AUSTRALIA – ARE THEY SUITABLE FOR A NORTHERN FOOD BOWL: EVIDENCE FROM RESIDENCE TIMES AND GEOCHEMICAL ANALYSES OF GROUND AND SURFACE WATERS IN THE LAWN HILL REGION, NORTHWEST QUEENSLAND

Mira van der Ley[1,2], Dioni I Cendón[2] & Ian T Graham[1]

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Water resources in the northern regions of Australia have become increasingly important with the possible development of a northern 'food-bowl'. Understanding the chemistry, flow systems, and mean residence time (MRT) of groundwater systems in this region is therefore essential.

The Lawn Hill region of northwest Queensland is subjected to a semi-arid monsoonal climate with an average of 542 mm/a – the majority falling in the warmer months through November–March. Due to the polarity of rainfall, most streams run dry during the dry season. However, four major perennial streams are maintained by groundwater discharge, highlighting the importance of groundwater–surface water interaction and our understanding of such systems. The regional geology is dominated by the Barkly Tableland, an expansive Cambrian carbonate plateau, or siliciclastic formations of the Proterozoic Mount Isa Inlier.

The carbonate and siliciclastic lithologies exhibit variable influences on groundwater chemistry and flow. There are distinct differences in chemical signatures whereby the carbonate-hosted groundwater was found to be strongly influenced by carbonate dissolution with little evidence of evapotranspirative enrichment as indicated by both Cl concentrations and stable water isotopes (SWI). Conversely, major ion chemistry and SWI composition of the siliciclastic-hosted groundwaters suggest they are strongly influenced by evapotranspirative enrichment and less by later water–rock interactions (though these do impart a signature on groundwater chemistry). Importantly, the limited influence of evapotranspiration on carbonate-hosted groundwater with TDS values ranging 540–611 mg/L means these waters are classified as freshwater and represent a low–medium irrigation salinity risk. Comparatively, the siliciclastic-hosted groundwaters have much higher TDS values (599–7204 mg/L), which spans the fresh–brackish–saline classifications and represents a medium–high salinity risk. These differences highlight the fact that suitability of groundwater for irrigation purposes greatly depends on the geological controls through water–rock interactions and influence on groundwater infiltration.

The mean residence time (MRT) of groundwater is an important indicator for groundwater sustainability. Again, there is a clear distinction between carbonate and siliciclastic hosted groundwaters. Both tritium and radiocarbon analyses of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) indicate a modern age for carbonate groundwaters with fast recharge indicating the carbonate groundwater is less susceptible to depletion but more susceptible to anthropogenic influences. Comparatively, measurable tritium concentrations in siliciclastic groundwaters indicate a modern system; however, DIC and DOC radiocarbon analyses indicate a much older groundwater up to *ca* 10 000 a (depending on the flow model applied). The differences between tritium and radiocarbon MRT may indicate more complex mixing between young and old groundwater and slower recharge, suggesting siliciclastic groundwaters may be susceptible to depletion.

01EVB – HYDROGEOLOGY, THE WATER WITHIN

01EVB-01. VERTICAL PERMEABILITY OF AQUITARDS – CORE TESTS TO BASIN SCALE MODELLING

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Direct measurement of hydraulic connectivity at multiple scales (core, bore, site and basin scale) can provide confidence in groundwater models of groundwater extraction for water supply and for mining and gas extraction projects. A lack of aquitard data often leads to indirect modelling of aquitards *via* a constant assumed 'vertical conductance' term between aquifers but contributes to non-unique models that are unreliable as a basis for management decisions. This paper proposes a new leading practice for evaluating the possibility of vertical connectivity in aquifer/aquitard systems through direct measurement and advanced multiple model techniques. Bore testing methods typically provide hydraulic conductivity in a horizontal (K_h) orientation, while aquifer pump tests have a lower limit K of 10^{-8} m/s. Core-scale testing can add value to drilling data by providing high-resolution vertical data including K_h or K_v for ultra-low K confining strata. For example, testing of silty cores by standard rigid and flexible wall column techniques require 1–2 weeks, compared with <1 week in a geotechnical centrifuge permeameter (CP). Hydraulic testing of half cores or semi-saturated cores (20 to 100 mm diameter) may only be viable by CP, with advantages for quantifying coupled hydromechanical or hydrochemical processes under specific *in-situ* conditions. Leading practice evaluation of vertical connectivity would involve many steps including: drill coring and appropriate core preservation on site, permeability testing using a suitable method (eg. gas permeation, triaxial cell or geotechnical centrifuge). A geostatistically relevant number of representative cores of a specified lithology (determined by a data worth evaluation) are examined, followed by fluvial process modelling to generate multiple permeability distributions for groundwater flow modelling. Permeability estimates of specific facies can be calibrated to match the bulk-averaged values from core scale testing. Examples of multi-scale measurements and modelling of aquifer–aquitard systems will be provided for alluvial and sedimentary rock groundwater systems.

01EVB-02. UNCERTAINTY IN EFFECTIVE HYDRAULIC CONDUCTIVITY DUE TO GEOLOGICAL HETEROGENEITY

Sanjeev Kumar Jha[1], George Mathews[2], Florian Wawra[1] & John Vial[2]

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Any hydrogeological study requires determining an appropriate representative macroscopic volume (RMV) and assigning an effective hydraulic conductivity (K_{eff}) value to it. The hydraulic conductivity values are measured at a small scale called representative elementary volume (REV). In an alluvium setting, it is important to understand the arrangement of geobodies, their sizes, horizontal and vertical connectivity etc., to be able to determine how much uncertainty in K_{eff} value is caused by small and large scale geological features while translating the geological information from REV to RMV scale.

In this study, a systematic investigation is performed to determine the influence of channel orientation and aspect ratio on the K_{eff} values over different RMVs. The geology is composed of meandering channels in a shallow fluvial aquifer consisting of two facies, sand and clay. The proportion of each facies is considered as 50%. 3D binary facies models are obtained by applying multiple-point geostatistical simulation (MPS) and parameterising the 3D structures by applying a rotation parameter. Channels of two different depths and 7 orientations are considered. Fifty realisations of each model produced a total of 700 (2×7×50) facies models for flow studies. The steady state simulations are then performed using the MODFLOW-2005 code to obtain effective hydraulic conductivity values ($K_{x,eff}$, $K_{y,eff}$, $K_{z,eff}$). Four contrasts of hydraulic conductivity values are considered in the flow simulations. Multiple realisations from MPS simulations enable us to obtain a probability distribution over the upscaled hydraulic parameter fields at the RMV scale. Results show that the K_{eff} values are greatly influenced by the aspect ratio of channels than the orientation of the channels.

01EVB-03. ESTIMATING DIFFUSION IN HETEROGENEOUS GROUNDWATER SYSTEMS USING SHORT-LIVED RADIO-ISOTOPES AND STABLE ISOTOPES OF IODINE OR BROMINE

Mark A Peterson[1], Dioni Cendón[1], Martin S Andersen[2], Lida Mokhber-Shahin[1], Henri Wong[1] & Brett Rowling[1]

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Diffusion is an important and ubiquitous phenomenon in nature, but too often neglected or unmeasured in water resource hydrogeology or solute transport. Diffusion may, in fact, be the dominant process that dictates hydrogeochemistry and affects tracers. Conservative and age tracers are commonly used for water resource or contaminant plume transport estimations, but will give misleading results, if diffusion is ignored. Diffusion of tracers into aquitards, matrix pores of fractured rocks, blind fractures or other low conductivity zones lead to retardation and possible adsorption, exchange, precipitation or decay. This becomes increasingly important as heterogeneity of flow domains increase, for example, in fractured rock aquifers, interlayered sediments or aquifers associated with aquitards. Traditional methods of measuring diffusion coefficients in small slices of heterogeneous rock are unreliable for upscaling, so this study presents an alternative method based on lab-scale drill-core tests and suggests field-scale borehole tracer tests.

Fick's first law shows that diffusion rates are driven by concentration gradients. Short-lived radiotracers soon reach a steady-state concentration gradient with enhanced flux where diffusion rate equals decay, while stable tracers trend towards saturation and ever-decreasing fluxes. We compare diffusion of short-lived radiotracers ^{131}I (half-life 8 days) or ^{82}Br (half-life 1.5 days) to their stable equivalent (I or Br) into 45–50 cm lengths of ~60 mm diameter drill core. Five cores were selected from three fractured rock environments: sandstone, limestone and metavolcanics. By regularly sampling and refilling the annulus with tracers around the enclosed core, we are able to discern differential in-diffusion between stable- and radio-tracers.

For example, the annulus was sampled and refilled weekly with an (equivalent decayed) ^{131}I activity of 22 Bq/g and within three weeks (2.6 half-lives) each core had reached a characteristic steady state flux. The net fluxes were around 1.0 Bq/cm^2/week in the sandstone cores, 0.2 Bq/cm^2/week in the metavolcanics, and 0.05 Bq/cm^2/week in the limestone. This was compared to stable iodine weekly refills at 2.6 mg/L, which gave ever-diminishing diffusion results. The net fluxes of stable iodine diminished steadily, e.g. over three weeks from 98 to 26 ng/cm^2/week for the most porous (medium sandstone ~15%), and from 11 to 7 ng/cm^2/week for the least porous (limestone ~2%).

Experiments were also performed using ^{82}Br and stable bromine, with sampling and refills performed on a daily (0.68 half-lives) basis. Similar trends were apparent, though the data was noisier due to more frequent refills and less time for diffusion to generate significant changes in the annulus reservoir solutions.

This method enables analysis of drill cores for comparative effective diffusion coefficients of different systems. Quantitative interpretation is currently being refined. In principle, the method should be transferrable to single boreholes or tracer tests between multiple boreholes to gain larger scale representation of effective diffusion within a groundwater system. The normally confounding factors, such as dilution, advection, exchange, adsorption and precipitation, are negated by comparing the stable with radio-tracer results, as all isotopes of these elements are identically affected by such processes and losses.

01EVB-04. A HYDROGEOCHEMICAL STUDY OF SHALLOW SALINE GROUNDWATER IN SOUTH WEST SYDNEY, AUSTRALIA

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Groundwater in western Sydney has been known to be saline for many years. The source of the salinity has not yet been identified, though many have suggested that the marine origin of the Wianamatta Shales, which are the dominant geological formation in areas of known high salinity, combined with the bowl-like topography of western Sydney are significant contributors. Others have suggested that due to the high solubility of halite this is unlikely as the sediments are over 200 million years old, and that dry deposition and evaporative concentration of precipitation are the likely sources of the salt. Knowledge of the type and source of salts in groundwater in the area would be useful for land managers at all levels, as it would enable them to make informed decisions about future practices to prevent possible land degradation through salinisation.

A hydrogeochemical study was conducted in the Mt Annan area of southwest Sydney with monthly data collected between July 2011 and July 2012 presented in this study from six permanently wet and one seasonally wet monitoring bores. Seasonal variation in composition was not apparent, with electrical conductivity varying less than 10% between seasons at most sites, while the variation in seasonal rainfall was greater than 50%. It is thought that an unusually wet summer and autumn in early 2012 may be obscuring any seasonality. Averaged electrical conductivities of the sites ranged from 3863 µS/cm at Banksia to 22385 µS/cm at Lake Fitzpatrick 1, with averaged pH being circumneutral for all sites. All groundwaters were Na–Cl dominated with chloride ranging from 27% of TDS in the least saline samples to 43% of TDS in the most saline samples where it is the major constituent. Sodium content ranged from 35–41% of TDS in the averaged data. Plots of sodium and chloride concentrations indicate that most sodium is sourced from precipitation originating from ocean water as would be expected in a coastal location. Other ions such as magnesium, calcium and carbonate however are enriched, thus water–rock interactions and cation exchange could be contributing to the ion load of the groundwater. Stable isotope analysis revealed that the samples fall on a local evaporation line ($y = 5.29x + 0.08$, $R^2 = 0.91$), suggesting that enrichment through evaporation is an important source of salts. The proximity of the data to the LMWL and the GMWL indicate that connate water is unlikely to be present.

01EVC – HYDROGEOLOGY, THE WATER WITHIN

01EVC-01. HYDROGEOPHYSICAL DATA ACQUISITION STRATEGIES FOR NEAR-SURFACE HYDROGEOLOGICAL INVESTIGATIONS IN THE AUSTRALIAN LANDSCAPE CONTEXT

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Hydrogeophysical data are increasingly acquired as part of investigations to map key functional elements of hydrogeological systems, and to underpin groundwater management. Within the suite of geophysical tools available, airborne electromagnetics (AEM) provides a rapid cost-effective means of mapping relatively large, hydrogeologically complex areas. In Australia's highly salinised landscapes, AEM, combined with ground and borehole control, is the only broad-scale technique capable of mapping groundwater systems and groundwater salinity to depths of 200–300 m. A wide range of AEM systems and acquisition platforms are available, and the technology is now recognised as mature, and capable of mapping complex hydrogeology and groundwater salinity relationships in a variety of landscape and geological settings. Optimisation of AEM data requires careful consideration of AEM system suitability, calibration, validation and inversion methods. The choice of an appropriate AEM system for a given task should be based on a comparative analysis of candidate systems, consisting of both theoretical considerations and field studies including test lines over representative hydrostratigraphic targets.

For the Broken Hill Managed Aquifer Recharge (BHMAR) project the SkyTEM AEM system was chosen, after a rigorous selection process, to map groundwater quality (salinity) distribution within a multi-layered sequence of sand and gravel aquifers and clay aquitards to depths of ~120 m within unconsolidated sediments of the Murray Geological Basin. The AEM acquisition strategy was governed by the need to rapidly identify and assess potential managed aquifer recharge (MAR) and groundwater resource targets over a large area (>7500 km^2), with a high degree of confidence. Utilising a flight line spacing of 200–300 m, the AEM data, validated by drilling, successfully mapped the key elements of the hydrostratigraphy, critical Neogene-to-recent tectonic features, and 14 potential MAR and groundwater resource targets.

Subsequent to successful completion of the project the AEM data were re-inverted to assess optimal line spacings for the different mapping objectives. Data for the central project area were re-inverted corresponding to a line spacing of 200 m, 600 m, 1 km, 2 km and 5 km. Analysis of these data show that some key features of the hydrogeological system (e.g. aquitard distribution and discrete faults) required for MAR target mapping and evaluation as well as the understanding of groundwater processes, are only mapped with the required confidence using higher resolution (200–300 m) line spacings. In contrast, the larger groundwater resource targets and the principal near-surface aquifers can be identified at coarser line spacing (even at kilometre spacing).

For many groundwater mapping objectives, reconnaissance surveys at wide line spacings can be used to identify broad-scale features, with higher resolution data in selected areas acquired subsequently to address specific questions. This multi-scale strategy is not always possible in project timelines, and, in the BHMAR project, it was fortunate that a large number of targets were mapped at high resolution simultaneously due to a high failure rate in MAR evaluations. Ultimately, the line spacing required will depend on the project objectives, the scale of key landscape elements, and the nature of the hydrological system.

01EVC-02. GROUNDWATER REQUIREMENTS FOR A MINING OR COAL SEAM GAS GATEWAY APPLICATION

George Gates (retired)

NSW Office of Water, NSW 2001, Australia.

This talk has been prepared to assist applicants and others understand the groundwater information requirements for a Gateway application.

The Mining and Petroleum Gateway process ('Gateway process') is an independent, scientific assessment of how a state significant mining or CSG production proposal will impact the agricultural values of the land on which it is proposed to be located.

The Gateway assessment is undertaken by an independent expert panel – the Mining and Petroleum Gateway Panel. Members include: Mr Terry Short (Chair), Professor Garry Willgoose, Mr George Gates PSM, Dr Ian Lavering, Dr Brett Whelan and Dr Russell Frith.

The Gateway process is established through Part 4AA of the State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007 (the Mining SEPP). The Mining and Petroleum Gateway Panel website shows the panel assessments completed to date. See www.mpgp.nsw.gov.au

Strategic agricultural land (SAL) is highly productive land that has both unique natural resource characteristics (such as soil and water resources) as well as socio-economic value (such as high productivity, infrastructure availability and access to markets). Two categories of SAL have been identified: Biophysical SAL and Critical Industry Clusters (CICs).

The Panel expects applicants to address all of the criteria listed in the Mining SEPP. For groundwater there are eleven areas were information is requested. This information will be used to assess the project against the criteria specified in 'Table 1 – Minimal Impact Considerations for Aquifer Interference Activities' in the Aquifer Interference

Policy (AIP). The AIP can be found at: www.water.nsw.gov.au/Water-management/Law-and-policy/Key-policies/Aquifer-interference/Aquifer-interference

The requirement for a simple groundwater flow model will be discussed together with appropriate field studies to determine baseline hydrogeological conditions. Community concerns about the uncertainty of modelling results will also be touched upon.

01EVD – GROUNDWATER QUALITY IMPLICATIONS OF CHANGES IN PHYSICAL WATER MANAGEMENT

01EVD-01. GROUNDWATER MODERNISATION AND ASSOCIATED CHEMICAL CHANGES IN A HAWKESBURY SANDSTONE AQUIFER (KULNURA–MANGROVE MOUNTAIN, NSW, AUSTRALIA)

Dioni Cendón[1,2,4], Stuart Hankin[1], John Paul Williams[3] & Ian Graham[4]

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Land and groundwater usage has the potential to influence the groundwater chemistry of an aquifer. Progressive modernisation of groundwater, variation in pH and associated water/rock reactions have been identified in areas of the Kulnura–Mangrove Mountain aquifer (KMMA).

Detailed temporal and spatial sampling of groundwater (general hydrogeochemistry, H_2O stable isotopes, $\delta^{13}C_{DIC}$, ^{3}H, ^{14}C and $^{87}Sr/^{86}Sr$) revealed important inter-annual variations driven by groundwater extraction showing a progressive influx of modern groundwater at >100 m depth in some areas. In the Peats Ridge plateau, shallow groundwater samples show high ^{14}C bomb pulse signatures, indicating modern recharged groundwater, while deeper groundwater shows a yearly increase in modern ^{14}C inputs, instead of lower a^{14}C values, as observed in other wells and generally expected. Values evolved from 36.1 pMC (5.2 ka BP) in 2007, to modern values of 103 pMC in 2010 with the latest sample in 2012 failing to graphitise, probably due to the high CO_2 generally linked in the study area with modern groundwater. The ^{3}H activities have also evolved from values below the quantification limit in 2007 and 2008 to values of ~1.1 TU in 2012.

The minimal buffering capacity of the quartzose sandstone aquifer, at least in its upper zone where dispersed carbonates have long been dissolved, means that shallow groundwater generally has a low pH. Limited historical data (1998) shows higher pH for all samples compared to the same wells analysed for this work. However, it is in the central area where pH changes are most evident. During 2007, groundwater pH was similar to that expected for samples at similar depths with consistent groundwater residence times; however, successive samples show a shift to lower pH similar to those found in much shallower samples, as well as modern groundwater ages. Groundwater extraction is therefore causing an inflow of modern waters at depth with associated acidification.

An important consequence of acidification is the capacity to mobilise trace metals. Of particular interest is aluminium as it has been linked to enhanced risks of cognitive decline for subjects with a high daily intake from drinking water ($\geq 3.7\ \mu M \cdot day^{-1}$). Shallow samples in the Mangrove Mountain area and some of the deeper samples with Al concentrations of ~3.45 µM are a risk for average drinking water intakes. The movement of low pH shallow groundwater is causing an increase in Al concentrations, particularly in the central area of the KMMA, and this may be affecting groundwater for local consumption or that recovered in bottling plants.

01EVE – GROUNDWATER QUALITY IMPLICATIONS OF CHANGES IN PHYSICAL WATER MANAGEMENT

01EVE-01. LINKING GROUNDWATER DYNAMICS AND ESTUARINE WETLAND RESTORATION

William Glamore, Duncan Rayner & Jamie Ruprecht

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Estuaries are dynamic systems with fluctuating groundwater systems, water quality and inflows. In Australia more than 5 million hectares of estuarine sediments contain acid sulfate soils. Large-scale drainage of these soils following major floods in the 1950s has resulted in the oxidation of sulfidic sediments and the production of acidic soils and groundwater. When leached to adjoining estuarine waters, the acidic and extremely high concentrations of metals, including arsenic, can have devastating impacts on the environment and destroy infrastructure. The most common method for remediating these soils is the restoration of tidal flows that contain natural buffering agents.

To date, extensive research has been undertaken to characterise the chemical dynamics, soil structure and solute transport of the sulfuric subsoils. Onsite investigations have traditionally focused on soil acidity levels, localised groundwater transport and impacts to agricultural infrastructure with limited investigations of catchment wide processes including solute transport, acid plume coupling and buffering dynamics. The traditional site based approach provides detailed information on localised acid hotspots but limited understanding of the larger catchment dynamics and restoration potential of the site.

To better link groundwater and estuarine dynamics within a wetland restoration context, a catchment wide systems approach is recommended. This alternative approach includes assessing a range of groundwater quality and subcatchment variables to develop a prioritisation ranking for each groundwater subsystem. The potential impact of each subsystem is then assessed across the estuary by examining the fate/transport of acidic plumes, the sensitive receivers within the estuary landscapes, the flushing dynamics of the entire estuary, and the groundwater dynamics under different forcing factors (including climate change).

This paper provides a detailed description of the catchment approach supported by conceptual models. Two case studies are provided on large estuarine systems in New South Wales, Australia. The Shoalhaven River case study provides a detailed example of the catchment wide site prioritisation study, which resulted in the ranking of 39 subcatchment systems for future restoration. The Manning River case study provides a detailed on-ground example of how this prioritisation method and estuary wide approach can result in significant physical changes to onsite water management.

01EVE-02. USING CONTAMINANT MASS FLUX AND MASS DISCHARGE TO SUPPORT GROUNDWATER REMEDIATION AT BARANGAROO, SYDNEY, AUSTRALIA

Graham Hawkes[1] & Mark Burns[2]

[1]AECOM. [2]Lend Lease

The calculation of contaminant mass flux and mass discharge at Barangaroo, Sydney has been undertaken to support approval by the regulators of a remediation approach and methodology. Subsurface conditions at Barangaroo, one of Australia's largest remediation sites, are geologically complex; the site being perched on the edge of Darling Harbour and progressively developed and reclaimed for the past 120 years. Contamination at the site including petroleum hydrocarbons and polyaromatic hydrocarbons is derived from the former gasworks facility, historic wharves and associated commercial activities, and historical filling practices. The contaminant mass is located within the fill and marine sediments that underlie the site.

Developing a remediation strategy at a site like Barangaroo is dependent upon understanding the distribution of contaminants across the site and the dissolved mass flux or load of contaminants from contamination source zones that might impact on sensitive receptors. The concepts of mass flux and mass discharge as a tool to support other lines of evidence are increasingly becoming more recognised by Australian regulators as a means of protecting receiving waters rather than setting groundwater concentration trigger levels.

After the development of a conceptual site model, mass flux modelling was conducted to assess the flux of contamination that was proposed to remain *in situ* following the proposed remediation works and the improvement in groundwater quality that could be expected to be realised as a result of the proposed remediation. Mass flux discharge modelling using the Mass Flux Toolkit, developed by GSI Environmental, demonstrated that following the removal of the contaminant mass within the proposed remediation extent, the groundwater quality reaching Darling Harbour would be below the adopted marine water quality criteria for protection of the environment.

01EVE-03. RIPARIAN ZONE PROCESSES AND IMPLICATIONS FOR WATER QUALITY AND MANAGEMENT OF CONNECTED WATER SYSTEMS: A CASE EXAMPLE OF ARSENIC GEOCHEMISTRY

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Water management in Australia's arid and semi-arid regions has, in recent decades, focused on managing the quantities of water in an environment of drought and increasing water demand from irrigated agriculture. Aspects of riverbed ecology and water quality related to arid and semi-arid water management are only starting to be considered. The increase in groundwater resource development has changed groundwater flow paths in riparian zones on a massive scale. In arid and semi-arid catchments with large groundwater abstraction, streams and rivers are transitioning from overall gaining to losing conditions. This has implications for biogeochemical reactions and the transport of dissolved constituents between riparian aquifers and rivers. The shallow riparian groundwater zone (here including the hyporheic zone) often has an abundance of fresh reactive organic matter either from recent sedimentation or *via* infiltration of dissolved and particulate organic matter from the river. The oxidative demand of this organic matter from microbial metabolism drives the reduced redox conditions of the groundwater in this zone, which is therefore depleted in oxygen and contains high concentrations of dissolved reduced species (Fe(II), Mn(II), H_2S, As(III), etc.). A gaining scenario is able to confine these species to the riparian groundwater zone, from where they would eventually be discharged to the river, diluted in the surface water flow, re-oxidised, and for some species (Fe(III), Mn(IV), As(V), etc.) precipitated as oxides. In contrast, in the losing scenario caused by groundwater abstraction, the reduced water would instead migrate towards the abstraction bores and have no further interaction with the stream. Considerable questions and uncertainty remains about these processes and their effect on the fate of groundwater contaminants, especially arsenic. In this talk the release and mobility of arsenic in the riparian zone will presented and the subsequent biogeochemical reactions discussed in terms of the aquifer geochemistry beyond the riparian groundwater zone.

ENERGY

01EGA – OVERVIEW

01EGA-01. ENERGY IN AUSTRALIA – AN OVERVIEW

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Australia's domestic and export energy sectors are set to undergo a major transformation. However the exact outcome of this transformation is uncertain. Three forces are typically identified as the shaping factors of the sector. They are the desires to

- Enhance Australia's economic prosperity
- Maximise the sustainability of energy resource developments and use
- Maintain energy security

While these factors are important we will argue that in the absence of strong political intervention it will in fact be the successful development and commercialisation of science and technology that will shape the future of energy in Australia (and the world). We will review the current state of the sector, discuss possible scenarios of the evolution of both the domestic and export energy sectors, and highlight a number of examples that will show how science and technology can shape the future of energy.

01EGB – NUCLEAR ENERGY

01EGB-01. MAPPING THE ARCHITECTURE OF SANDSTONE-HOSTED URANIUM MINERAL SYSTEMS IN THE CALLABONNA SUB-BASIN, LAKE FROME REGION, USING REGIONAL-SCALE AIRBORNE ELECTROMAGNETIC (AEM) DATA

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The Frome airborne electromagnetic (AEM) survey delivers fit-for-purpose pre-competitive AEM data to aid the search for energy and mineral resources around the Lake Frome region of South Australia. The Survey includes a total of 32,317 line kilometres of high quality airborne geophysical data over an area of 95,450 km^2, or 10% of South Australia, at a flight line spacing mostly of 2.5 km, expanding to 5 km spaced lines in the Marree–Strzelecki Desert area to the north.

The Lake Frome region contains a large number of sandstone-hosted uranium deposits associated with Paleogene and Neogene paleodrainage systems flowing from uranium-enriched Proterozoic rocks of the Curnamona Province. Known resources are ~60 000 tonnes of U_3O_8 including the *In-situ* Recovery (ISR) operations at Beverley, Pepegoona, Pannikin and Honeymoon, and deposits at Four Mile East, Four Mile West, Yagdlin, Goulds Dam, Oban and Junction Dam. The region continues to be a focus for the South Australian uranium exploration industry, particularly in the southern Lake Frome area and around the flanks of the northern Flinders Ranges.

An integrated interpretation approach including a review of sandstone-hosted uranium mineral systems models in the Lake Frome region improved the understanding of mineral systems in this area. This informed the mapping of critical features of sandstone-hosted uranium mineral systems including basin architecture, paleovalley morphology, sedimentary facies changes, hydrological connections between uranium sources and uranium sinks, and geological structures. A synthesis of pre-existing groundwater flow systems data, isotopic dates of uranium deposits, thermochronology data and zircon provenance data further constrain a landscape evolution model for the Mount Painter and Mount Babbage inliers in the northern Flinders Ranges, affecting the mineral systems models.

The AEM data and subsequent interpretation comprehensively remap paleovalley systems in the southern Lake Frome area and point to the potential for new uranium discoveries in New South Wales adjoining the survey area to the east. The data provide a new understanding of the interaction between range-bounding fault systems and the Mesozoic and Cenozoic stratigraphy around the northern Flinders Ranges and new insights for sandstone-hosted uranium systems models for this area. New paleodrainage systems to the north of the Flinders Ranges, associated with sandstone-hosted uranium discoveries, have also been interpreted from the AEM data.

The Frome AEM Survey dataset maps critical features of sandstone-hosted uranium mineral systems, geological surfaces and depth of cover to ~300 m. By providing a regional framework for mineral explorers, the results reduce exploration risk by showing where AEM is effective and what it responds to, and also allows mineral explorers to merge their own tenement scale exploration results and high resolution ground EM or AEM surveys and place them in a regional context.

Note: this presentation is taken from a draft AJES paper detailing the mapping of critical elements of sandstone-hosted uranium mineral systems in the Lake Frome area.

GEOCAT # 79172

01EGC – NUCLEAR ENERGY

01EGC-01. THE FUTURE FOR NUCLEAR POWER IN AUSTRALIA

Tony Irwin

SMR Nuclear Technology Pty Ltd

Nuclear power makes an important contribution to baseload, low emissions electricity generation in 31 countries, but not in Australia, which has been dependent on cheap coal. As Australia begins to consider all low emissions options, the perceptions and concerns about nuclear energy have to be addressed. These include safety, proliferation, economics, sustainability, total emissions and radioactive waste.

Small Modular Reactors may be a suitable option for Australia's small grids and remote locations.

Looking to the future, Generation IV reactors, including the Integral Fast Reactor, Very High Temperature Gas Reactors and Molten Salt reactors have the potential to transform the way we use nuclear power. Finally, fusion power, forever "50 years away", is getting nearer.

01EGD – CLEAN ENERGY

01EGD-01. GOING DEEPER AND HOTTER FOR CLEANER, UNCONVENTIONAL ENERGY AND MINERAL RESOURCES

Klaus Regenauer-Lieb and the Laboratory for Multiscale Earth System Dynamics and Geothermal Research

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The Earth's available resources fuel our rapidly developing human civilisation. This coming century will test our innovative capability to adapt to a rapidly changing environment. Both the ever-increasing population and the significant decline of the easily accessible conventional resources threaten our well-being, advanced societal network, global economy and the international balance of power. Unconventional energy and mineral resources define the most abundant resources available on our planet and are attractive targets for novel exploration, stimulation and production techniques. Unconventional Energy (geothermal, shale gas, shale oil, tight gas, coalbed methane, heavy oil/tar sands, methane hydrates) and mineral resources (deep *in-situ* leaching) are generally trapped in a low porosity/permeability environment and are difficult to produce.

In this sense deep geothermal energy exploration in Australia has been pioneering the boundaries of current geomaterial models through going deeper and hotter than ever reached before. A characteristic of material behaviour at such conditions is that the material parameters develop a distinct dependence on the temperature conditions in addition to their well-known pressure dependence. Although this is commonly neglected, the process already starts at relatively shallow depth for clay rich rocks (like in unconventional shale gas plays), which can deform in a ductile manner at geological strain rates. In addition they display dewatering reactions at a critical temperature where the clay minerals dehydrate. The same style of temperature dependence is repeated for different lithologies at greater depth. The presence of water has the effect of lowering this critical boundary. In the Soultz-sous-Forets geothermal project in Europe, for instance, the interaction of the hydrothermal activity with the granite produces clay rich shear zones, which lower the realm of localised ductile deformation to relatively low temperature levels.

Thinking outside the box of hydraulic fracturing of brittle media is required for understanding and safely exploiting geothermal and other unconventional reservoirs. New innovative approaches and concepts are required to unlock the Australian unconventional geothermal, gas and mineral resources. The talk will present a new multidisciplinary fundamental science based approach for the unconventional resource challenge. The approach consists of combining a recent multiphysics, multiscale based geomechanics theory with laboratory and modern computationally assisted petrophysics and material science concepts. The talk will be illustrated with field data, core lab experiments results and numerical modelling of geothermal and deep hot shale gas prospects.

01EGE – SHALE GAS AND TIGHT GAS

01EGE-01. UNCONVENTIONAL GAS PROSPECTIVITY OF THE COOPER BASIN

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The Cooper Basin is an upper Carboniferous–Middle Triassic intracratonic sag basin in northeastern South Australia and southwestern Queensland. The basin is Australia's premier onshore hydrocarbon producing province and is nationally significant, providing domestic gas for the East Coast Gas Market. Exploration activity in the region is experiencing a revival with numerous explorers pursuing newly identified unconventional hydrocarbon plays, in addition to conventional gas and oil prospects that are more clearly defined by 3D seismic. However, the undiscovered unconventional gas resources in the basin remain poorly defined.

This study reviews the hydrocarbon prospectivity of the Cooper Basin with a focus on unconventional gas resources. Regional basin architecture is characterised through compilation and integration of formation tops, structure surfaces and isopach maps, indicating the wider extent of the Permian Toolachee and Patchawarra formations further north in Queensland. Source distribution and quality are reviewed demonstrating the abundance of potential source rocks across the whole basin. The Toolachee and Patchawarra formations are the richest source units, however organic-rich rocks are also present in the Nappamerri, Daralingie and Epsilon formations, and the

Roseneath and Murteree shales. Petroleum systems modelling, incorporating new compositional kinetics, source quality and Total Organic Carbon (TOC) maps, highlights the variability in burial, thermal and hydrocarbon generation histories between depocentres. Although hydrocarbon generation began in the Permian, peak oil and gas expulsion across the basin occurred in the Cretaceous. Pressure distribution estimates are made for all major depocentres to better characterise variation in overpressure.

The Cooper Basin hosts a range of unconventional gas play types, including the very extensive basin-centred and tight gas accumulations in the Gidgealpa Group, deep dry coal gas associated with the Patchawarra and Toolachee formations, and the less extensive shale gas plays in the Murteree and Roseneath shales. However, the overlapping nature of these plays makes it more convenient to consider them collectively as a composite Gidgealpa Group unconventional gas play. The possible extent of the composite Gidgealpa Group gas play fairway is defined using a common risk segment mapping workflow. Low and high confidence play fairway extents are also calculated.

In South Australia and the southwestern-most areas of Queensland, the composite Gidgealpa Group gas play fairway maps show that the Nappamerri and Allunga troughs are highly prospective, along with the deepest areas of the Patchawarra and Arrabury troughs. The play fairway maps also show the prospectivity potential for unconventional gas further to the northeast in Queensland, including areas of the Windorah Tough and Ullenbury Depression.

The prospectivity of the Cooper Basin for composite unconventional gas plays far exceeds its currently known conventional resources by at least an order of magnitude. Whilst significant additional work is required to better characterise key petroleum systems elements, the play fairway area estimated for the combined Gidgealpa Group gas play is significantly larger than that of the Roseneath and Murteree shale gas plays alone, suggesting very large volumes of gas in-place and highlighting the Cooper Basin's significance as a world class unconventional gas province.

01EGE-02. PETROPHYSICAL CHARACTERISATION OF COOPER BASIN SHALE AND ADAPTABILITY OF TRADITIONAL FRACCING TECHNOLOGIES

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The Cooper Basin shale is distinctively different from North American shales. Whilst it has the highest likelihood of producing shale gas in Australia with its existing infrastructure and long history of natural gas development, as of yet, there are no commercial lacustrine shale plays anywhere in the world. Lacustrine shales consist of considerably higher clay content than marine shales. If the clay is non-reactive, this may not necessarily reduce the commerciality of the shale play substantially. Nevertheless, it will certainly mean less clastic content compared to marine shales, which could become a potential barrier for fracture stimulation. Having reactive clays will certainly not be desirable as this will cause significant self-healing of stimulated fractures. In addition, complex formation networks with low porosities will lead to less free gas content. Coupled with rapid depletion rates, it will certainly be challenging to make shale gas operations economical due to the higher upfront costs required.

Fraccing is a mature technology developed in the US and employed successfully in many marine shale environments. The fracccing fluid consists of a base fluid, proppants and a small amount of chemicals. The base fluid carries the proppants with the chemical constituents, increasing the extent and efficiency of fracture stimulation. The primary objective of this technology is to increase the permeability of the formations, allowing the gas to flow. The permeability is reported to increase by more than 1000 times the original levels. So far, the applications on lacustrine shales in the Cooper basin have proven to be reasonably effective, with around 20 wells drilled to date. Yet, the question remains as to whether the most approriate technology is being used to maximise the gas extraction potential based on the *in-situ* geological characteristics. Further research and development will be required. Likewise, more needs to be known about the effectiveness of the chemicals being used to ensure adequate brittleness of the lacustrine formations. Slickwater fraccing (in which synthetic polymers are used to thicken the fluid and reduce friction between the fracturing fluids and rock formations) has been found to be more productive in regards to US marine shales, as it uses less guar gum (thereby reducing costs) whilst still producing good reservoir deliverability. Nevertheless, it is unclear whether it will be similarly effective for the non-marine shales in Australia. In this study, a field dataset from the Cooper Basin will be used to estimate the impacts on reservoir deliverability for lacustrine shale. The development data based on US marine shales will be used to evaluate the success of lacustrine shales. Further, gaps in understanding will be identified that will demand more research to increase the shale gas development potential from lacustrine shale.

Key Words: Brittleness, Lacustrine shale, Fraccing, Permeability

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01EGE-03. CHANGES IN MICROSTRUCTURE AND ELASTIC PROPERTIES OF ORGANIC-RICH MANCOS AND KIMMERIDGE SHALES AFTER PYROLYSIS

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Organic-rich shales, traditionally considered as source rocks, have recently become an ambitious goal for the oil and gas industry as important unconventional reservoirs. Understanding of initiation and development of fractures in organic-rich shales is crucially important as they drastically increase permeability of these low permeable shales. Fracturing can be induced by rapid decomposition of organic matter caused by either natural heating, such as emplacement of magmatic bodies into sedimentary basins or thermal methods used for enhanced oil recovery. In this study we integrate laboratory experiment and numerical modelling to study fracture development in organic-rich shale.

At the first step, we heated a cylindrical sample up to the temperature of 330°C. At the second step, we obtained high-resolution (voxel size 3.4 micrometer cube) microtomographic (microCT) images of the Kimmeridge and Mancos shale samples. At the third step static and dynamic elastic properties of the Mancos shale were measured.

Large kerogen-filled pores and cracks initiated by the heating can be identified from these micro CT images. We repeated these steps for several temperatures in the range 330–550°C. The microtomographic images were processed using AVIZO (Visualization Sciences Group) to estimate the dependency between the total area of fractures and the temperature experienced by the sample. Total organic carbon content was tested in the samples exposed to the same temperatures. This approach enables a quantitative analysis of fracture initiation and development in organic-rich shales during heating.

Increase in both dynamic and static elastic moduli and decrease of Poisson's ratios of the Mancos shale has been observed in the samples that experienced temperatures up to about 400°C. The samples heated to the higher temperatures up to 550°C exhibit the decrease of elastic moduli and increase of the Poisson's ratio. Comparison of the registered micro-CT images of the samples of Mancos shale subjected to temperatures up to 550°C shows significant shrinkage of the kerogen-filling pore spaces resulted from bitumen expulsion into the pores.

01EGE-04. APPLICATION OF HYPER-SPECTRAL CATHODOLUMINESCENCE TO STUDY QUARTZ OVERGROWTH IN SANDSTONES AND GAS SHALES

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Cathodoluminescence (CL) is sensitive to material composition and crystal structure, trace level concentrations of luminescence activators, and chemical valence of activator ions. Cathodoluminescence analysis can reveal the heterogeneity of minerals including lattice mismatch within crystals and mineral/crystal defects resulting from crystal heterogeneous growth (complex forming history, overgrowths, dissolution, and crack filling) during diagenesis. Such knowledge can, in turn, be used to reconstruct the processes of mineral formation, alteration and diagenesis. We have applied hyperspectral CL and X-ray imaging to the study of a suite of sandstone and shale samples from Australia, the United States of America and Germany to investigate what new information can be revealed.

An electron microprobe equipped with wave-length dispersive spectrometry, spectral energy-dispersive spectrometry and an integrated grating cathodoluminscence spectrometer, has been used to study the samples. The resulting CL and X-ray maps were analysed to determine the mineral assemblages and types of quartz present as well as gain evidence on fractures and cement overgrowths. The results indicate that this form of analysis is a powerful and effective tool to evaluate the heterogeneous growth of minerals in sandstones and shales and reveal diagenetic textures, which unravel the occurrence of fractures and associated healing as well as quartz overgrowths. Such knowledge can provide a better understanding of the diagenetic history of the rocks, and assist in the interpretation and understanding of basin-scale thermal processes that any associated organic matter has undergone. Insights into the hydrocarbon generation and charging history may also be gained to assist in hydrocarbon resource evaluation.

Sandstone samples: The CL-maps clearly illustrate the microstructures, rock fabrics, and distribution of natural fractures including healed fractures in the minerals. The cementing and overgrowth of minerals are clearly visible in the CL-maps, in particular quartz overgrowths are consistently visible. The overgrowth textures are chemically indistinguishable by X-rays and backscattered electron imaging making CL imaging an indispensible technique.

Shale samples: The features are generally not as obvious as for the sandstones, however, some general observations can be made:

Microstructure of gas shales, including shale fabric and distribution and grain-relationships of various minerals can be well illustrated by CL-mapping.

Other diagenetic features including inter-granular cementing among minerals including quartz, feldspar and carbonates, or in some cases, overgrowth of some minerals (quartz in particular) are also evident.

The CL images show mid-blue areas (peaks at 1.94 and 2.77eV) with variable intensity, consistent with detrital quartz grains, and dark-blue areas (peaks at 1.94, 2.77, 3.1 and 3.6eV) with significantly lower intensity for overgrowths or the cementing quartz.

01EGF – ENHANCING RECOVERY AND UNDERSTANDING FUGITIVE EMISSIONS

01EGF-01. DESCRIPTION OF A CO_2 ENHANCED COAL BED METHANE FIELD TRIAL USING A MULTI-LATERAL HORIZONTAL WELL

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Enhanced recovery of coal bed methane by CO_2 injection (CO_2-ECBM) offers the potential of increasing recovery of the gas-in-place relative to primary recovery methods while storing CO_2. This paper describes a CO_2-ECBM field trial that used a multilateral horizontal well with 2.3 km in seam length for injection. The trial, performed in China's Shanxi basin, involved transport of liquid CO_2 to the injection site and pumping of this directly into the injection well. A u-tube sampling system was installed in a monitoring well 25 m from the main horizontal branch close to the vertical section of the injection well. This u-tube system comprised three intervals separated by inflatable packers from which gas and water samples were automatically collected and recovered to an on-site field laboratory for gas analysis. The middle interval of this packer assembly was positioned to collect fluid samples from the coal seam targeted for ECBM. At the start and towards the end of the period of CO_2 injection, a pulse of non-adsorbing tracer gas was added to the CO_2. There was clear breakthrough of the tracer in the middle packer interval of the monitoring well, demonstrating the good connection between the injection and monitoring wells. The CO_2 composition of the gas sample from the coal seam gradually increased over time as injected CO_2 migrated to the monitoring well and reached a maximum of 12%. Coal permeability, and thus CO_2 injectivity, has been observed to decline during other CO_2-ECBM field trials as higher adsorbing CO_2 displaces reservoir methane. However, in this trial there was no clear trend of decreasing injectivity with time, possibly due to the flow behaviour in the long horizontal well and the short periods of CO_2 injection.

01EGF-02. THE EFFECT OF RESIDUAL WATER ON CH_4–CO_2 DISPERSION IN CONSOLIDATED ROCK CORES

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Carbon dioxide (CO_2) sequestration has been considered as a promising technology to mitigate atmospheric emissions and control climate change. Although CO_2 has been recently stored in underground formations such as aquifers or depleted oil or gas reservoirs, it has not been yet injected into producing natural gas reservoirs at the early stage of their lives. Additionally, natural gas and CO_2 are miscible in all proportions at reservoir conditions. Thus, it magnifies the main potential risks associated with the enhanced gas recovery (EGR) process; early breakthrough of CO_2 into the production wells and production of natural gas largely mixed and contaminated with injected CO_2. Accurate prediction of the mixing between CO_2 and natural gas is, therefore, essential to determine the reliability of the EGR process. This mixing process can be captured in reservoir simulators if accurate correlations anchored to high-quality dispersion coefficient data for the two supercritical fluids.

In this work, we accurately measured the dispersion coefficients of CO_2 and CH_4 at reservoir conditions. The specialised core flood apparatus was used to measure this coefficient through sandstone cores at dry and wet conditions with different water saturation levels. It showed that the resulting dispersion of the CO_2–CH_4 system was relatively the lowest in dry core and increased with increasing residual water saturation. Subsequently, the dispersivity of the rock core, which is the physical property of a rock core and a measure of rock core heterogeneity, increased as the water saturation increased. Based on our NMR-pore size distribution data, it was hypothesised that the dispersivity change caused by increasing rock tortuosity (and heterogeneity). Finally, a generalised correlation which captured the effects of pressure, temperature, flow velocity and water saturation was developed in a form to be used in reservoir simulators.

01EGF-03. DIRECT MEASUREMENT OF FUGITIVE GAS EMISSIONS FROM OPEN CUT COAL MINES

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During open cut coal mining, significant volumes of gas are emitted from exposed coal seams, and from fractured strata beneath the extracted seam into the atmosphere. The volume of emissions would depend on the gas content of various gas-bearing sedimentary units and on their gas migration properties. This study discusses a direct method of quantifying emissions from surface coal mining that has been trialled in Australia. The method is based on direct measurement of surface emissions from uncovered coal seams in mine pits, concurrent measurement of residual gas content of blasted coal in mine pits, and measurement of pre-mining gas content of the same seam from cores retrieved from exploration boreholes drilled away from active mining.

The results from two Australian coal mines are presented in this paper: one in the Sydney Basin with mixed gas (CH_4 and CO_2) in the coal seams and the other in the Bowen Basin with seam gas mostly CH_4.

In the Sydney Basin mine, the pre-mining gas content of the target seam was measured using cores from an exploration borehole away from active mining. Gas content varied from 0.7 to 0.8 m^3/t and gas composition varied from 16 to 21% CH_4 (84–79% CO_2). In-pit measurements included seam surface emissions and residual gas content of blasted and ripped coal. Residual gas content varied from 0.09 to 0.15 m^3/t; less than twofold across a mine pit. Composition of the residual gas was in general 90% CO_2 and 10% CH_4, with slight variation between samples. Coal seam surface emissions flux varied from 1.03 to 7.50 mL (CO_2–e) per minute and per square metre of the ground surface (mL min^{-1} m^{-2}), a sevenfold variation across the mine pit. In the Bowen Basin mine, the pre-mining gas content of the target seam was ~1.4 m^3/t and composed mainly of CH_4. In-pit residual gas content varied from 0.5 to 1.1 m^3/t; a twofold variation across the mine pit. Composition of the residual gas was in general 94–97% CH_4 and 3–6% CO_2. Coal seam surface emissions from this varied from 18.4 to 205.9 mL min^{-1} $m^{-2}CO_2$–e, more than tenfold across a mine pit.

01EGF-04. THE COMPLEXITIES OF CONTINUOUS AIR MONITORING IN ATTRIBUTING METHANE TO SOURCES OF PRODUCTION

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There is increasing interest in the use of mobile gas measurement systems for measuring fugitive methane (CH_4) emissions from coal seam gas developments. However, there are many sources of CH_4 in the atmosphere ranging from pre-existing geological seeps and fugitive emissions from open cut coal mines, to methanogens in the soil, and the digestive systems of ruminants. The isotopes of carbon within CH_4 may have the potential to fingerprint sources

of methane in the atmosphere, but our baseline ($\delta^{13}C_{CH4}$) data sets of CH_4 production from different landscape settings and under different climatic conditions are still few in number.

We present preliminary survey results of a mobile CH_4 and carbon dioxide (CO_2) survey from Sydney, New South Wales to Dalby, Queensland, Australia. This survey passed through major cities, national parks, vineyards, dry-land crop farming, livestock farming, irrigation farming, coal mining districts, and coal seam gas developments.

At all locations a combination of continuous concentration data and grab bag samples were collected. A continuous-wave cavity ringdown spectrometer (CW-CRDS) (Picarro G2301) was used to measure CH_4 and CO_2 concentrations. The grab samples, which were stored in 3L tedlar bags, were analysed for CH_4 concentration and isotopic carbon ratio in the laboratory using two methods. At Royal Holloway, University of London, the concentration was measured using a Picarro G1301, and the $\delta^{13}C_{CH4}$ measurements were made using a trace gas GC-IRMS system. At the UNSW Australia, the samples were analysed using an isotopic CW-CRDS (Picarro G2132-i).

Repeat surveys one week apart show variations in both the CH_4 concentration and isotopic composition. This work highlights the need for a combination of continuous point measurements combined with repeat mobile surveying to understand the existing sources of CH_4. This would enable a rigorous assessment of the impact of increased coal seam gas activity. We also discuss the complexities of attributing CH_4 measured in the air to one or more sources due to the overlapping of carbon isotope signatures.

DYNAMIC PLANET

01DPA1 – OROCLINES IN THE TASMANIDES

01DPA1-01. THE GIANT LACHLAN OROCLINE: WHERE? WHEN? HOW? WHY? AND SOME ECONOMIC IMPLICATIONS FOR EASTERN AUSTRALIA

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After decades of modern study, the Lachlan Fold Belt (LFB) remains an enigma. A new concept is needed. The New England Fold Belt has oroclinal folds and is fragmented-concepts relevant to the LFB, with roll-back recognised as critical to post-Ordovician evolution. Victoria has exposure that spans LFB width, with key timing and context constraints. NSW aeromagnetic data reveals a giant oroclinal fold superimposed on the northern Stawell Zone, cut by the north-trending Bootheragandra/Kiewa–Kancoona dextral strike-slip fault system. Stawell Zone and Darling Basin age constraints allow Silurian anticlockwise palinspastic unfolding of the northern Stawell Zone restoring, with the Kayrunnera Zone, a linear, continuous Cambrian accretionary wedge along east Gondwanaland. Restoration closes the Darling Basin and displacement on the Kiewa–Kancoona Fault. Ordovician relationships between Victorian LFB 'zones' mean that this unfolding must cascade zone-by-zone far into the eastern LFB, only halted at the Melbourne Zone–Tabberabbera zone boundary–Early Devonian, the site of a major paleogeographic discontinuity.

The result of this wholesale palinspastic restoration is a narrow, linear, accretionary LFB with a single arc – the Macquarie Arc – active along east Gondwanaland in the Ordovician. Explaining LFB evolution through the Silurian–Devonian to its present complex configuration requires a new geodynamic model. In the Late Ordovician, the Macquarie Arc subduction–accretion system transitioned into convergence as a micro-continent – Vandieland – entered its southern end. The Benambran Orogeny was the result, extinguishing the Macquarie Arc and forming the LFB. After this, part of the subduction zone was congested, with LFB segments trapped behind Vandieland as the 'western LFB'.

North of Vandieland the paleo-Pacific plate was uncongested but unable to advance, so rolled-back. Pinned by the microcontinent in the south, slab roll-back pivoted to create a curved asymmetry that progressively wrapped the eastern LFB around the northern and eastern edges of Vandieland. This formed a giant Z-shaped orocline, with the present day LFB configuration established by the Early Devonian. Throughout this time, these parts of the LFB lay in trans-tension, folding and fragmenting along extensional and strike-slip faults that chased asymmetric southeast-directed slab roll-back from NSW, through eastern Victoria and eventually into northeastern Tasmania. Transtension thinned the crust, opening distributed back-arc rifts – the Omeo Metamorphic Complex, followed by the Darling Basin and numerous other rifts and troughs. Waves of rejuvenated marine sedimentation and arc-related magmatism kept pace with orocline growth, culminating in NE Tasmania in the Lower Devonian with deposition of the Mathinna Group and intrusion of the Blue Tier Batholith complex.

Today, the Lachlan Orocline is approximately 400 km in amplitude with well-defined limbs enclosing a fault-disrupted core. It has effectively doubled apparent LFB width and introduced complexity that confounded all previous attempts at a comprehensive explanation. Economic implications: Much more Macquarie Arc exists buried beneath younger rocks in Eastern Australia than previously anticipated, and in totally unexpected places. Identification of these, and of related fore- and back-arc settings under younger cover is a fantastic boon for exploration for buried mineral systems in NSW, Victoria and Queensland.

01DPA1-02. TESTING THE TASMANIDE OROCLINES

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Arcuate structural elements are present throughout the assemblage of late Neoproterozoic to Paleozoic orogens that constitute the eastern Australian Tasmanides, although the status of several of these as oroclines has not been formally tested. The tightly recurved New England Orogen is generally accepted to include at least one orocline, although the number of folds, mode of construction and even identification as an orocline have been questioned. Curvature in the Delamerian Orogen is clearly expressed as an S-shaped pair of structural arcs in the Adelaide Fold Belt, but the northern element, the Nackara Arc, has been interpreted as largely non-rotational, and so not an orocline. Hinge rotations of rigid deep crustal elements underlie the thin-skinned Delamerian deformation. Recently, an orocline has been proposed within the Thomson Orogen of northern Queensland as the result of oblique collision involving a ribbon continent. Repetition of tectonic terranes in the southern part of the Lachlan Orogen has been recognised for many years, but only after advances in filtering of aeromagnetic data allowed structures to be traced below thick post-tectonic cover was this geometry reinterpreted as part of a pair of oroclines that displaced most of the Lachlan Orogen.

Orocline tests comprise a plot of the coherence between the orientation of an early-formed directional element and geological strike. Paleomagnetic declinations from the southern New England Orogen, when expressed as anomalous declinations relative to the Gondwana polar wander path, plot linearly with strike with a gradient (m) of 0.98 — a positive (if incomplete) orocline test. Large strike-slip displacements that have been inferred from the paleomagnetic data are not necessary. The circular distribution of paleomagnetic poles from the Nackara Arc has been interpreted in terms of polar wander, but instead provides a positive orocline test (m = 0.97) for this part of the Cambrian Delamerian orocline. Orocline tests for the North Queensland and Lachlan oroclines are less direct, but also appear to be positive. An isolated Silurian pole from the northern Thomson Orogen can be reconciled with the Gondwana polar wander path by removal of the proposed North Queensland orocline. Paleocurrent directions from Ordovician turbidites in the Lachlan Orogen appear to support oroclinal rotation around the eastern (“Tambo”) fold of the Lachlan orocline. The gradient of the plot of paleocurrent direction against strike of the orocline limbs is 0.57, reflecting the incorporation of some pre-Ordovician (Delamerian) curvature in the geometry of the Lachlan orocline. Ordovician to Early Devonian paleomagnetic poles from the eastern Lachlan Orogen are distributed along a small circle, and the rate of change of declination is linear over the interval between the Benambran and Bindian orogenies. Although it is not clear whether this represents rotation of an orocline limb, or rotation around smaller secondary folds, the observation is consistent with oroclinal displacement in the late Silurian. Preliminary paleomagnetic results from Cambrian basement on the limbs of the western (“Boosey”) fold of the Lachlan orocline also pass the orocline test (m = 1.02).

01DPB1 – OROCLINES IN THE TASMANIDES

01DPB1-01. A POSITIVE TEST FOR THE NAMBUCCA OROCLINE?

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Controversy surrounds the geometry and number of oroclines in the southern New England Orogen (SNEO). Whereas the presence of the northern Texas and Coffs Harbour bends is founded on structural, lithological and geophysical grounds, supporting evidence of the southern Manning and Nambucca oroclinal bends is less convincing. Geological evidence for the presence of the Nambucca Orocline is based on the reconstruction of a broadly linear extensional fault and basin system that formed prior to oroclinal bending. The relevance of the Nambucca Orocline to regional-scale structural models and the late Permian–early Triassic geodynamic model of eastern Australia will also be discussed.

One type of test for oroclinal bending requires the identification of broadly linear pre-oroclinal features in an orogenic belt. This has been shown in Cordilleran and Mediterranean examples, where linear orogenic features (such as the forearc basin, arc, ophiolite and accretionary wedge and their associated faulted contacts), provide critical piercing points that can be used to trace out the oroclinal structure. Where this approach has been used with some success in the southern New England Orogen, locating the Manning and Nambucca bends within the complexly deformed rocks of the accretionary wedge creates difficulties. As a result, pre-orocline linear features need to be identified in the Tablelands Complex.

As part of the Geological Survey of NSW Statewide Seamless Geology Project, structural, metamorphic and geochronological data have been compiled for the Tablelands Complex. This compilation supports the occurrence of a broadly linear extensional fault–basin system of Permian age. Geological evidence includes the manifestation of high-strain deformation, HT–LP metamorphism and S-type magmatism along the trace of regional-scale faults. Significantly, the geometry of these faults is coincident with that of known extensional fault systems, comprising both normal and transfer components situated oblique to right angles. To the east of the fault system, the Nambucca Basin formed synchronously. Faults identified in the Nambucca Basin have the same orientation and geometry as the faults associated with high-strain, HT–LP metamorphism and S-type magmatism in the Tablelands Complex, and may represent growth faults. Further work is required to confirm the nature of these basin faults. Reactivation of the extensional system took place during oroclinal tightening in the late Permian–Early Triassic Hunter-Bowen event. Structural overprinting of extensional structures and inversion of the sedimentary basins took place during this event.

With respect to the southern New England Orocline models, the Nambucca Orocline can be interpreted in two ways, namely: (i) The Nambucca Orocline is the inner hinge of the Texas Orocline, or (ii) the Nambucca Orocline represents a component of a complex 3 or 4 orocline system. These contrasting geometries influence potential geodynamic models for orocline development in the SNEO respectively, summarised as: (i) oroclinal bending formed out of response to dextral transpression along a north−south striking subduction zone, or (ii) oroclines formed in response to subduction rollback and advance cycles.

01DPB1-02. WHY THE MANNING AND HASTINGS (NAMBUCCA) OROCLINES DO NOT EXIST

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The southern New England Orogen from west to east, consists of a buried volcanic arc, concave to the east forearc (Tamworth Belt) and a subduction–accretion complex (Tablelands Complex) associated with a W-dipping subduction zone. Many authors believe that it was deformed into a megafold in the north (Texas-Coffs Harbour Orocline) and two smaller scale, megafolds (Manning-Hastings/Nambucca Orocline) in the south between 275–260 Ma. It is generally accepted that the Texas-Coffs Harbour Orocline is a classical orocline because it shows rotation of bedding and early foliations about a vertical axis. By contrast, the Manning and Hastings/Nambucca Oroclines have been the subject of much speculation with some advocating their existence, others sceptical of their existence.

The Manning Orocline has been defined, by some authors, by the distribution of early Permian granites in the Tablelands Complex, discrete linear belts of serpentinite and forearc sequences in the southern Tamworth Belt and Hastings Block. However, there are problems with this approach. For example, the distribution of granites may not reflect ductile bending around an orocline, but merely vertical movement of fault-bounded blocks containing a group of granites in a sheet. Further, the serpentinites are not of the same age (Port Macquarie Block 427–444 Ma; W margin of the Hastings Block post 377 Ma) and they do not form a continuous ribbon around the Hastings Block. Rather they occur as isolated north–south ribbons bounding the western part of the Hastings Block and as a series of ribbons west of Hastings Block. There are no serpentinites on the northeastern limb of the Hastings Block. Finally, it has been suggested that the hinge of this orocline is north of Mt George or alternatively 60–65 km to the west, near Walcha. The bedding south and east of Mt George does not define a megafold as expected if the hinge zone existed in this area. Further, in the Walcha district the foliation formed during two metamorphic events and thus cannot be used to define the hinge zone as suggested by other authors. Thus neither interpretation fits the structural patterns in these areas. There are also features of the Hastings/Nambucca Orocline that do not support it being an oroclinal structure. Firstly the Parrabel Dome, northern Hastings Block within the core of this orocline plunges gently rather than subvertical as expected with a classical orocline. Secondly, the northern Hastings Block was translated between faults and underwent rotation of 130° clockwise or 230° anticlockwise in the earliest Permian prior to deposition of Permian sequences in the overlying Nambucca Block. Subsequently, south-directed movement of the Coffs Harbour Block, during oroclinal bending, produced structures in the Northern Hastings Block similar to those in the Nambucca Block. These features all argue against the presence of this orocline.

01DPC1 – EARTHQUAKES AND VOLCANOES IN THE NOT-SO-STABLE PLATE

01DPC1-01. TWENTY (+) POTENTIAL SITES FOR AUSTRALIA'S NEXT VOLCANO: BASED ON 3 MA VOLCANIC AREAS (LAT. 9–41°S), VOLCANIC TRENDS, DYNAMIC PLATE-SETTINGS AND DEEP THERMAL UPWELLING MANTLE AREAS

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The eastern Australian plate and its extended intraplate volcanism (100–0.004 Ma) contains over 20 areas with <3 Ma activity, based on extensive isotopic, fission track and cosmogenic dating. Many young volcanics lie in areas of repeated volcanic episodes. Although young basaltic volcanism prevails, felsic events are now increasingly recognised. The young volcanic fields of western Victoria– SE South Australia and NE Queensland are usually favoured for delivering the next volcano. The present survey suggests several other sites over the 4000 km-long belt may deliver a volcanic surprise. Besides extensive basalt dating, the study uses zircon fission track dating to suggest that sporadic breccia-pipe outbursts punctuate less active areas. The inputs also involve dynamic factors related to Australian plate movements and stresses, and modelling of mantle upwelling sources under the migrating lithosphere since 3Ma. Potential areas for a volcanic wake-up from north to south are:

Murray Islands, Torres Strait (9.2–9.7°S), where episodic events include young cones.

Northeast Queensland (15–21°S), where major episodes are rife (Piebald, McLean, Atherton, McBride, Chudleigh, Nulla, Sturgeon Provinces) and extend to <15 ka, while other isolated young fields include preserved cones (Mount Fox).

Central-West Queensland (21–27°S), from an area south of broad northern activity trends towards young buried intrusions and related basalt-derived escaping gases (Hughenden–SW Queensland).

Southeast Queensland (24.7–27°S), where WSW-trending eruptions form a migratory line from Bundaberg (1 Ma), Coalstoun Lakes (0.6 Ma) to Brigooda (0.4 Ma), may be related to stress field effects and form a present potential eruption site near Chinchilla.

East New South Wales (30–35°S), where young zircon annealing ages and felsic breccias in areas of basaltic episodes (New England, Yarrowitch, Barrington Plateau) suggest potential eruptive trends towards Sydney Basin regions.

SW New South Wales–NW Victoria (35–37.5°S), within an area of 2 Ma bentonitic ash beds and young interpreted vents to the south.

Northeast Victoria (36–38°S), in a region of young annealed zircons and minor 2 Ma basalt flows.

Western Victoria (36–38°S), across extensive episodes of young flows, vents and maars, including Holocene features, in the Central Highlands and Plains Western District subprovinces.

SE South Australia (37.5–38°S), within 1–0.5 Ma young flows and vents of the Mount Gambier subprovince formed above a deep secondary mantle plume. .

Bass Strait–Central Tasman Sea margins (38–41°S), within a deep thermal, active seismic region across predicted plume-like migratory sources and mantle gas discharges in northern Tasmania.

All these potential sites of impending volcanism can be considered within a model of major long-term thermal mantle upwelling under the sea-floor spreading margins of the East Australian Plate.

01DPC1-02. NEW FAULTS IN THE BARROW SUB-BASIN: ACCOMMODATION OF PRESENT-DAY STRAIN THROUGH REACTIVATION, INVERSION AND DISCRETE NEW FAULT ZONES

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The Barrow Sub-basin has long been known to host reactivation and inversion in the Neogene. Features such as the Barrow Anticline and the Cape Range of WA have also long been known to be inversion anticlines with gentle limb dips, adjacent to associated faults (the Barrow and the Giralia faults, respectively). More recently seismicity data indicated that many present-day earthquakes in WA exhibit strike-slip focal mechanisms, and a range of possible strike-slip reactivation features have been identified along the NW WA coast, including on Barrow Island.

To further investigate the role of neotectonics and young deformation, a number of 3D seismic datasets in the region of Barrow Island were interpreted with respect to young and surface-breaching faults, and their links at depth. Across the Shelley, Panaeus and NW Barrow data sets a number of young features were identified, defining a strong and localised strain gradient in the region. Strong strain partitioning inboard on the Peedamullah Shelf accommodates much of the recent strain. However an intriguing area of young faults also occurs around the Veranus Islands, to the NE of Barrow Island. A number of anomalous, high strain (in terms of displacement) NNW- and NW-trending faults breach the surface and form a complex array with NE- and E-trending faults. The entire area has geometries consistent with strike-slip (transpressional) reactivation that affect only the seafloor – very few of the faults link at depth. In addition, a number of other very young faults occur only at the seafloor and have no connections at depth at all. We interpret these to be new faults, trending mainly to the NW – these coincide with a sharp, linear NW-trending topographic change offshore of Barrow Island.

Therefore 3D seismic data around the Barrow Island Anticline show strong strain partitioning of present-day strain by two quite different areas: 1) strong reactivation of the Peedamullah Shelf with a sharp strain gradient; and 2) diffuse transpressional deformation on extremely young faults outboard of the Peedamullah Shelf, including a number of faults that occur only at the surface and may be evidence of brand new faults forming at the present-time.

01DPD1 – EARTHQUAKES AND VOLCANOES IN THE NOT-SO-STABLE PLATE

01DPD1-01. DO EARTHQUAKES HAPPEN ON FAULTS?

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'Earthquakes happen on fault-lines' is a paradigm well entrenched in the public consciousness. Unfortunately the recorded earthquakes in Australia are widely scatted and do not appear to support the paradigm. It is well known that in most cases our earthquake epicentres are inaccurate, and we seem to have many thrust mechanisms, which would suggest scattered earthquakes. However when the better quality data are reviewed, they also do not show a preference for fault lines, and there is no known mapped fault in Australia that has regular activity occurring on it. Earthquakes have caused a small number of ruptures in Australia since 1968, and mostly these do not support repeated events at the same site.

While it is clearly true that in many places, principally active ones, that earthquakes align well with faults, there are many other places where this is not the case.

Hazard analyses of recent decades usually have a component related to faults. This commonly affects the map more than the measured seismicity. If the best cases in Australia do not show repeated activity on faults, then hazard weighting on faults should not dominate. In an analysis, we assume that activity is random in the shorter term, but fairly regular in the very long term. Clearly this is not the case. An engineer is much more interested in a 1% chance of a large event in the next 100 years, than looking at a return period of 10 000 years.

It has been argued that small earthquakes will occur almost anywhere, but large earthquakes will preferentially occur on major faults. However if we look at the size of the damaging earthquakes in Australia, it can be shown that well located events of such sizes do not preferentially align with faults.

There may be a need to more fully outline the completeness, accuracy and applicability of fault investigation before it is used in hazard analysis. Most geologists are well aware of the lack of completeness, but this is a case where it should be made explicit. Another relevant question is to what extent faults can heal, and stress be redistributed.

It is very difficult to work outside accepted paradigms. However, if we are not prepared to tackle the difficult questions, we may end up with hazard maps that are well accepted, but wrong.

01DPD1-02. USING STUDIES OF THE PHYSICAL FEATURES OF YOUNG MONOGENETIC VOLCANIC FIELDS, INCLUDING THE NEWER VOLCANIC PROVINCE OF SOUTHEASTERN AUSTRALIA, TO HELP EXPLORE RELATIONSHIPS BETWEEN VOLCANISM, EARTHQUAKES AND TECTONIC SETTING

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Young monogenetic volcanic fields are widely distributed across the Earth, and recent improvements in dating their activity increasingly indicate high risks of future activity, and substantial local hazards in many closely populated areas.

Three important areas are Auckland, New Zealand, the Auvergne region of France, and the Eifel of Germany. Similar monogenetic fields include the extensive young volcanic areas of northern Queensland and southeastern Australia.

The young monogenetic volcanoes of the extensive Newer Volcanic Province (NVP) of central and western Victoria and adjacent southeastern South Australia have been extensively studied, and provide a detailed story of activity over the last 5 Ma that can be traced up to just a few thousand years ago. Some 400 large and small scoria cones, lava shields and maar craters have been catalogued and the distribution of lava flows and ash deposits mapped. Many volcanoes are on the western plains, but a major concentration of some 100 scoria volcanoes, commonly as little as 2 km apart, are clustered in an upland area around Creswick, and resemble in appearance parts of the Auvergne region of France.

K/Ar dating and newer techniques including cosmogenic exposure dating are providing a more detailed story of the youngest activity, and geomorphic and regolith mapping have been used to fill gaps and provide a more complete history of activity. Geostatistical modelling has allowed an analysis of activity over time, identifying cycles of activity and periods of little or no activity.

On the plains in the far west of the NVP, in a period of concentrated activity over the last 20 000 to 30 000 years, a dozen volcanoes have erupted. If these were not clustered or overlapping in time this indicates a repose interval or recurrence rate (i.e. eruption frequency) of some 2000 years. The recent redating at *ca* 5500 years BP of the Mt Gambier volcanic complex, as the youngest identified eruption centre, demonstrates the need to consider long-term volcanic risk and hazard.

Such recent detailed studies of the physical volcanology of monogenetic volcanic fields of the NVP and other fields across the world, together with the application of new dating methods providing an overview of past eruption history across each monogenetic province, show the need to explore the relationship of such volcanism to local tectonic settings, and also local earthquake records, as a way to further refine the story of where and when future activity may occur.

01DPE1 – ARCHEAN AND PROTEROZOIC HOT OROGENS

01DPE1-01. FROM ARCHEAN LID TECTONICS TO MODERN PLATE TECTONICS: THE ROLE OF EARLY CONTINENTS

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On the modern Earth, plate tectonics rejuvenate the oceanic lithosphere, assembles continents into supercontinents and breaks them apart. In the Archean however, the tectonics of the conductive lid (i.e. outer more rigid part of the Earth above the convective mantle) may have been different for several reasons. First, because the convective mantle was hotter, partial melting of the mantle may have produced thicker basaltic crust and therefore more buoyant lids lacking the ability to subduct spontaneously. Second, crustal geotherms may also have been hotter, making continents weaker, which would have promoted homogeneous deformation, rather than deformation localised along narrow mountain belts and rifts. Third, peculiar lithological associations, such as Tonalite–Trondjhemite–Granodiorite (TTG), and the interlayering of komatiite, tholeiite, calc-alkaline and felsic volcanics, have little modern equivalents. Fourth, the stratification of the sub-continental lithospheric mantle – with strongly depleted and buoyant mantle above moderately to fertile mantle – also points to unique tectonic/geodynamic processes in the Archean.

To explore tectonic processes in the Archean, we performed several series of 2D coupled thermal–mechanical numerical experiments to test the mechanical and thermal behaviour of a composite continental–oceanic lid above a convecting mantle. The composite lid includes a 225 km thick and buoyant continent adjacent to a stable oceanic lid. The continent consists of 55 km thick crust – made of TTG and continental flood basalts – above a strongly depleted, strong and buoyant lithospheric mantle. These experiments suggest a tectonic regime in which continents spread laterally toward adjacent oceanic lids. The spreading and thinning of the continent drives exhumation of the fertile subcontinental mantle, which in turn promotes polybaric decompression melting first from deep (>100 km) then to shallow depths (<100 km). Continental boudinage and rifting accompanying the spreading drives further upwelling and decompression melting to even shallower depths. This partial melting produces a moderately depleted mantle layer, progressively incorporated through cooling into the lid.

Our numerical experiments also show that early continents forced the adjacent oceanic lid into the convective mantle. Upon reaching a depth of 200 km, the slab pull force becomes large enough to promote subduction of the oceanic lid even when the continent has lost its driving power through spreading and thinning. Although neither melting due to the hydration of the mantle wedge nor slab melting are taken into account in our models, our experiments predict that subduction of the lid would produce sanukitoid and TTG melts that would metasomatise the lid above the subducting slab.

This simple model explains a range of hitherto puzzling observation including: 1/ the strong stratification of the mantle lid; 2/ the multimodal polybaric (i.e. from deep >100 km to shallow <100 km) decompression melting of the mantle; and 3/ regional and temporal overlap between komatiitic–tholeiitic basalts with arc-volcanism. In addition, it suggests a way to transition from an early Archean transient stagnant lid regime to a steady-state plate tectonic regime, with continents acting as kick-starters of subduction until subduction becomes spontaneous through the increasing negative buoyancy of the oceanic lithosphere.

01DPF1 – ARCHEAN AND PROTEROZOIC HOT OROGENS

01DPF1-01. LINKING MINERAL SYSTEMS WITH GEODYNAMICS AND TECTONICS – A 'WHOLE OF GEOLOGY APPROACH' TO THE GEOLOGICAL HISTORY

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The geological evolution of a region is the result of many factors, all of which need to be assessed when determining the geological history and mineralisation potential. Structural domains and fluid flow systematics are the result of a complex interaction of many factors including tectonic environment, geodynamics, crustal evolution, sedimentation regimes, metamorphism and igneous activity. While detailed studies in any one of these areas are critical to our understanding, only a broad-scale assessment that links all of these processes, can deliver a geologically defensible and robust interpretation. Unless our model explains all of the known data, across all disciplines, then the interpretation is open to debate.

The Mount Isa Province, in northwest Queensland, is one of the most intensely mineralised terrains in the world. The various styles of mineral endowment present in the province leads to the juxtaposing, both spatially and temporally, of multiple world-class mineral deposits, with different styles and related to different tectonic settings. The Mount Isa mine for example, contains a world-class Pb–Zn orebody, formed in a late sedimentary or early diagenetic setting, in the same mine as a world-class Cu orebody, formed during the Isan Orogeny about 100 Ma later. An understanding of the different regimes for these two deposits is critical to understanding the mineralisation in the inlier.

The Paleoproterozoic rocks in Mount Isa Province developed in a succession of three extensional basins, the Leichhardt Superbasin, the Calvert Superbasin and the Isa Superbasin, separated by periods of relaxation of extensional stress, with only local compression. These basins are developed on a thick Archean to early Paleoproterozoic crystalline basement. Sedimentation ceased close to the end of the Paleoproterozoic and was followed during the Mesoproterozoic by several compressive and metamorphic events, which together make up the Isan Orogeny. Recent interpretations suggest that early compression in the Isan Orogeny was coeval with continuing sedimentation, particularly in the Lawn Hill Platform in the northwestern part of the province.

Mineralisation mostly falls into two broad categories:

Pb–Zn mineralisation linked to saline fluid being drawn down during graben formation during superbasin formation followed by expulsion of Pb–Zn bearing fluid during relaxation. The relative impact of graben-phase sedimentation and sag-phase sedimentation is related to heatflow in the crust during extension and can be shown to vary across the province. Major structures and mineral deposition occurs at the boundaries of different heat flow regimes, and their character is closely related to the different regimes.

Cu–Au mineralisation is linked to expulsion of deeper-seated fluids during region-wide compression related to the Isan Orogeny. Many of the structures, developed during the early dynamic events, were reused by deep-seated fluids resulting in the overlap of mineralising events with widely different styles.

Not all mineralisation fits into these two categories, raising the possibility of other, as yet not fully documented, mineralising events.

A better understanding about the tectonic and geodynamic forces, which shaped the Mount Isa Province, is emerging as new models are developed for Proterozoic supercontinent reconstructions and how the province fits within this global setting.

01DPF1-02. STRUCTURE AND GEOMETRY OF THE FRASER ZONE, EAST ALBANY-FRASER OROGEN

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Structural analysis and forward modelling of potential field data from the 425 km long, 50 km wide, Mesoproterozoic, metagabbro-dominated Fraser Zone in the east Albany-Fraser Orogen has led to new interpretations of its structural architecture. The Fraser Zone contains interlayered gabbro–granite sheets that intruded into Archean–Paleoproterozoic crust in the vicinity of the Biranup-Nornalup Zone boundary, and into overlying sediments of the Arid Basin. These rocks were deformed under granulite facies conditions shortly after *ca* 1290 Ma, during Stage I of the Albany-Fraser Orogeny. The interpretation of high resolution aeromagnetic data and field-based structural information shows that the Fraser Zone can be divided into two types of domains: those that are dominated by regional-scale, northeast-trending tight to isoclinal folds, and domains that contain northeast-trending dextral shear zones. These structures suggest that strain was strongly partitioned during deformation under a transpressional regime. The Fraser Zone is also host to the recently discovered Nova-Bollinger Ni–Cu deposit, which coincides with a structural feature defined in aeromagnetic data known as 'The Eye'. The 'Eye' is one of several similar features throughout the Fraser Zone that have sigmoidal geometries, interpreted to be due to dextral rotation of more competent material (e.g. gabbro) during the formation of the dextral shear zones.

2.5 D potential field, crustal-scale modelling was undertaken along two profiles across the Fraser Zone and the adjacent Biranup and Nornalup zones, constrained by geological and petrophysical data. The Fraser Zone was modelled with a density of 3 $g.cm^{-3}$ (median density of Fraser Zone density samples), and interpreted as near-triangular in shape in both profiles, extending to depths of 12 to 15.5 km. The geometry is consistent with a pop-up structure, which is likely to have formed initially from injection of magma along the shear zone separating the Biranup and Nornalup Zones, followed by structural modification and emplacement during transpression. In profile 2, a long wavelength (~150 km) gravity anomaly to the southeast of the Fraser Zone is interpreted as a sill-like body of mafic–ultramafic material that is likely to contain a significant proportion of cumulates. This sill is interpreted to be located in the middle-crust and, when attributed the same density as the Fraser Zone, to have a maximum thickness of 14.5 km. It is potentially a deeper level intrusion related to the Fraser Zone.

01DPF1-03. MAGNETOTELLURIC SURVEY ACROSS CENTRAL AUSTRALIA: NEW CONSTRAINTS ON LITHOSPHERIC ARCHITECTURE

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Central Australia is characterised by intraplate orogens, which expose Meso and Paleoproterozoic crust that record Grenvillian-aged (*ca* 1200–1100 Ma) events. A 350 km long north–south MT profile with 26 long-period (LP, 10–10 000 s periodicity) MT stations was deployed in July 2013 along the Stuart Highway from the SA–NT border to circa 100 km north of Alice Springs. To the south, the profile crosses the eastern part of the Musgrave–Albany Fraser

Orogen and extends across the Amadeus Basin into the Arunta region north of the Redbank Shear Zone. In addition to the LP MT stations, another 20 broadband (0.002–500 s) stations were deployed every 1 km across the Redbank Shear Zone.

The profile is situated between previous MT profiles to the west by Selway *et al.* (2009) and the Georgina MT survey by Geoscience Australia to the east. Additionally, our LP profile also connects to the Goma MT line in South Australia (Duan *et al.* 2011; Selway *et al.* 2011), significantly extending the profile to more than 500 km.

Horizontal magnetic transfer functions at longer periods (>100 s) of the LP data sense conductive features oblique to the profile and are likely related to sediments to the east. For periods below 100 s, the horizontal magnetic transfer functions are primarily related to the east–west trending shear zones, visible from potential field data. The significant step functions in the gravity data of the E–W aligned orogens are also visible in the phase tensor representation of the LP MT data along the 350 km N–S profile. The electromagnetic response from phase tensors along the profile can be divided into 4 distinct zones: the Musgrave, the Amadeus Basin, the Arunta region south of the Redbank Shear Zone and the Arunta region north of the Redbank Shear Zone.

Initial inverse modelling of the LP MT profile supports the phase tensor observation. Near the surface the Amadeus Basin is electrically conductive in the top few kilometres in the sedimentary strata but shows a homogeneous crust underneath. The Musgrave and Arunta regions are characterised by deep trans-lithospheric faults of low electrical resistivity extending into the mantle. The faults are connected to a region of enhanced conductivity at around 150 km depth with resistivities of a few tens of Ohmm. The Redbank Shear Zone shows a sharp resistivity gradient comparable to previous surveys.

The initial results reveal a previously unknown deep mantle conductor that appears connected to both the Musgrave and the Arunta regions, despite their contrasting ages. Additional modelling with other available MT data sets will significantly enhance our understanding of the lithospheric architecture of Central Australia and provide constraints on fluid flow and areas of deformation in the crust and mantle.

01DPF1-04. FROM THE SURFACE TO THE MOHO AND BACK IN A FEW Million years: PARTICLE'S FLOW PATH IN A SAGDUCTION SYSTEM

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Archean granitic domes and intervening greenstone basins are commonly interpreted in terms of sagduction, a process, which corresponds to the gravitational sinking of surficial greenstone covers and coeval exhumation of deeper granitic crust into broad domes. Alternatives models that can account for the regional dome and basin pattern include fold interferences and extensional metamorphic core complexes. To distinguish between these models we investigate the flow path of crustal particle in a typical Archean domes and basins terrane.

In the East Pilbara craton (Western Australia), the Warrawoona greenstone belt (which includes the Warrawoona Group *ca* 3530–3430 Ma, and the Kelly Group 3335–3312 Ma) and adjacent Mount Edgar granitoid dome (with older 3470–3430 Ma gneisses on the rim, and younger 3330–3220 Ma granites at the core), are particularly well preserved and exposed. Doming occurred at *ca* 3310 Ma shortly after the deposition of the Charteris formation (3315–3312 Ma).

Garnet-bearing metasediments and metabasalts collected along the southern rim of the Mount Edgar dome reveal higher-P but lower-T of equilibration (0.9–1.1 GPa and 450–550°C) than enclaves collected in the core of the dome (0.6–0.7 GPa and 650–750°C). *In-situ* oxygen isotope analysis and U–Pb dating of zircons from the enclaves indicate a metasedimentary origin ($\delta^{18}O \sim 13‰$) for the protolith and a metamorphic age of 3313 ± 5 Ma, with no sign of older zircon. In contrast, monazites included in garnet from the SW dome margin yield an age of 3443 ± 5 Ma, which points to an older metamorphic cycle coeval with the emplacement of the Warrawoona Group. Clearly, these older gneisses are not the source of the metasedimentary enclaves in the Mount Edgar. The age of metamorphism in the metasedimentary enclaves is very close to the deposition age of the Charteris formation. Since doming occurred shortly after the deposition of the Charteris formation, we suggest that surface sediments where buried to lower crustal conditions and exhumed back to the surface in a few million years.

To test this hypothesis we performed a series of thermal–mechanical numerical experiments.

Results of forward thermo-mechanical modelling show that during sagduction, upper crustal rocks are buried then exhumed in a few million years recording P–T–t evolutions similar to those deduced from the metasedimentary enclaves in the Mount Edgar dome. Such a crustal flow is hard to reconcile with metamorphic core complexes and fold interferences. Our numerical experiments show a large range of possible apparent geothermal gradients during sagduction, including low apparent geothermal gradients that are similar to those proposed for Archean and modern subduction. The wide range of gradients obtained in our sagduction modelling (i.e. 10–45°C/km) is in disagreement with the distinction between sagduction and subduction based on high (>25°C/km) *vs* low (12–15°C/km) apparent geothermal gradients, respectively. Thereby, petrology and apparent geothermal gradient don't seem sufficient to discriminate between contrasting tectonic settings such as subduction and sagduction as both involve the burial of cold surface rocks. A range of other observables must be invoked including duration and rates of processes, as well as regional strain and flow patterns.

01DPA2 – MOON AND PLANETS

01DPA2-01. SIMILARITIES AND DIFFERENCES BETWEEN THE COMPOSITIONS OF THE EARTH'S MANTLE AND THE MOON, AND THEIR IMPLICATIONS FOR THE MOON'S ORIGINS

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Hypotheses on the origin of the Moon necessarily carry implications for whether the Moon's chemical composition is related to the Earth's. Simple capture models imply that there is no compositional relationship beyond that expected among inner solar system objects in general. At the other extreme, fission models derive the Moon entirely from the Earth's mantle. Giant Impact models conceptually fall in between, with some proportion of the Moon being derived from the proto-Earth and the rest from the Impactor.

Increasingly precise determinations of the isotopic compositions of more and more elements in terrestrial, lunar and other solar-system materials are emphasising just how extraordinary is the coincidence in the isotopic make-up of elements in the Moon and the Earth's mantle. Meanwhile, recent modelling of solar system formation challenges many of the old presumptions about how the terrestrial planets might have formed. It is timely therefore to revisit the question of the similarities and differences between the average composition of the Earth's mantle plus crust, known as the "Bulk Silicate Earth" (BSE), and its lunar equivalent, the average composition of the Moon or "Bulk Moon" (BM). Understanding the compositional nexus constrains how the Moon formed, from a perspective distinct from the dynamical considerations. But this exercise is not an easy one. All the planets and rocky objects of the inner solar system share a common composition, which is their inheritance from the solar nebula.

To establish the degree of relationship requires knowing the composition of the BSE, and its uncertainties, especially for key elements used in the Earth–Moon comparison; how and why this BSE composition is distinguishable from other possible solar-system rocky-planet compositions (both the size of the Earth and contingent events during Earth's accretion might be involved); and the composition of the BM, and how well this is known, given our limited knowledge of the Moon's interior. Where significant differences in composition can be established, the question then arises of how much of these differences are caused by the formation of the Moon, as opposed to inherited from precursor materials like the putative Impactor.

With our present knowledge, robustly estimated significant differences in composition turn out to be few. One is the extreme but general depletion in the BM of all the moderately volatile elements (e.g., Na, K, Zn and many others), but not Mn. This could be caused by volatile loss of such elements during the Moon's formation. The second difference is that the BM appears to be richer in FeO than BSE, although the BM is much poorer in total Fe than the Bulk Earth (i.e., including Earth's core). Allowing for a small lunar core hints at an accompanying BM enrichment of Ni and Co. This compositional feature points towards the Moon being formed from a combination proto-Earth's mantle and a highly oxidised Impactor, with a somewhat higher proportion of this Impactor in the material of the BM than in the BSE. Such a scenario is not necessarily inconsistent with the similarity in oxygen isotopes.

01DPA2-02. IS THERE A WINDOW FOR PLATE TECTONICS IN TERRESTRIAL PLANET EVOLUTION?

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The tectonic regime of a planet depends critically on the contributions of basal and internal heating to the planetary mantle, and how these evolve through time. We use viscoplastic mantle convection simulations, with evolving core–mantle boundary temperatures, and radiogenic heat decay, to explore how these factors affect tectonic regime over the lifetime of a planet.

The simulations demonstrate i) hot, initial starting conditions can produce a "hot" stagnant-lid regime, whilst simulations starting cool may begin in a plate tectonic regime; ii) planets may evolve from an initial hot stagnant-lid condition, through an episodic regime lasting 1–3 Ga, into a plate-tectonic regime, and finally into a cold, senescent stagnant lid regime after *ca* 10 Ga of evolution, as heat production and basal temperatures wane; and iii) initial conditions are one of the most sensitive parameters affecting planetary evolution – systems with exactly the same physical parameters may exhibit completely different tectonics depending on initial conditions employed.

Estimates of Earth's initial temperatures suggest Earth may have begun in a hot stagnant lid mode, evolving into an episodic regime throughout most of the Archean, before finally passing into a plate tectonic regime. The implication of these results is that, for many cases, plate tectonics may be a phase in planetary evolution between hot and cold stagnant states, rather than an end-member.

01DPB2 – TECTONICS OF THE TASMANIDES

01DPB2-01. MECHANISMS OF CONTINENTAL GROWTH ALONG EASTERN GONDWANA DURING THE PALEOZOIC: ALTERNATING PERIODS OF TERRANE ACCRETION AND CONTINENTAL MAGMATIC FLARE-UPS

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New zircon geochronology from lithologies previously regarded as difficult to date, including eclogites and gabbros, within the southern New England Orogen (NEO) are revealing surprisingly different ages to previously published dates. This suggests that the tectonic evolution of the southern NEO is much more complex than the long-lived, west-dipping subduction/accretion model that has dominated the literature since the advent of plate tectonics in the 1970's. Of particular significance are the volcano-sedimentary Carboniferous to Permo-Triassic zircons obtained from the Rocky Beach eclogite at Port Macquarie suggesting that the Ordovician K–Ar dates obtained from phengites may have been prone to excess argon issues and therefore not accurate. Likewise the Tacking Point Gabbro at Port Macquarie was found to be Devonian (*ca* 390 Ma) rather than Permian as previously based on compositional similarities with the Clarence River Suite. Ordovician detrital zircons from a volcaniclastic sandstone interbedded with pillow basalts of the Watonga Formation confirm the presence of Ordovican conodonts in cherts of the Watonga Formation. Small remnants of Ordovician to Silurian sedimentary rocks occur scattered throughout the New England Orogen, including the Watonga Formation at Port Macquarie and the Murrawong Formation at Nundle. These along with the disrupted Cambrian ophiolitic blocks within the Weraerai terrane hint at an early Paleozoic evolution of the NEO that began in a subduction factory somewhere in the Panthalassic Ocean, well away from the continental influence of Gondwana, at the same time that the Macquarie Arc was being formed. Metamorphic zircon ages from the Attunga Eclogite indicate an age of *ca* 490 Ma with a 530–510 Ma inheritance. The REE chemistry of the Attunga metamorphic zircons indicate growth in the presence of garnet but not plagioclase, indicating eclogite facies metamorphism has been dated. We suggest that the Attunga Eclogite may represent a portion of the metamorphic sole of the Weraerai terrane ophiolite that itself may represent the basement material onto which the younger island-arc Gamilaroi terrane was built during the Silurian–Devonian. Final collision of the Gamilaroi terrane with Gondwana occurred in the latest Devonian resulting in the Kanimblan Orogeny and coinciding with the termination of magmatic activity in the Lachlan Orogen in the Middle Devonian. The subsequent subduction flip resulted in a magmatic flare-up along eastern Gondwana that started with the Carboniferous Bathurst Granites/Currububula Arc and migrated eastward by the Permian resulting in the emplacement of the New England Batholith. The next quantum addition of juvenile crust is associated with the collision of the Gympie terrane – another exotic, island-arc complex, which is responsible for the Hunter-Bowen Orogeny and termination of magmatic activity within the New England Batholith at about the Permo-Triassic boundary. It also led to the exhumation of the Port Macquarie eclogite/serpentinite before onset of another magmatic flare-up in the Late Triassic associated with the Lorne and Clarence-Moreton basins.

01DPB2-02. GEOCHEMICAL EVIDENCE FOR PROVENANCE OF ORDOVICIAN CHERTS IN SOUTHEASTERN AUSTRALIA

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Lower to Middle Ordovician cherts and cherty siltstones, associated with distal turbidite deposits of the Girilambone and Adaminaby groups, are widespread in the Lachlan Orogen in central New South Wales. These cherts are well-constrained biostratigraphically by conodonts ranging in age from the upper Tremadocian to lowermost Sandbian. Broadly contemporaneous cherts are also present in two small remnants of postulated oceanic derivation now exposed on the coast of NSW, in the Narooma Terrane (Furongian, i.e. latest Cambrian to Darriwilian), and in allochthonous blocks (of late Middle and Upper Ordovician age) of the New England Orogen at Port Macquarie. Darriwilian to earliest Gisbornian cherts interbedded with volcaniclastics in the Kiandra–Tumut region of southern NSW provide a unique tectonic association with the Macquarie Volcanic Belt. Sixty samples representative of these regions were analysed for selected major, trace and rare earth elements (REE).

Geochemical investigations of Ordovician cherts, to determine their provenance and compare depositional settings in differing environments, have not previously been attempted in the Tasmanides of eastern Australia. Although Th/Sc and La/Sc ratios have commonly been employed as provenance indicators in studies of turbidite sequences elsewhere, we demonstrate that such ratios are less reliable than the Al_2O_3/TiO_2 ratio as a proxy for the composition of the terrigenous component in cherts. The Al_2O_3/TiO_2 ratio indicates two dominant sources from which the sediment fraction of the cherts was derived at different times in the evolution of the Tasmanides; one indicative of detrital deposition along a mature continental margin and the other sourced from a juvenile continent or submarine plateau.

Cherts from the Albury-Bega and Hermidale terranes are LREE enriched, with small negative Ce anomalies, moderately prominent negative Eu anomalies, relatively low total REEs and near-chondritic Y/Ho ratios. These REE signatures characterise continental margin chert, and are consistent with deposition in an enclosed moderate sized basin receiving terrigenous input predominantly from the Gondwana continental margin, but also tapping a juvenile source in the late Lancefieldian–late Bendigonian and again in the mid Darriwilian. The Kiandra cherts are interpreted to have been deposited proximal to a continental margin as overall they are LREE enriched, have small Ce anomalies and low total REE abundances. The younger Kiandra samples are unique in having high Al_2O_3/TiO_2 ratios coupled with virtually no Eu anomalies and may indicate a metalliferous contribution from an immature volcanic source. They compare in age and REE chemistry with the older chert (upper Darriwilian–lower Gisbornian) from Port Macquarie, whereas the younger chert from Port Macquarie appears to have formed further outboard, tapping a mixed clastic source with no evidence of volcanic arc input. Narooma Terrane cherts are also consistent with continental margin deposition but record definitive source variations, from a juvenile continent or submarine plateau in the latest Cambrian to Early Ordovician, to a Gondwana source in the late Bendigonian–Chewtonian and finally a mixed source in the late Darriwilian. There is no evidence of an undifferentiated volcanic arc contribution in the Narooma cherts.

01DPB2-03. KINEMATIC RECONSTRUCTION OF THE HASTINGS BLOCK, SOUTHERN NEW ENGLAND OROGEN

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This research project used 3D geological modelling software to build a 3D structural surface model of the Permo-Carboniferous fore-arc rocks in the Northern Hastings Block (NHB; Lennox *et al.* 1999). The model was built using a comprehensive field data set and a digital elevation model. It is designed to unravel a comprehensively mapped, complexly folded, extensively faulted, layer-cake sequence without drill hole data. It is believed that this new workflow will be widely applicable in the oil, gas, mining, and groundwater sectors.

There are a number of tectonic models that have been proposed to explain the structural and tectonic development of the Hasting Block, which is outboard of similar forearc basin sequences in the Tamworth Belt. They include emplacement either by faulting, with or without rotation, or rotation during folding of the southern section of the Tamworth Belt. The new 3D model will enable testing of the validity of these existing tectonic models. It will assist in constraining the relative timing of fault development, testing fault emplacement of the block and verifying the number and orientation of folding events in the NHB. In this case study, the model is constrained by structural evolution consistent with surface mapped features.

The NHB is dominated by an open, ~40 x 30 km NW-trending dome with the dominant fold axis plunging gently northwest (Lennox *et al.* 1999). It has been extensively faulted and possibly rotated after fault development. Construction of the 3D model fault block by fault block, has highlighted the shortcomings with the existing geology map of the NHB (Roberts *et al.* 1995). This includes the variability in the orientation of bedding within some fault blocks, between adjacent fault blocks and around significant sections of the dome. Resolution of these challenges has resulted in a re-appraisal of the simple dome model for the NHB. Each fault in the NHB was analysed systematically to determine the duration of faulting, apparent sense of movement and relationship to other faults and the folds. The fault history plays an important role in building backward and forward models. Comparison between the cross sections constructed from the 3D model and those from the existing fieldwork provide better constraints on the validity of the 3D modelling.

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01DPB2-04. GEOCHEMISTRY OF METASOMATISED AND SUBDUCTED MAFIC ROCKS IN THE NAROOMA ACCRETIONARY COMPLEX – CLUES TO THEIR TECTONIC SETTING?

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It is commonly assumed that the tectonic setting of mafic rocks can only be determined from their chemical composition if they are pristine or slightly altered. In this study it will be shown that the geochemistry of mafic rocks that have been metasomatised and recrystallised during subduction can reveal the magmatic affinity and setting provided immobile elements (REE, Th, Nb, Zr, Hf, Y, V, Cr, Ni and Ti) are used in the determination.

The samples studied come from the Cambro-Ordovician Wagonga Group at Batemans Bay and Narooma that contains metamorphosed more massive, finely foliated basalt, basalt clasts in melange and basaltic breccia units. The latter is associated with middle to upper Cambrian parautochonous limestone and mesoscopically may show remnant igneous textures such as pillow structures and amygdales. However, most are highly deformed, white mica-rich and exhibit one to two foliations. Petrographic studies indicate that initially, they were hydrothermally altered and subsequently intensely deformed during subduction. They further reveal that quartz, white mica, titanite, mixed-layer clay, opaque minerals and uncommon chlorite were produced during the alteration and white mica, less common chlorite and semi-opaque aggregates during subduction. Relict igneous textures in the form of ghost outlines of plagioclase laths and flattened amygdales occur in some samples. K-white mica studies reveal that they attained lower greenschist facies grade and a depth of ~15 km during subduction that $^{40}Ar/^{39}Ar$ dating indicated took place at *ca* 445Ma.

Despite alteration, immobile elements show coherent patterns and reveal distinctive ocean island basalt (OIB), seamount-like signatures in some basalt samples and back arc basin signatures in others. The former are indicated by their alkaline basaltic affinity, light rare earth element (LREE)-enriched, chondrite and LILE-enriched, primitive mantle-normalised patterns, and the latter by a tholeiitic basaltic affinity, MORB-like (LREE) depleted and flat heavy rare earth element (HREE) chondrite normalised patterns and primitive mantle-normalised patterns featuring slight Nb, Ta, Hf, Zr and Ti depletion. One sample showed a slight LREE-enriched chondrite normalised pattern, Th enrichment and Nb, Ta, Ti, Zr and Hf depletion in a primitive mantle-normalised pattern characteristic of intraoceanic arc magmas. The OIB signature of the alkali basaltic samples and tectonic setting of the BAB and ARC samples is confirmed by V–Ti, Y/15–La/10–Nb/8 and Th/Yb–Nb/Yb diagrams. These samples that formerly belonged to a Cambrian intraoceanic island arc sequence, offshore from the Gondwana margin, were transported and eventually subducted during the Late Ordovician.

01DPC2 – TECTONICS OF THE TASMANIDES

01DPC2-01. THE NAROOMA TERRANE ON THE NEW SOUTH WALES CONTINENTAL SLOPE AND A CONNECTION WITH CENTRAL VICTORIA

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Regionally metamorphosed Benambran Cycle, Narooma Terrane foliated pelites, mafic volcanics and serpentinite as well as Siluro-Devonian Tabberabberan Cycle fossiliferous limestone, Moruya Suite granodiorite and undeformed contact metamorphosed dacitic volcanics have been dredged from nine sites on the outer continental slope between Tuross Heads and Green Cape. Corals from the limestone from off Tuross Heads and the granodiorite with K/Ar hornblende dated at 381 ± 10 Ma from off Green Cape have been previously reported.

Green Cape Narooma Terrane dredge hauls are dominated by greenschist and lower amphibolite facies mafic rocks, with subordinate amounts of fine-grained siliceous rocks (initially cherts), as well as rare marble and pelitic rocks (some with minor silt content). Small collections of mafic rocks, chert and marble were recovered from three sites east of Bermagui. Serpentinised foliated and non-foliated ultramafics that could be part of a Narooma Terrane ophiolite were also dredged east of Green Cape and Bermagui, at one site with chert and metabasalt and at another exclusively with earliest Permian mudstone. Spider diagrams show that most meta-mafic rocks have affinities with the ocean island basalt similar to lithologies described onshore while others have ?MORB affinities; more significantly a few, have boninitic characteristics. None of these mafic lithologies have geochemical signatures indicative of arc-volcanism. These findings extend the Narooma Terrane offshore a distance 200 km to the south of its onshore exposure at Batemans Bay.

We interpret the Wagonga–Adaminaby group boundaries as a Benambran thrust between the Narooma Terrane, with an ?early Cambrian basement, and the Albury-Bega Terrane, with a mid “middle Cambrian” basement as dated on the Howqua River in the Tabberabbera Zone. There, the Eagles Peak Basalt (correlated with gabbro at Dookie (502 ± 0.7 Ma) is overlain by the Howqua Chert then the Adaminaby Group quartz turbidites (Lancefieldian at the base). The Batemans Bay Wagonga Group, Undillian to Mindyallan limestone blocks (502–497 Ma) with ocean island basalt must significantly postdate Narooma Terrane basement, which we correlate with the upper lower Cambrian boninitic Heathcote Volcanics and the poorly dated basal Lickhole Volcanics that flank the Melbourne Zone rather than paleo-Pacific crust.

We consider that the boninitic ophiolite arc that collided with Tasmania in the early Cambrian was also obducted onto the Selwyn block. The arc north of the Selwyn block, rifted. The forearc (now the Dimboola Complex) collidied with the Delamarian margin as it moved west generated the Botomian seafloor of the Magdala Volcanics and the Mt William Metabasalt (Heathcote Volcanics), behind it.

In the simplest model, a “middle Cambrian” oceanic rift formed the Albury-Bega Terrane basement as it rifted the Narooma Terrane basement off the eastern margin of the Melbourne Zone and/or the abandoned boninitic remnant arc. There was Ordovician freeboard of Narooma Terrane relative to the Albury-Bega crust because it was thicker and had a cover of ocean island volcanics. The thinner Albury-Bega crust cooled and subsided for 30 Ma before the influx of Ordovician clastics so that only the finest sediments reached the Narooma Terrane. This model is compromised by the ?Silurian emplacement of the Kiandra Belt Ordovician arc volcanic sliver between the east and west Albury-Bega Terrane.

No evidence was found offshore for an extensive Ordovician subduction complex. Benambran and metamorphism offshore was HT/LP, preceding Siluro-Devonian shallow water deposition, felsic volcanism and granite generation.

01DPD2 – THE THOMSON OROGEN IN QUEENSLAND AND NORTHWESTERN NSW

01DPD2-01. NEOPROTEROZOIC TO DEVONIAN THOMSON OROGEN, NORTHEASTERN AUSTRALIA: IMPLICATIONS FOR RODINIA ASSEMBLY AND GONDWANA PALEOPACIFIC PASSIVE TO ACTIVE MARGIN TECTONICS

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Gondwana developed in the Neoproterozoic to Cambrian from collision along the Mozambique and Kuunga sutures at about the same time that the Gondwana paleo-Pacific facing margin developed as a long-lived active margin. The early Paleozoic active margin is most widely exposed in southeastern Australia in the Lachlan Orogen but its tectonic development has involved considerable confusion and disagreement. In northwestern New South Wales and southern and central Queensland, basement to Permian and Mesozoic sedimentary basins is called the Thomson Orogen and has long been considered a northern continuation of the Lachlan Orogen, with which it has an overlapping history. New mapping and geochronology published over the last 10 years has resulted in a major reassessment of the geology of the Thomson Orogen based on its restricted surface exposures in central and north Queensland and also from a remarkable set of basement cores distributed throughout central and southern Queensland and northeastern South Australia.

Metamorphic units in the Charters Towers and Anakie provinces of north and central Queensland respectively show evidence of two successions from detrital zircon ages in meta-siliciclastic sedimentary rocks: an older succession with almost a single dominant zircon signature of 1300–1000 Ma "Grenvillean" ages and most likely derived from an eastern continuation of the Musgrave Province of central Australia, and a younger succession containing a detrital zircon signature more typical of Gondwana with both significant "Grenvillean" and 600–500 Ma "Pacific-Gondwana" ages. The older succession implies that a "Grenvillean" suture crossed the Australian part of East Gondwana and that the suture formed from collision of the North and South Australian cratons and that these were not necessarily connected as has been suggested in many recent publications. The younger succession followed development of an active margin along the paleo-Pacific facing part of Gondwana. The pre-existing passive margin was destroyed in the Delamerian Orogeny although the effects of this have been heavily overprinted by Early Ordovician extensional tectonics associated with rollback along the active margin. Development of the active margin is poorly constrained but must have been well established by the late Cambrian. Island arc collision in the Late Ordovician resulted in the Benambran Orogeny with widespread deformation, metamorphism and plutonism with reworking of regions previously deformed in the Delamerian Orogeny and affected by Early Ordovician extensional tectonics. A hiatus in the development of sedimentary and metamorphic rock systems followed the Benambran Orogeny in contrast to widespread igneous activity in southeastern Australia at that time, but was followed by Devonian basin development and continental margin igneous activity that continued in northeastern Australia into the Mesozoic.

01DPD2-02. INTERPRETING BASEMENT GEOLOGY IN THE SOUTHERN THOMSON OROGEN

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The Thomson Orogen (TO) of eastern Australia occupies a vast area but is poorly understood due to extensive cover. Restricted outcrop in central–north Qld and limited exposures in northwestern NSW and southern Queensland host several mineralisation styles (e.g. orogenic gold, VHMS, porphyry-related). Areas of shallow cover, such as the Eulo Ridge and greater southern TO region are therefore highly prospective. A geological framework is needed to underpin future mapping and exploration. We present a preliminary basement interpretation map, which integrates new geophysical data with observations from outcrops and scattered drill cores. This initial map is seamless across the Queensland–NSW border and is part of an ongoing collaborative project between the Queensland and NSW state geological surveys and Geoscience Australia.

Basement outcrop in the southern TO is restricted to small granitoid exposures in the Eulo Ridge, slightly larger exposures of granodiorite and metasedimentary rocks near Tibooburra, and around the southern margin near Louth. These provide important constraints and guide geophysical interpretation of the surrounding subsurface geology. Granitoid exposures range from foliated, coarsely porphyritc S-type granite (Granite Springs Granite), to homogeneous medium-grained biotite–hornblende granodiorite (Tibooburra Granodiorite), and have magmatic ages that span *ca* 460–380 Ma. Exposed metasedimentary rocks around Tibooburra (Warratta Group) are considered to be upper Cambrian to Lower Ordovician in age and comprise variably deformed and metamorphosed interbedded siltstone, sandstone and mudstone. Exposure in the Louth–Bourke area comprises Devonian volcanic rocks and Upper Ordovician slates.

Regional aeromagnetic and gravity datasets reveal significant detail and complexity under cover. Basement geophysical domains were interpreted and matched with observations from outcropping areas, water bore logs, seismic data, and recent mineral exploration drilling to tentatively define lithological units and major structures. Metasedimentary rocks are dominant and are commonly described as interbedded sandstone, siltstone and mudstone, but variation observed in magnetic character suggests significant compositional variation. Less extensive metavolcanic units are defined by magnetic anomalies and comprise intermediate to mafic volcanic and volcaniclastic deposits. Interpreted intrusions are grouped based on geophysical characteristics (including size and shape) to reflect different compositions, compositional variation, emplacement style, and ages. Some units lack any geological information and are interpreted solely on their geophysical character. These (particularly the volcanic units) are obvious targets for future investigations.

In areas of deeper cover, combinations of gravity and magnetic images define large-scale structures and intrusive bodies. Interpretation is aided by drill logs and observations of petroleum drill cores. Metasedimentary rocks intersected in drill cores have late Cambrian maximum depositional ages. Detailed observations indicate compositional variation across the region but separate geological units are difficult to define. Intersections of intrusive rocks correlate well with the geophysical interpretation and intrusions sampled to date exhibit a similar range of ages (*ca* 480–400 Ma), textures, and composition of outcropping rocks.

Further investigations that will test/enhance the preliminary map are planned. These include geophysics (AEM, MT), seismic interpretation, and investigations of the age and significance of volcanic units, and the thermal and structural history of the region.

01DPE2 – THE THOMSON OROGEN IN QUEENSLAND AND NORTHWESTERN NSW

01DPE2-01. PRE-COMPETITIVE MINERALS ACTIVITIES IN THE SOUTHERN THOMSON OROGEN: UNLOCKING THE REGION'S HIDDEN RESOURCE POTENTIAL

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The geology of the southern Thomson Orogen is poorly understood due to extensive cover by Mesozoic and younger sedimentary basins and regolith. Small outcrops of the Thomson Orogen are exposed along the Eulo Ridge (Queensland) and in the southwest around Tibooburra (New South Wales). Between these regions the thickness of cover averages ~200 m, which is within exploration and mining depths.

The southern Thomson Orogen is true 'greenfields' country. Although the mineral potential of the region is largely unknown, the northeastern Thomson Orogen (e.g., Thalanga, Charters Towers) and the similar-aged Lachlan Orogen to the south are well mineralised (e.g., Cadia, Cobar). In order to attract investment (exploration) into the southern Thomson Orogen, and also to improve the geological understanding of the area, Geoscience Australia, the Geological Survey of Queensland and the Geological Survey of New South Wales have commenced a collaborative project to collect new (and synthesise existing) pre-competitive data.

The project is well advanced in its first stage, which includes a synthesis of existing datasets across the state borders to create a revised solid geology map (see contributions by Purdy *et al.* and Doublier *et al.* in this theme). This map will form the basis of a 3D model (map), which will utilise pre-existing government and industry seismic and drilling data. In support of the 3D map, a programme of geophysical acquisition, processing and interpretation is under way. These datasets include: airborne electromagnetic (AEM – data acquisition and processing underway), broad-band magnetotelluric (MT) and gravity data (both in advanced planning stage).

In order to understand the nature of the cover rocks and their relationship to Paleozoic basement, the first sampling campaign of a surface geochemical survey has been carried out providing a higher resolution infill of the National Geochemical Survey of Australia (NGSA) by expanding an earlier CRC LEME survey northwards into southern Queensland.

In addition, the potential mineral systems of the region – and their relationship to adjacent areas – are currently being assessed, with initial studies focussing on timing, isotopic signatures, and structural context. Interim products and datasets will be released throughout the project, with the final results delivered to industry in 2016–17.

01DPE2-02. DECIPHERING THE STRUCTURAL FRAMEWORK OF THE CENTRAL AND SOUTHERN THOMSON OROGEN, AUSTRALIA

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The Thomson Orogen of eastern Australia is poorly exposed, and largely covered by the Eromanga Basin and underlying sedimentary basins. As part of the Southern Thomson Project — a collaborative project between Geoscience Australia and the state geological surveys of New South Wales and Queensland — the structural framework of the central and southern Thomson Orogen is currently being assessed. This contribution presents preliminary results of this ongoing work.

Deciphering the structural framework through time in covered terrains is challenging, and draws heavily on the interpretation of geophysical data such as gravity and aeromagnetic datasets, as well as crustal reflection seismic surveys. In the southern part of the Thomson Orogen, relatively shallow cover, in combination with lithologies characterised by high-amplitude/short-wavelength magnetic signatures, allows for a relatively detailed assessment of the shallow structure. The emerging picture is that of two structural domains.

In the southwestern structural domain, the trends of lithologies and segmenting shear zones largely mimic that of the bounding Olepoloko Fault, from a north-northwest trend in the west to an east-southeast to east trend in the south. This pattern is overprinted by northeast-trending mega-kink zones. Some of the shear zones are imaged in the seismic lines 05GA-TL2 and 05GA-TL3. Two groups can be distinguished, based on opposed apparent dip directions towards the south to southwest, and north to northeast, respectively. In contrast, the map view of the eastern structural domain (north of the Culgoa lineament) is dominated by a large-scale fold structure with a northeast-trending axial plane, interpreted as an antiform. Similarly to the southwestern structural domain, several generations of smaller scale folds indicate polyphase folding, the timing of which is unconstrained.

In the central Thomson Orogen, both aeromagnetic and gravity data reflect the thicker cover mainly caused by the presence of sub-Eromanga basin systems (e.g. Adavale, Cooper), making detailed interpretations of the basement more difficult. The Eromanga deep seismic reflection survey acquired in the early 1980s represents an important dataset for understanding of crustal architecture in the area. It reveals crustal thickening and stacking of sub-basin lithologies dominantly along structures with an apparent westward dip, but also underlines the importance of younger structures — such as those controlling the preservation of Adavale Basin remnants, which are partly controlled by basement structures.

At the larger regional scale, several large-scale sets of structures can be interpreted, including: (i) east–west trending faults/shear zones that are best observed in the southeastern part of the central Thomson Orogen, and commonly delineated by elongated intrusive bodies, one of which has been dated at *ca* 420 Ma; and (ii) west–northwest trending faults/shear zones. The latter zones extend to 1000 km or more, and locally seem to continue into the adjacent central and eastern Lachlan. In the southwestern structural domain, these shear zones cut granite intrusions, which postdate the regional folding.

Ongoing work aims to integrate the 3D orientation of structures (constrained by reflection seismic data) with the map pattern seen in potential field data, and to constrain their relative and absolute timing.

01DPE2-03. EXHUMATION OF THE THOMSON OROGEN WITHIN BASEMENT-CORED STRUCTURES OF EASTERN QUEENSLAND

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The Thomson Orogen, which comprises crystalline basement rocks underlying sedimentary and volcanic basins in much of eastern Australia, is exposed at the surface in only a few locations. The largest of these is the Anakie Inlier of eastern Queensland, a N–S elongate, 300 x 75 km basement exposure of Neoproterozoic–Cambrian metamorphic rocks and early to middle Paleozoic granites. Two smaller basement exposures, Fletcher's Awl Dome and Mt McLaren, lie roughly 30 km to the east of the Anakie Inlier. In all of these locations, Thomson Orogen rocks are overlain by Devonian volcanic and sedimentary rocks, and all three locations are structural domes or anticlines. The formation of these structures and the mechanisms by which metamorphic rocks of the Thomson Orogen were exhumed to the surface are topics that are largely unexplored. The basic geometries of these exposures suggest that they are basement-cored folds, metamorphic core complexes, or a combination of the two. New field observations and geothermochronology data, combined with reinterpretation of previous K–Ar and $^{40}Ar/^{39}Ar$ data from the Anakie Inlier, suggest four major phases in the metamorphic and exhumation history of the Thomson Orogen in the Anakie Inlier region: (1) Cambrian–Ordovician peak metamorphism; (2) a protracted period of cooling during the Late Devonian through earliest Permian that likely resulted from extensional exhumation; (3) Permian–Jurassic reheating that began with the Hunter-Bowen Orogeny during burial beneath thick sedimentary basins; and (4) Cretaceous and

Paleogene cooling during uplift and erosion. Phases 2 and 3 are closely related to the development of the Drummond and Bowen/Galilee basins, respectively, illustrating that the thermal history of the Thomson Orogen is linked with the formation and erosion of overlying basins.

01DPE2-04. THE FATE OF THE MOUNT WRIGHT ARC AND DEVELOPMENT OF THE SOUTHERN THOMSON OROGEN: EVIDENCE FROM THE KOONENBERRY BELT OF NORTHWEST NSW

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The Mount Wright Arc, in the Koonenberry Belt in eastern Australia, developed onto the late Neoproterozoic volcanic passive margin of East Gondwana. The volcanic component of the arc consists of a calc-alkaline basalt–andesite–dacite suite (Mount Wright Volcanics). Northeast of the Mount Wright Volcanics is the Ponto Group, a deep marine sedimentary package that includes tholeiitic lavas (Bittles Tank Volcanics) and felsic tuffs (of the same age and chemistry as the arc rocks), interpreted as part of a fore-arc sequence. The configuration of these units suggests the Mount Wright Arc developed on continental crust in response to west-dipping subduction along the East Gondwana margin. This convergent margin was deformed during the middle Cambrian Delamerian Orogeny, which involved initial co-axial shortening followed by sinistral transpression, and oroclinal folding around the edge of the Curnamona Province. Pre-Delamerian reconstruction suggests the Ponto Group extended outboard of the continental margin parallel to the current northwest-trending Koonenberry Belt, and it is likely that the calc-alkaline volcanics of the Loch Lilly–Kars Belt also followed that trend prior to the Delamerian.

Following deformation and uplift, the Cambro-Ordovician Warratta Group was deposited onto the Delamerian unconformity surface. This turbidite package contains mafic alkaline Evelyn Creek Volcanics, as well as rare limestone and boulder-diamictite. It is interpreted to represent the westernmost unit exposed in the Thomson Orogen, suggesting a pre-Delamerian connection to the Koonenberry Belt, however imaging the Koonenberry Belt–Thomson Orogen boundary here has proven difficult.

This western boundary of the Thomson Orogen with the Koonenberry Belt is interpreted as the Olepoloko Fault – defined further east at Louth as a major north-dipping structure with significant post-Devonian reverse movement. Regional mapping of the Warratta Group has shown that the intense contraction causing the inversion of the Warratta Group occurred during the Benambran Orogeny (or time-equivalent event) at *ca* 460–428 Ma. This event caused belt-parallel shortening and was probably southwest directed, with a later stage of deformation (*ca* 425–414 Ma) more south-directed resulting in dextral strike-slip faulting, drag-folding in the Tibooburra area (along the interpreted Olepoloko Fault) and pull-apart basin formation at Mount Daubney. The chemistry of the Evelyn Creek Volcanics, which are located approximately along the interpreted fault, suggests intraplate magmatism was active along the margin of the Thomson Orogen at least during the Cambro-Ordovician, and possibly into the Silurian with the intrusion of the I-type Tibooburra Suite.

RESOURCES

01REA – MINERALOGICAL EXPLORATION – A SESSION IN HONOUR AND MEMORY OF KEITH SCOTT

01REA-01. THE CONCEPT OF MINERALOGICAL EXPLORATION AND THE CONTRIBUTION OF KEITH SCOTT

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Ores, like most rocks, are composed of minerals. With the development of geochemistry and the application of elemental analysis to mineral exploration there has been a tendency to overlook or downplay the fundamental relationship between the elements and their naturally occurring chemical compounds or minerals. Mineralogical exploration applies knowledge of mineral assemblages, paragenesis and element–host mineral associations to the search for ore deposits and their mineralising systems. The range of applications includes:

The use of element associations in particular minerals as part of a geochemical sampling strategy. This association may be related to primary ore-forming processes (e.g. trace element patterns in accessory minerals such as magnetite) or developed during weathering-related secondary dispersion (e.g. the gold–calcrete association);

The use of indicator minerals in exploration for particular host rocks (e.g. kimberlites) or ore deposits (e.g. Cr- and V-bearing micas related to some gold deposits);

The identification of indicator, trace mineral inclusions in major and minor minerals associated with ore formation;

Mineral characterisation and mapping by reflectance spectroscopy, magnetic and radiometric properties, particularly to recognise host rock alteration related to mineralising events.

Some exampled approaches to establishing and utilising element-host mineral associations include: direct analysis of target mineral grains by microbeam techniques; selective dissolution or extraction methods designed to release elements hosted in, or attached to, particular minerals; and numerical modelling of bulk geochemical data to reveal relationships of elements with minerals known or suspected to be present in the ore or its associated alteration (e.g. PER and GER modelling).

During his career Keith Scott contributed a number of threads to the tapestry of mineral–ore relationships useful to mineralogical exploration. Keith's approach was generally as a mineralogist first and geochemist second, but always linking the two aspects. Much of his early work focused on gossan mineralogy and mineral chemistry as a means of identifying true gossans and their relative indications of ore potential. He had an ongoing interest in the alunite–jarosite solid solution series and the mineral chemistry of manganese minerals, particularly in relation to their hosting of dispersed ore elements. With co-workers he investigated the trace element chemistry and mineral inclusions in resistate minerals such as rutile, ilmenite and magnetite, for application to mineral exploration. He also worked on the trace element characteristics of host rock carbonates around the Century deposit, Queensland, as a means of detecting associated SEDEX mineralisation. Keith was involved in the development of radiometric and hyperspectral mineral logging, particularly on hydrothermal alteration minerals such as phengitic mica. Through his long association with CRC LEME he also contributed to many other mineral-related aspects of the regolith, including understanding the calcrete–gold association and target and pathfinder element absorption by clay minerals and iron oxides. Keith was very active in passing on his discoveries and knowledge to the mineral exploration industry and to younger geoscientists and students who he assisted and supported passionately.

01REA-02. MINERALOGICAL EXPLORATION, AN INDUSTRY PERSPECTIVE

Michael Whitbread

MMG Limited

Modern mineral exploration presents its protagonists with some interesting challenges. Resource nationalism, general sovereign risk, NIMBY-ism, fickle financing, skills decline and a lack of internal R&D capacity all hamper our ability to find future resources. These variables mean that we must maximise any window of exploration opportunity that opens up, quickly turn over ground, prove up resources and get mines under construction before the supportive conditions change.

A key, arguably under-utilised, toolset at our disposal is to use mineral chemistry, mineral indicators and mineralogical modelling (using lithogeochemistry) to augment basic examination of elemental abundance. These techniques can be applied at various exploration scales, from regional surveys to advanced drilling stage. Importantly, integration of various methods and visualisation in 3D using modern mining packages is key in extracting full value from the data.

At the regional or tenement package scale, stream sediments and soil sampling still play a major role in delineating targets for follow up. Commonly, there is little done to characterise the mineralogical nature and hence prospectivity of any anomalies that are identified, outside of comparison of elemental associations against idealised deposit alteration and dispersion models. Simple examination of the mineral host to Cu anomalism, for example, can enlighten the explorer as to the potential for hypogene or supergene exposure. This can inform us what remote sensing methods and ground-truthing are likely to be useful (e.g. SWIR, chipping, airborne geophysics, radiometrics), and even whether an NPV positive target is present (in the case of cash-recovering oxide vs primary sulfide targets).

In streams, the heavy mineral fraction commonly contains grains that are potentially sourced directly from the mineralised envelope. The presence of zircons, magnetites, spinels and garnets, amongst others, are all potential indicators of various base metal deposits. Critically, the composition of these will better constrain potential for mineralisation upstream, by allowing us to identify barren from fertile systems with better probability.

At the drilling stage, combined mineralogical modelling and spectral studies allow us to look at both the composition and the width of alteration in areas of interest. For example, the presence and composition of carbonates and micas can provide key insights into prospectivity of targets. Spectral mineralogy combined with assay data can also provide vectoring and/or geometallurgical domain information.

There are, in my view, no geochemical silver bullets for conducting successful mineral exploration. The challenge for the industry is not the state of the science, for the most part, but the correct and continued application of suitable available methods! It is also important to realise the limitations of academic data and the need for teams to generate their own 'real world' datasets. Given variable resourcing, downturns and skill turnover, perhaps there is value in companies sharing non-critical mineralogical data through an impartial 3rd party?

01REA-03. CAN PYRITE CHEMISTRY BETRAY PYRITE ORIGIN? APPLICATION OF DISCRIMINATION FUNCTION ANALYSIS TO ORE DEPOSIT HYDROTHERMAL PYRITE POPULATIONS

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Pyrite geochemistry is remarkably variable within and between pyrite types, rendering the task of chemically fingerprinting pyrite difficult. The use of Co/Ni ratios, a recommendation from some previous research, appears to have very limited application to general pyrite classification, once whole deposit populations are considered. One insight into this lack of success is the recognition that at low W/R ratios, fluids with low Co and Ni contents but high Co–Ni solubilities may leach large amounts of these metals from rock sequences, because Co and Ni are abundant and hydrothermally available in intermediate to mafic rock compositions and their sedimentary equivalents. Consequently, precipitation of disseminated pyrite at the hydrothermal front may be strongly locally influenced by local Co and Ni contents, rather than reflecting the chemistry of the incoming fluid.

In this study we approached pyrite classification using Discrimination Function Analysis, a multivariate element technique. This is a statistical method that is commonly employed to separate distinct populations, essentially reliant upon the differences between means of parameters. It is mainly applied to large descriptive data sets in which the distinctions between populations are subtle, or where the numbers of parameters employed is large. It can only be applied where each parameter analysed is normally distributed. We evaluated a large number of samples (30–40, with 6–10 analyses each) for several deposits in each deposit type, with the aim of encompassing the total variability that arises in a single deposit, from its centre to its altered periphery. This was intended to increase the robustness of the result. The main ore deposit types evaluated were Yilgarn-style orogenic gold, volcanic-hosted massive sulfide, porphyry Cu–Au, with smaller data sets for sedimentary (non-ore), komatiitic and IOCG-related pyrite. Discriminant analysis was undertaken through the software package Statistica 6.0. Only log normalised (base 10) averages were employed, to conform to the requirement that populations be normally distributed. To reduce the analysis to a workable number of parameters, elements shown to be mainly present as silicate- and oxide-based inclusions in pyrite were removed from the database (e.g., Ti, V, Cr, Zr, Sr, Ba, W), leaving 19 elements for initial analysis (Mn, Co, Ni, As, Sb, Cu, Pb, Zn, Ag, Bi, Au, Cd, U, Th, Te, Tl, Sn, Mo, Se). The basic ore deposit types were used as the classification criteria.

This approach produced 83% success in classifying pyrites in our dataset, and higher success rates with some assessment data fed into the classification functions. It resulted in the formulation of diagrammatic classification graphical templates for some common combinations of pyrite types, such as Archean greenstone belts (lode gold, sedimentary pyrite, komatiitic nickel pyrite, VHMS pyrite), and high level felsic magmatic zones (porphyry *vs* high sulfidation epithermal pyrites), amongst others. This early success suggests that discrimination function analysis is a promising avenue for recognising the origin of individual pyrite samples at an early stage in exploration programs.

01REB – MINERALOGICAL EXPLORATION – A SESSION IN HONOUR AND MEMORY OF KEITH SCOTT

01REB-01. ROLE OF GRAPHITE IN MODIFYING THE REDOX ENVIRONMENT FOR LOW-TEMPERATURE MINERAL ALTERATION ON SOUTHERN EYRE PENINSULA

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Metamorphic rocks on southern Eyre Peninsula, South Australia include graphitic schist and gneiss of Paleoproterozoic Hutchison Group metasediments (*ca* 2000–1850 Ma), recrystallised from fine-grained clastic, carbonaceous, and chemical sediments of marine origin. The rocks were metamorphosed to granulite facies and strongly deformed and sheared during the Kimban Orogeny (*ca* 1730–1700 Ma). At the Uley graphite mine, 18 km southwest of Port Lincoln and at Clem Cove on Sleaford Bay, weathered and highly altered graphitic schist contains irregular patches and veinlets of blue–green celadonite (iron-rich dioctahedral mica). At the Uley mine, nontronite (iron-rich smectite) is widespread as an alteration product of biotite-rich graphitic schist, and of amphibolite. Celadonite is most commonly associated with hydrothermally-altered mafic volcanic rocks at seafloor spreading centres. Celadonite from biotite alteration is unusual and was concluded to result from low-temperature hydrothermal activity, post high-grade metamorphism.

Eyre Peninsula celadonite was dated by K–Ar method and shown to have crystallised at *ca* 48 Ma (early Eocene) at Sleaford Bay and at *ca* 16 Ma (early–mid Miocene) at the Uley mine. The timeframes equate with local high sea levels and episodes of deep weathering. The probability is therefore that the alteration was related to weathering, possibly together with fluid circulation in fault and fracture zones. Given that deep weathering and extensive fracture zones are common across basement rocks on southern Eyre Peninsula, the question arises as to why celadonite alteration appears restricted to zones around high-grade graphitic rocks.

Weathering creates a potential difference between the surface oxidised zone and more reduced unweathered rocks at depth. Where the zones are connected by a conductive body, such as graphite, natural electrical currents in the conductive body develop, as negative charges flow toward the weathered zone. This gives rise to a spontaneous or 'self' potential (SP) that can be measured at the surface using non-polarising electrodes. The SP anomaly measured over graphite at the Uley mine was –250 mV. Offshore, ~12 km south of Sleaford Bay, in 80 m water depth, an SP anomaly of –100 mV was recorded previously, and interpreted as due to offshore extension of the graphitic zone in Hutchison Group. The movement of charge-carrying, redox-active ions into the zone of weathering around a graphite conductor will modify the electro-chemical environment within the zone of active oxidation. In this environment soluble Fe^{2+} ions released from biotite and hornblende dissolution will have more opportunity to remain in solution and interact with other ions to form minerals such as celadonite, incorporating both Fe^{2+} and Fe^{3+}, and nontronite, under neutral to slightly alkaline conditions. This modified environment about a graphitic conductor may enhance the effectiveness of released Fe^{2+} ions to act as reducing agent for other ions in solution, including the reduction of circulating soluble U^{6+} ions, to precipitate insoluble U^{4+} species. If this is the case, then the influence of graphitic conductors on the grade and extent of uranium mineralisation in 'unconformity-style' deposits may need to be reassessed.

01REB-02. THE FORMATION OF PRECIOUS OPAL IN CENTRAL AUSTRALIA

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After 150 years of opal mining in the Great Artesian Basin (GAB), Australia is still producing the bulk of the world's precious opal. Over the past decade however, opal mining has slowed considerably, accelerating the decline of many townships. This is due in part to a decline in the number of active miners strongly affected by the rising cost of mining, and the lack of discovery of new opal fields. Nevertheless, opal is still part of the economic fabric and cultural identity of many townships of central Australia. Given the lack of science to guide exploration it is surprising that the opal Industry as managed to stay alive albeit almost unchanged for decades. Yet, precious opal is a rare commodity based on which an entire new industry could be built. To understand why so much precious opal can be found in central Australia, one has to understand its peculiar geology.

The Lower Cretaceous history of the GAB is that of a high-latitude flexural foreland basin associated to a Cordillera Orogen built along the Pacific margin of Gondwana. The basin, flooded by the Eromanga Sea, acted as a sink for volcaniclastic sediments eroded from the Cordillera's volcanic arc. The Eromanga Sea was shallow, cold, poorly connected to the open ocean, muddy and stagnant, which explain the absence of significant carbonates. Iron-rich and organic matter-rich sediments contributed to the development of an anoxic sub-seafloor in which anaerobic, pyrite-producing bacteria thrived. Rich in pyrite, ferrous iron, feldspar, volcanic fragments and volcanic ashes, Lower

Cretaceous lithologies have an exceptionally large acidification potential and pH neutralisation capacity. This makes Lower Cretaceous lithologies particularly reactive to oxidative weathering. From 97 to 60 Ma, Australia remained at high latitude and a protracted period of uplift, erosion, denudation and cooling unfolded. It is possibly during this drying out period that the bulk of precious opal was formed, *via* a regional episode of acidic oxidative weathering unique on Earth. When uplift stopped at *ca* 60 Ma, the opalised redox front was preserved by the widespread deposition of a veneer of Cenozoic sediments. This oxidation led to the production of a large volume of sulfuric acid *via* oxidation of biogenic pyrite, and acid produced *via* ferrolysis of reduced iron. The quasi-absence of carbonate was key to the development of very acidic conditions across the GAB. The acidic oxidative weathering of volcaniclastic rocks led to the formation of large volumes of amorphous silica, through the weathering of feldspars and volcanic ashes into clay, and clay into amorphous silica and goethite. Once formed, amorphous silica evolved in closed environments in which pH fluctuated from alkaline conditions – at time of higher water table – favourable for the production of colloid with negatively charged silica spheres of homogeneous size, to acidic – at time of lower water table – favourable to the precipitation and self-assembly of neutrally charged silica spheres to form precious opal.

01REB-03. SOIL CARBONATE: PUTTING THE FIZZ BACK INTO GOLD EXPLORATION

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Soil carbonate was once considered a diluent and hindrance to mineral exploration. After all, how can a wind blown mineral like calcite, whose immediate origins are found at sea, be a target for mineral exploration? Calcite and dolomite were not part of the mineral explorers' tool box until it was shown that they could be used for Au exploration. The original discovery was made at the Bounty Gold Deposit in 1987. Nowadays, experienced exploration geologists have an acid bottle in their arsenal to test for carbonate minerals and so determine the best soil horizon to sample.

It is more than two decades since the CSIRO report "*The distribution of gold and other elements in soils and vegetation at Panglo, WA" co*-authored with Keith Scott, in which we observed that Au was correlated with soil carbonate. The Panglo gold deposit (located just north of Kalgoorlie) was where Keith did a considerable amount of his research. It was the second Au-in-carbonate case history, following on from the Bounty Gold Deposit, and it was highly significant discovery for a number of reasons. Firstly, it suggested the Au–carbonate association was widespread and not restricted to Bounty some 250 km southwest. Secondly, while the Bounty case study was an example of Au in calcareous soil developed in Au-bearing saprolite, the case study at Panglo demonstrated that a strong Au–carbonate association could develop at the surface above mineralisation in transported cover up to 10 m thick; the Au deposit itself was many metres further down still. Thirdly, and perhaps most importantly, the idea was spawned that *Eucalyptus* trees might be sucking up Au from depth to the surface and forming anomalies in calcrete. But such a mechanism for anomaly formation, while giving credibility to a given exploration method and constraining where and when it can be used, is difficult to prove. Biogeochemistry is a technique that has been used in mineral exploration in North America and Russia for many years. Therefore, while it has been known for many years that plants can be analysed for their Au content, it was never entirely certain that the Au analysed in *Eucalyptus* foliage, at the time, was truly in the plant or as dust on the outside. One of the problems was being able to detect small particles – finding a Au needle in an analyst's haystack. Recently small Au nuggets have been found within *Eucalyptus* trees using the CSIRO-Brookhaven Maia detector at the Australian Synchrotron. We now have compelling evidence for Au in a *Eucalyptus* tree being brought up from great depths to the surface, first suggested by results from Panglo. Gold in *Eucalyptus* is now inextricably linked to the evapotranspiration model of Au anomaly formation in carbonate and part of the Au biogeochemical cycle at the Earth's surface.

Calcrete sampling for Au exploration is experiencing resurgence. Recently, a new mineral province has emerged in Western Australia (Albany Fraser), using calcrete as one of its principal tool's for exploration. The latest case histories from the Albany Fraser Province will be presented and will demonstrate how calcrete continues to be important for Au discovery in Australia today.

01REC – MINERALOGICAL EXPLORATION – A SESSION IN HONOUR AND MEMORY OF KEITH SCOTT

01REC-01. LANDSCAPE EVOLUTION AND REGOLITH ARCHITECTURE AS CRITICAL ELEMENTS FOR SURFACE GEOCHEMICAL INTERPRETATION IN GREENFIELDS MINERAL EXPLORATION: THE ALBANY-FRASER OROGEN CASE

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Regolith-dominated terrains extend throughout Australia. Many of these areas display deeply weathered profiles, which have been developing for at least the last 65 Ma, reaching depths of up to 150 m. Most of western Australia represents an ancient, stable and weathered landscape.

The Albany Fraser Orogen (AFO) is a regolith-dominated terrain adjacent to the Yilgarn Craton, where transported packages with exotic mineralogical and geochemical features contribute to increase the total thickness of the regolith profile. These overburden units act as filters, or even impermeable barriers, to vertical geochemical dispersion. Thus these units can significantly reduce, if not prevent, any ore pathfinder element or anomalous geochemical proxy from reaching the surface, and being detectable in exploration.

A new conceptual model of the Albany-Fraser Orogen/Yilgarn Craton margin as a region dominated geomorphologically by landforms produced by successive marine transgression- regression cycles, with numerous islands and estuarine zones, is proposed. This model involves extensive erosion, sedimentation and saprolite development taking place in different styles of regolith development.

"On inland" and "on island" weathering profiles may vary in maturity and saprolite development, with or without transported cover derived from exotic terrigenous marine sediment and/or limestone, and also with a provenance contribution from the Yilgarn Craton. Such areas are more reliable for understanding geochemical anomaly - basement relationships; whereas the "sea-flooded" areas require a more detailed investigation due to the combined effects of mechanical dispersion, sediment mixing, rejuvenated weathering profiles and short-term vertical element dispersion processes.

Based on the results of this study, four different regolith settings with diverse regolith architecture have been defined: the Albany, Kalgoorlie-Norseman, Esperance and Neale settings. Mineral exploration protocols, sampling media and interpretation of geochemical data should be carefully linked with the characteristics of the regolith-landform setting. Deep weathering profiles (Kalgoorlie-Norseman and Neale settings) present obstacles to metal mobility from the basement due to transported cover and the depleted section of the upper saprolite; whereas "rejuvenated" regolith profiles (Albany and Esperance settings) lack depleted upper saprolite and/or thin transported cover, requiring shallower drilling to sample the basement, and present thin regolith horizons for vertical metal dispersion.

Thus mapping the palaeo-coastlines, coupled with identification of palaeo-islands and estuarine zones, and the extent of marine limestone/sediment influence inland, will have an extensive impact on the planning and execution of exploration campaigns, and consequently their results, in the Albany-Fraser region.

01RED – GOLD MINERAL DEPOSITS OF SIBERIA AND FAR EAST RUSSIA

01RED-01. MESOZOIC GOLD DEPOSITS OF EASTERN RUSSIA

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Gold deposits in East Russia formed throughout geological history from the Precambrian to the Cenozoic. Except for the Omolon microcontinent (Kubaka, Birkachan), the gold metallogeny of this vast region from the Precambrian to the Paleozoic was of little economic significance. By contrast, intense and widespread tectono-thermal activity in East Russia in the late Mesozoic–Cenozoic is associated with gold metallogeny forming several world-class deposits. This is largely because of the. Clock-wise rotation of the Siberian craton throughout Mesozoic time with nearly synchronous tectonic activity in the fold belts in the NE and SE of the craton's margins, coupled with the Mesozoic subduction processes along the western Pacific rim and the Arctic Ocean, resulted in collision and accretionary processes: the Yana-Kolyma (YaKOB), North of the Arctic (NOB), the Mongol-Okhotsk (MOOB), Okhotsk-Koryak (OKOB) and Sikhote-Alin (SAOB) orogenic belts. Mesozoic events include: (1) Early Jurassic tensile structures in the deformed passive margin of the Siberian continent (YaKOB), and the orogeny on the western flank of MOOB resulted in orogenic type gold mineralisation; (2) Middle–Late Jurassic Uyandina-Yasachnenskaya arc in the YaKOB and strike-slip movements, rifting and tectono-thermal events in the Trans-Baikal sector of MOOB formed Au–Bi orogenic deposits; (3) Late Jurassic–Early Cretaceous early orogenic gold mineralisation in YaKOB and strike-slip faults-related rifting with formation of gold–silver epithermal mineralisation in the Trans-Baikal sector of MOOB and simultaneous accretion events in the eastern flank of the Uda sector of MOOB; (4) Early Cretaceous gold–antimony mineralisation in the YaKOB, easterly-directed movements, strike-slip faulting and rifting in the eastern sector of MOOB, accretion events in NOB trenches and orogenic magmatism in SAOB with gold mineralisation; (5) Late Cretaceous gold mineralisation associated with late diagonally-directed movements in the trenches, with active magmatism in the Okhotsk-Chukotka and East Sikhote-Alin volcano-plutonic zones. These processes were all accompanied by a variety of gold-dominant mineral systems, including: (1) orogenic gold-disseminated sulfide (Natalka, Maiskoye, Albazino, Pogromnoye; (2) orogenic gold–quartz (Karalveyem, Badran, Tokur); (3) orogenic gold–antimony (Sarylakh, Kyuchyus) in terrigenous sediments; (4) gold–bismuth mineralisation associated with orogenic granitoids (Kirovskoye, Berezitovoe, Chistoye, Malysh); (5) subduction-related epithermal gold–silver (Kupol, Julietta, Mnogovershinnoye); (6) rift-related epithermal gold–silver (Kuranah, Baley, Pokrovsky); and (7) subduction-related granitoids gold–bismuth (Teutedzhak, Halali). These types of gold mineral systems occur in different zones and geodynamic regimes, with the mineralogical and geochemical characteristics, reflecting the geodynamic conditions of their formation.

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01RED-02. THE DARASUN, KARIISKY AND BALEY LARGE GOLD ORE DEPOSITS OF TRANS-BAIKAL REGION

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The Trans-Baikal region incorporates 42 deposits and over 1000 ore occurrences of gold, the largest ones being the Darasun and Kariisky gold-porphyry deposits, and Baley epithermal deposit of gold–silver formation. All deposits are located within the central part of the Mongol-Okhotsk suture, through which the Siberian continent collided with the Mongolian–Chinese continent between Early and Middle Jurassic. At the collision stage the mesothermal deposits of gold-porphyry mineralisation formed in Middle–Late Jurassic time, whereas the epithermal deposits formed at the rifting stage in Early Cretaceous time. All systems are genetically linked with high-K latite magmatism. The age of Darasun deposit, beginning from ore-producing magmatism is estimated as 175–100 Ma, Kariisky (176–120 Ma) and Baley (150–114 Ma).

Gold mineralisation of Darasun deposit represents veins, mineralised zones of fracture, veinlets and combined morphological types. Stages of mineralisation include: (1) tourmaline, (2) pyrites (association of quartz, pyrite, arsenopyrite and chalcopyrite), (3) polymetallic (association of galena, sphalerite, pyrite, quartz and carbonates), (4) sulfosalt (pyrrhotite, chalcopyrite, gold, tellurides, sulfosalts of Cu, Bi, Pb, As, Sb and Ag), (5) sulfoantimony (carbonate, quartz, antimonite, sulfoantimonites of lead, realgar, auripigment, cinnabar, kleiofane and metacinnabarite). The mineral associations of all stages contain gold, but the main types of gold-bearing ores are chalcopyrite–pyrrhotite, chalcopyrite with grey copper ore (Au contents from 20 to 300 ppm), pyrite–arsenopyrite (Au 25–35 ppm) and sphalerite–galena. The important geochemical feature of ores is high silver concentrations.

Gold mineralisation of the Kariisky deposit represents three ore types: (1) vein (Au contents from traces to 100 ppm), (2) dispersed and veinlet-impregnated (stockwork) with Au contents from traces to 19.8 ppm, and (3) gold-bearing dykes (Au 5–168.8 ppm). Three stages of gold ore mineralisation were identified: (1) early gold–sulfide–quartz (gold, quartz, pyrite, tourmaline, minerals Bi and Te; (2) molybdenite–sericite–quartz (molybdenite, scheelite, pyrite, chalcopyrite and bismuthite), and (3) complex sulfide–quartz (gold–quartz–tourmaline, gold–quartz–actinolite–magnetite, gold–quartz–arsenopyrite, quartz–carbonate polymetallic types of ores).

The gold-bearing bodies of the Baley deposit contain veins and veinlet zones. The most productive stages are typified by adularia–carbonate–quartz with gold and gold–pyrrhotite–myargirite–carbonate–quartz.

The parameters of hydrothermal process were defined as: at the Darasun deposit the temperature was 430–120°C, pressure 1560–60 bar, salt concentrations 44.8–0.7 wt% equiv. NaCl; at the Kariisky deposit T = 575–85°C, P = 2820–

85 bar, salt concentrations 56–0.5 wt% equiv. NaCl; and at the Baley deposit T = 353–131°C, P = 150–30 bar, salt concentrations 7.6–0.5 wt% equiv. NaCl.

Using the results of T–P geochemical and isotope studies, with the ore-producing magmatism and geodynamic development of Trans-Baikal region, it is proposed that these deposits formed at different levels within a unified porphyry–epithermal fluid-magmatic system: at the top the Baley, in the middle the Darasun and at the bottom the Kariisky deposit.

01REE – ORGANIC GEOCHEMISTRY OF MINERAL SYSTEMS

01REE-01. ORGANIC MATTER METAL INTERACTION IN THE FORMATION OF ORE DEPOSITS

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The role of organic matter (OM) in the formation of ore deposits has been reviewed recently (Greenwood *et al.* 2013), highlighting the importance of new analytical methods in our understanding of metallogenic systems. As these modern instrumental approaches become more widely available, their application towards organic–inorganic interactions will guide in exploration of economic resources. This presentations serves as introduction to the session “Organic geochemistry of mineral systems” by i) reviewing existing models of (bio)geochemical interaction between organic matter and metals, ii) outlining the methodological approaches for these studies, and iii) discussing a suite of organic matter associated metallogenic systems.

Current views of organic matter–metal associations will be presented for the Permian Kupferschiefer/Marl Slate of NW Europe (Cu, Pb, Zn, Au, Ag), the HYC-deposit of the McArthur Basin, Australia (Pb, Zn), MVT-deposits including Pine Point, Canada (Pb, Zn), Carlin type gold deposits of Nevada, and Manto-type deposits in Chile (Cu, Au). The focus of this presentation will lie on the organic solvent extractable fraction of organic matter (bitumen), which can be structurally and isotopically characterised by gas chromatography coupled to mass spectrometry to reveal information on primary organic matter sources, diagenetic/thermal alteration of organic matter, biodegradation and redox reactions involving organic matter and dissolved metal species.

Reference

Greenwood P F, Brocks J J, Grice K, Schwark L, Jaraula C, Dick J M & Evans K A 2013. Organic geochemistry and mineralogy. I. Characterisation of organic matter associated with metal deposits. *Ore Geology Reviews* **50**, 1–27.

01REE-02. COMBINED SULFUR, CARBON AND REDOX BUDGET CONSTRAINTS ON GENETIC MODELS FOR CLASTIC-DOMINATED BASE-METAL SULFIDE DEPOSITS: EXAMPLES FROM THE HERE'S YOUR CHANCE PB–ZN DEPOSIT, AUSTRALIA

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A common explanation for the occurrence of base metal sulfide deposits in organic-rich sediments is that reduction of sulfate by oxidation of organic matter provides the necessary sulfide. The amounts of organic matter reacted and sulfide minerals formed can be estimated by mass balance calculations, but previous studies do not integrate simultaneously the redox balance and the quantities of carbon and sulfur in different chemical reservoirs in the sediments, rocks and fluids. In this study, an integrated mass balance expression is formulated that takes into account the sulfide mineral content, organic carbon content and H/C ratios of mineralised and non-mineralised rocks representative of the ore and protolith, respectively. Model calculations based on carbon, sulfur and redox budget balances suggest that the extent of oxidation of the organic matter present at the Here's Your Chance (HYC) Pb–Zn deposit is insufficient for reduction of the required quantity of sulfate. The results show that externally derived reducing capacity and/or reduced sulfur is required to account for the observed metal resource. Possible sources include methane-rich fluids from deeper parts of the sedimentary sequence or formation of sulfide and organic matter as products of bacterial sulfate reduction (BSR) during sedimentation/early diagenesis.

A major implication of this study is that genetic models for HYC, which have a single major source of redox budget for sulfate reduction, may not be consistent with all available evidence. Sulfidic deep ocean water would be one possibility for an external reservoir, which could provide reduced carbon and/or sulfur that would provide electrons to reduce sulfate in the ore-forming fluid and facilitate synsedimentary mineralisation. However, an exclusively synsedimentary model is problematic because some mineral veins clearly crosscut bedding so at least some mineralisation was diagenetic rather than synsedimentary. Likewise, the organic matter associated with the deposit is oxidised in comparison with surrounding unmineralised host rock, suggesting that some reducing capacity is derived from alteration of organic matter during diagenesis. Some combination of these processes may have operated, so for example, early synsedimentary mineralisation driven by interaction of dense metalliferous brines with deep sulfidic seawater could have been overprinted by later interactions of the same ore fluids with fluids rich in sulfur and carbon within the rock porosity.

A comprehensive approach to elemental mass balance, as described here, has the potential to allow recognition of global patterns in the relative contributions of internally and externally derived redox budget in the formation of Pb–Zn deposits. Insufficiency of local sources (i.e. spatially coincident with the deposit itself) to account for sulfur and/or redox budgets is consistent with earlier reported mass-balance estimates for some Mississippi-Valley Type deposits. The mass balance relationships presented here, which may be augmented in the future by the addition of sulfur isotope constraints and limitations imposed by the physics of fluid mixing and flow in porous media, provide new insight into the conditions of ore genesis at HYC and elsewhere.

01REE-03. ORGANIC MATTER IN OROGENIC GOLD (AU) SYSTEMS

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The association of organic matter (OM) with metallogenic systems has been a well-observed and studied phenomenon in low to moderate (<350°C) temperature regimes. Organic compounds can react with metal and sulfur species through a variety of processes such as redox reactions and may influence physico-chemical properties important to mineralisation (e.g. pH, mineral solubility, precipitation temperatures, rock porosity and permeability). Thermally mature systems (>350°C) however, common to most orogenic Au deposits in Australia, challenge traditional analytical methods used for OM analyses. In this study, various state-of-the-art techniques (e.g., catalytic Hydropyrolysis (HyPy), Gas Chromatography (GC) isotope ratio Mass Spectrometry (irMS), Scanning Electron Microscopy (SEM) Energy-dispersive X-ray spectroscopy (EDS)) were employed to characterise OM. The study area is the high temperature (≥550 °C) orogenic Au deposit at the Cosmo-Howley mine, NT. Data obtained from this novel combination of methods show promising links between OM and mineralisation, despite the low organic carbon content and high thermal maturity of the samples.

Indigenous HyPy-released hydrocarbons (HCs) display a homologous series of C_{15} to C_{36} *n*-alkanes (*n*-C_{18}, $\delta^{13}C$ = –28.4 ‰) with a distinctive even carbon number preference. Other HyPy products detected included polycyclic aromatic HCs (PAHs), mainly pyrene ($\delta^{13}C$ = –16.3 ‰) and a series of partially saturated analogues of pyrene, which could be artefacts of the HyPy method or related to mineralisation of the sample. The $\delta^{13}C$ values of the *n*-alkanes suggest biological (i.e. algal/bacterial) origins and the relatively heavier isotopes for the PAHs are likely related to the thermal maturity of the samples. These HCs are structurally distinct from the carbonaceous “graphite” like material in the matrix and infill to mineral grains detected in SEM-EDS. HyPy products of samples 50 m from the ore zone *vs* those proximal to the ore zone show an increase in the PAHs over *n*-alkanes, however an increase in *n*-alkanes over PAHs at the ore zone is still being investigated.

Further analyses of samples with spatial variation in proximity to the ore using other techniques (e.g. Raman spectroscopy and X-ray microspectroscopy) will be conducted to further establish any trends or hydrothermal footprint in the petrogenic markers and its possible relationship to Au mineralisation.

39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

01SBA - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

01SBA-01. THE EMPLOYMENT CYCLE FOR GEOSCIENTISTS: WHERE TO NEXT?

Geoff Sharrock

President, The Australasian Institute of Mining and Metallurgy

Coal is the principal mineral commodity produced in the Sydney-Gunnedah Basin, and during the last forty years coal exports from have increased dramatically due to the demand from Asia. Initially, this demand was from Japan and Korea and most recently from China. NSW coal production increased from 48 million tonnes in 1980 to 250 million tonnes in 2013. Export capacity at the port of Newcastle has increased from 16 million tonnes in 1976 to 180 million tonnes in 2013.

In 2004 demand outstripped supply, coal prices rose rapidly, and the need to identify and prove coal resources and reserves to sustain additional capacity resulted in a significant increase in exploration activity and consequently jobs for geoscientists.

By mid-2012 coal export prices began falling. Operators moved quickly to reduce costs, with exploration activity reducing dramatically. Contractors were the first to bear the brunt of staff reductions followed by employees. Capital flows to junior explorers dried up. Projects were put "on hold" or abandoned.

The coal industry has been particularly hard-hit compared to other sectors of the mining industry that also boomed in the last decade. Mines in the Sydney-Gunnedah Basin more so than those in the Bowen Basin, due to the predominance of thermal coal in this basin. Many mines would now be operating below cash cost, with export tonnages remaining high due in part to "take or pay" contracts with rail and port operators.

Members of the Australasian Institute of Mining and Metallurgy, just as those in kindred professional societies, have suffered from the downturn in commodity prices, and, in some cases, the complete cessation of exploration activities.

Last year, the AusIMM conducted a survey of members and found that unemployment and underemployment had risen from 2% to 10%. AIG surveys show that 19% of members are unemployed and 15% are underemployed. Recent data indicates that this unemployment is continuing to rise.

Professionals who have been in the industry a long time have seen downturns in the coal sector before, including reductions in revenue. Coal prices reduced year on year in the late 1980's, and factors such as concentration of ownership resulted in mining professionals losing their employment.

The current downturn has factors that were not in evidence during previous contractions. We now have the mining industry under community pressure as never before. We have other industries running campaigns against coal mining and investment fund managers expressing a view that they do not want to invest in coal.

The Institute has responded to the situation in a number of ways. We have put in place a Member Assistance Program (MAP) to help our members through this difficult time. We have raised the matter of the large number of unemployed geologists with the Federal Minister for Resources. We have made suggestions for alleviating unemployment. Geologists are trained scientists who are able to carry out other duties but this resource does not seem to be recognised by many companies.

Even with these issues, Australian coal will be needed in Asia for many years to come and professionals will be needed to operate the industry, albeit perhaps not at the levels of employment seen during the boom. Employment prospects and potential career paths for geoscientists, both within and outside the industry, are discussed.

01SBB - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

01SBB-01. A CHARACTER SET IN STONE: LANDSCAPE, GEOLOGY AND THE 1788 SETTLEMENT AT SYDNEY COVE

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The newly occupied landscape of Sydney Cove is only briefly described in accounts of the first British settlement. Authors focus on the human dramas that unfolded between settlers and Aboriginals, and within the European community (e.g. Tench 1789, 1793). References to landscape tend to be observations about potential exploitation: anchorages, reliable water sources, soil quality and building materials (e.g. Collins 1798, 1802). Yet despite the constraints of the new settlement, trained personnel recorded many landscape features on maps and charts, including shorelines: rocky bluffs, cliffs and wave-cut platforms; sandstone ledges; alluvial flats, beaches, mud flats and mangroves; water courses and wetlands; vegetation density; and topography. Paintings, drawings and written accounts provide additional detailed information. Modern development has obscured most of these details and it is now difficult to envision the landscape that settlers first saw in 1788. It was the aim of this study to draw together the various observations and to combine them in a single landscape map compilation. No such reconstruction exists in the literature. A particular goal was to determine how geology influenced the earliest phase of Sydney's development.

The mapping-based approach produced detailed landscape feature maps of Sydney Cove, which then formed the basis for a 3D digital terrain model (Figure 1), calibrated by modern topographic data. Geological mapping (e.g. Herbert 1983; Osch 2007) was referenced against the landscape maps and model to determine the influences of geology on the 1788 landscape. The results reveal that geology had a profound influence on early Sydney, from the choice of the site (reliable freshwater, secure anchorage), to the pattern of its subsequent development.

The landscape of inlets and headlands was produced by the interactions of northeast-trending structures and the shallowly dipping strata. The ridgelines bordering both shores of Sydney Cove (Bennelong Point to the east and Dawes Point to the west) slope more gently on their eastern sides, and are steeper and more prominently bluffed on their western sides. This asymmetry is probably the result of the undulating dip of strata in the underlying Hawkesbury Sandstone (particularly the "facies bedding" and "clay seams" described by Pells 2002). The more gently sloping but rocky eastern shore of Dawes Point became the site of most of the original 1788 encampment and eventually evolved into 'The Rocks' area (Sydney's oldest residential suburb).

The reliable freshwater source was a rivulet rising from springs at the contact between the Wianamatta Group and the underlying Hawkesbury Sandstone at the head of the 'Tank Stream Valley' (e.g. Collins 1798; Karskens 2009). It flowed northward through the valley, roughly following the trace of the 'GPO Fault Zone' (Osch, Pells & Braybrooke 2004) and divided the military (western) from the administrative (eastern) sector of the first camp (Phillip 1789). Government institutions still dominate the east of the CBD. Temporary shelters were first placed in the more level areas with fewer trees on the western shore of the cove. Sandstone outcrops still formed obstacles that the settlers had to work around, particularly on the western side. Huts were located on flat spots while a network of interconnecting paths developed around the sandstone ledges and approximately parallel to the strike of bedding (e.g. Karskens 1999). Tracks eventually became roads such as George Street. Early farming was mostly unsuccessful because the sandstone soils were poor and alluvial flats provided the first arable land (Farm Cove). Shale-derived soils were of better quality but occurred mainly to the west, where a second settlement was founded at Parramatta (e.g. Karskens 2009). This shifted the centre of agriculture westward.

The study shows that the geology and landscape of Sydney Cove set development patterns in place that have persisted throughout its subsequent history.

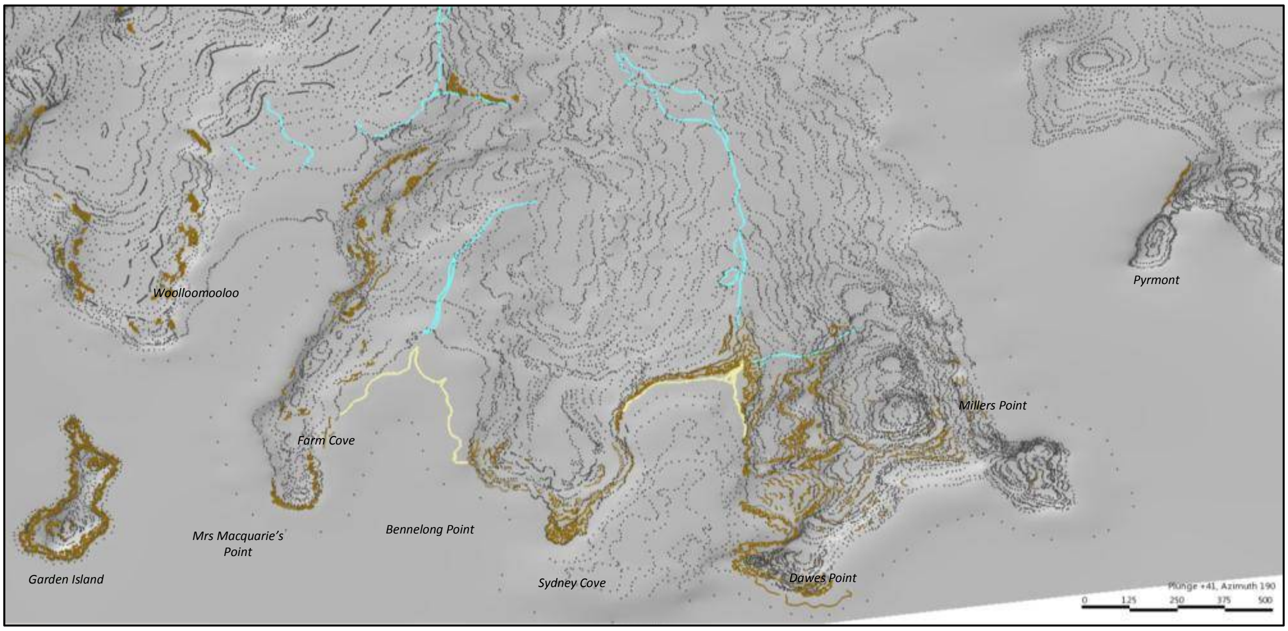

Figure 1. Two views of Sydney Cove (Circular Quay) comparing the reconstruction of the 1788 landscape (upper) to the modern Sydney CBD (Google image, lower). Both views are taken from approximately the same viewpoint and are looking to the south, along the course of the 'Tank Stream' Valley. The upper image presents a screen shot of part of the 3D digital terrain model developed from the historic map compilation. Features shown include rocky bluffs and platforms (brown lines), historic drainage lines (light blue lines), wetlands (light blue polygons), and beaches (yellow lines). Spot height information is shown as dark grey point data overlain on the shaded DTM triangulation (pale grey), to illustrate the subtle variations in the original landscape of the city. The floor of Sydney Cove is modelled as a part of the DTM surface and is based on 1788 depth soundings. The DTM model was created using Leapfrog and Vulcan.

01SBB-02. COAL EXPLORATION – 1830 STYLE

Russell Rigby

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The Australian Agricultural Company (AACo) shipped the first coal from its new mine (A Pit) in Newcastle in December 1831. Although most of the miners were convicts, the coal was raised in the shaft by a steam winding engine, sent to the wharf along the first railway in Australia, and loaded into the first steam ship in Australia, using a high level chute. For the previous 30 years mining had been been a Government operation, with the convict work force winding the coal using a hand windlass or horse whin, wheel barrows and bullock wagon to transport the coal to the wharf, and loading using baskets. Convicts were sent to work in the mines in Newcastle as punishment for secondary offences, as much as to provide productive labour.

The changes in technology were not restricted to the mining operations. Before the AACo decided to establish the new mine, John Henderson, the Company's Colliery Superintendent, had inspected the Government mines in 1827, and commented that the condition of the mines was so bad, and the layout so unplanned, that the Company should not consider taking over the operation, but start a completely new mine in the Yard Seam. Because there was still a dispute about the terms of the Company's coal grant Henderson did not get this opportunity until 1830. In the meantime he drilled several bores on Macarthur's and Blaxland's properties on the Parramatta River looking for coal, without any success.

By the time Henderson returned from England in 1830 the issues with the coal grant had been resolved, and he conducted a boring program in the area immediately west of Newcastle town to plan for the new pit. The prospecting included field mapping and drilling seven holes to test the extent, thickness and quality of the seams. This was the first systematic mineral exploration program in Australia.

Copies of Henderson's original reports still survive in the Butlin Archives of the Australian National University. The large scale plan and sections of the 1830 exploration and mine planning were drawn up by Henderson and the AACo surveyor John Armstrong, and are now held by the Turnbull Library in New Zealand. The level of detail of the plan and sections enables detailed logs of the bores to be made, and the accuracy of the surveying means that the collar position and level of the bores can be located to within one or two metres. The geological data contained in the reports and plans is directly relevant to present and future planning of the inner city area of Newcastle.

Henderson recognised that there was potential for more coal seams beneath the Yard Seam. The bores intersected another thin seam, but it was not until 1848 that the 3 m thick Borehole Seam was discovered (in a borehole!) about 3.5 km west of the A Pit. Subsequently this seam was intersected 55 m under the AACo's early operations, beyond the reach of Henderson's equipment (approx 37 m). The seam was 6 m thick – what might have been?

01SBB-03. LITHOLOGY AND ENGINEERING BEHAVIOUR, NEWCASTLE COAL MEASURES

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This presentation relates the lithology and fabric of the four main groups of the Newcastle Coal Measures' rock types to their geotechnical properties and engineering behaviour. The four groups are: massive sandstone and conglomerate; claystones and tuffs; mudstone, shale and siltstone; and the coal itself. Although their geological relevance is primarily concerned with underground coal mining, these rocks are exposed at the surface across most of Newcastle and its suburbs, and are thus significant in terms of urban environmental geology.

The key mining issues include longwall support design and panel layouts, caving and subsidence mechanisms, soft floors and stiff roofs, water inflows and pillar design.

The urban geotechnical issues include landslides and rock falls, shallow abandoned mine workings, reactive and erodible soils, waste disposal and potential sources for geomaterials.

KEYWORDS: geotechnical, coal, conglomerate, tuff, subsidence, Newcastle

01SBB-04. A GOLD-BEARING ALKALINE INTRUSION IN THE SOUTHERN SYDNEY BASIN

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Of the many Jurassic intrusions emplaced in the southern Sydney Basin only that at Mount Broughton 4.5 km south of Moss Vale is known to contain mineralisation, albeit of minor significance. The *Conlons Find* gold–silver occurrence was described by J.E. Carne in 1908 as "disseminated coarse visible gold in chalcedonic quartz stringers cutting weathered 'diorite' host rock which also assayed a trace of gold". A composite chip sample of discontinuous veinlets assayed 1.65 gm/t gold and 3.3 gm/t silver. The probable site with old shallow workings has been relocated, but chalcedony veinlets so far collected in the vicinity lack visible gold.

On different generations of geological maps Mount Broughton is shown variously as Tertiary basalt–basanite or as a syenite–microsyenite body resembling major intrusions to the north at Mount Gibraltar (The Gib) and Mount Misery in the Southern Highlands of New South Wales. Recent construction of a large stone wall at Mount Broughton from local outcrops has provided uncommonly fresh intrusive material dominated by plagioclase phenocrysts, differing mineralogically and texturally from the other Southern Highlands intrusions. Remnants of Tertiary basanite occur near the crest of the 90 m high Mount Broughton. Alkali basalts overlying laterite and Wianamatta Group shales surround its base. The intrusion is extensively weathered.

The fresh intrusive rock is compact and pale grey in colour. Relatively close-packed plagioclase phenocrysts are stout, euhedral to subhedral laths of uniform size in particular specimens but varying from 5 mm to 1 cm in length at different outcrops. In places they are distinctly aligned. They range from An30 to An20 in composition with thin albite rims and occasional overgrowths of alkali feldspar, and are set in a finer mesostasis dominated by thin laths (0.2–1 mm long) of alkali feldspar (Or60–Or90), themselves enclosed by a groundmass of carbonate aggregates (calcite, ankerite and siderite) with deep green Fe-chlorite, or by interstitial chalcedony or rare coarser quartz. Plagioclase phenocrysts contain common apatite needles and are accompanied by minor magnetite. Primary mafic silicates are lacking, but scarce pseudomorphs after former amphibole and pyroxene now consist of Fe-chlorite plus carbonate and chalcedony and a clay mineral (kaolin?), respectively. Infrequent miarolitic cavities are typically lined by tiny quartz crystals followed by complex layers of carbonate, Fe-chlorite, and hematite, with a final chalcedony infill. Amoeboid patches of chalcedony within the mesostasis are less clearly filling cavities. Sulfides are absent.

Darker grey patches of segregated, alkali feldspar-dominated mesostasis within the more abundant plagioclase-rich assemblage range from microscopic bodies to pods several centimetres across. Plagioclase-free mesostasis-like material also forms 'dykes' up to 10 cm wide with irregular, non-matching borders. These all appear the product of a dilation and 'filter pressing' stage during magma crystallisation. Since late stage alteration products including carbonates are pervasive throughout the intrusion without indications of an external fluid source, igneous crystallisation evidently merged into a hydrothermal-deuteric phase involving replacement of mafic minerals and deposition of the same assemblages in miarolitic cavities. Fracture-filling chalcedony veinlets (presumably equivalent to those in which Carne identified visible gold) constitute the final stage.

The bulk CO_2 content (7.4 wt%) of a typical Mount Broughton intrusive sample implies about 15 wt% carbonate, which would account for a substantial proportion of the bulk Fe and Ca. Adjusting for carbonate, bulk SiO_2 content (53.0 wt%) becomes about 64 wt% for the feldspar-dominated silicate component. The bulk K_2O/Na_2O weight ratio of 0.79, allowing for average mineral compositions, corresponds to a ratio of about 40% alkali feldspar and 60% plagioclase, classifying the rock as (leuco)monzonite. It contains elevated P and rare earth elements, with pronounced LREE enrichment but negligible Eu anomaly in chondrite-normalised plots. Relative to 'calc-alkaline' monzonites Mount Broughton is also highly enriched in K, Rb, Zr, Ba, and Th, and is depleted in Sc and V, reflecting its alkaline affinity and leucocratic character. 'Ore element' abundances are unexceptional (Cu 33, Zn 165, Ag 0.6, Au 0.01, all ppm), as is bulk sulfur (100 ppm).

The mesostasis-like pods and dykes at Mount Broughton probably resemble K-rich Mount Gibraltar microsyenite in geochemistry, whereas the bulk monzonite represents a prior stage of fractionation from which early-formed plagioclase has not been removed. No evidence exists in the region of a likely mafic parental magma – nearby Jurassic dolerite at Mount Gingenbullen is tholeiitic rather than alkaline. Nor, indeed is it clear what structural or tectonic features govern the presence of the Jurassic alkaline intrusive provenance at the southern end of the Sydney Basin.

The gold described by Carne at Mount Broughton has evidently concentrated in the final silica precipitate within dilational fractures following extensive magma fractionation and hydrothermal deposition, especially of carbonates.

Since sulfides are absent, gold may have been leached and transported as a hydroxide complex in an ultimately oxidised CO_2-rich aqueous fluid, and deposited as a consequence of cooling. Alkaline microsyenites at Mount Gibraltar and Mount Misery near Bowral and Berrima, respectively, also contain carbonates, chlorite and chalcedonic quartz as alteration products of scarce mafic minerals (including riebeckite and aegirine), as a groundmass to dominant potassium feldspar, and as fillings of miarolitic cavities. Their secondary minerals are distinctly less abundant than at Mount Broughton, but the same post-magmatic hydrothermal processes were operative. The restricted occurrence of mineralisation at Mount Broughton and the lack of discoveries at other alkaline intrusions, however, discount the Southern Highlands of New South Wales as a significant gold province deserving comprehensive exploration.

01SBC - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

01SBC-01. CA-IDTIMS DATING IN AUSTRALIA: THE PAST, PRESENT AND FUTURE

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Chemical Abrasion-Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-IDTIMS) is a refinement of the classical IDTIMS technique. In this relatively new technique, target zircons are selected using a traditional combination of optical evidence for good crystallinity and cathodoluminescence evidence indicating a single crystal growth phase. The zircons are then annealed at high temperatures, followed by 'chemical abrasion' using hot concentrated, pressurised hydrofluoric acid. The annealing repairs minor crystal lattice defects, while the chemical abrasion removes domains that are damaged beyond repair. Surviving crystalline zircon tends to have an undisturbed isotopic composition, the measurement of which is limited only by the rapidly improving sensitivity of modern mass spectrometers.

CA-IDTIMS analyses provide unprecedented analytical precision, with 95% confidence intervals routinely less than 100 000 years. This yields unique opportunities to resolve very closely spaced magmatic events, even if they occurred hundreds of millions of years ago. This allows us to improve the accuracy of correlation of eruptive events, infer rates of sedimentation, and constrain the timing of geological and biological events. The precision is such that the variations in residence times of zircon crystals in the magma chamber need to be taken into consideration when interpreting results.

Studies in Australia which eventually led to the current CA-IDTIMS work started in 2005 with a pilot study on upper Permian tuffs in the Bowen Basin by Ian Metcalfe (UNE), Bob Nicoll (ANU) and Roland Mundil (Berkeley Geochronology Center, USA). This was followed by an ARC Discovery grant to Metcalfe, Nicoll and Yuri Amelin (RSES, ANU), which initially focused on middle Permian to Lower Triassic tuffs in the Bowen, Gunnedah and Sydney basins. With Geoscience Australia's involvement, and the support of industry, state geological surveys and universities, the scope of the program has widened to include the Permian in the Canning, Tasmania, Southern Carnarvon and Perth basins and the Mesozoic in the Eromanga and Surat basins, as well as the Paleozoic in the Lachlan Fold Belt.

The overarching aim of these studies is threefold: To refine lithostratigraphic correlations across the continent; to improve the calibration of Australian biostratigraphic zonation to the International Geological Time Scale; and to improve the calibration of the timescale itself. To date the program and its collaborators have collected more than 450 samples, of which about 140 samples have been analysed, with approximately 100 of these providing usable dates (Figure 1) ranging in age from the early Cambrian to the Late Cretaceous (Figure 2). Dating of the samples is being undertaken by laboratories at Boise State University (Boise, Idaho) and the Research School of Earth Sciences, Australian National University (Canberra, ACT).

The bulk of the samples have been collected from Permian rocks in the Sydney, Gunnedah and Bowen basins. Additionally, Late Triassic samples have been acquired from sediments in Queensland and Tasmania and initial test samples of early Cambrian (SA), Ordovician (WA), Silurian (ACT), Carboniferous (NSW) and Cretaceous (Queensland) rocks have also been obtained. Jurassic samples from Queensland and New South Wales have been discussed with interested collaborators but not yet collected. Sampling selection is constrained by the presence of felsic igneous rocks, such as rhyolites or rhyolitic ash deposits, as zircons are normally restricted to rocks of this composition. Zircon abundance can be highly variable, with samples as small as 200 g producing results, but where possible samples of 3 to 5 kg are collected. Natural and man-made exposures, mine sections and drill core have been collected; drill cuttings are avoided due to potential downhole contamination. Supporting biostratigraphic analyses are required to allow calibration of biostratigraphic schemes to the International Geological Time Scale. In the case of palynomorphs, fresh rock samples are required as weathered rock usually contains no usable palynomorphs. On the other hand, macro-fossils tend to survive weathering better and natural outcrops are preferred because of the ability to take larger samples.

The middle and late Permian study in the Sydney, Gunnedah, Bowen and Canning basins (Figure 3) has demonstrated very significant changes to the ages generally ascribed to the palynostratigraphic zones (further described in Laurie *et al.* this volume). This can also lead to significant changes in the correlations of lithostratigraphic units and the understanding of depositional rates, as well as the precise timing of geological and biological events. In addition it has also been possible to correlate some of the ashfall tuffs to individual eruptive events. Results so far demonstrate that the Awaba Tuff across the Newcastle Coalfield is approximately 253.2 Ma in age, and that it is the same unit as the Nalleen Tuff in the Hunter Coalfield, confirming a correlation based on geochemical analysis; that the Nobbys Tuff across the Newcastle and Hunter coalfields is approximately 255.0 Ma in age; and that enough datable zircons can be obtained from thin tuffs in core material to provide useful dates.

This project is possible thanks to collaborators from universities, state geological surveys and private companies: Yuri Amelin (Australian National University); Ian Metcalfe (University of New England); Joan Esterle and Syeeda Areeba (University of Queensland); Scott Bryant (Queensland University of Technology); Peter McCabe (University of Adelaide); Jim Crowley (Boise State University); Kevin Ruming, Erin Holmes and Phil Blevin (New South Wales Trade and Investment, Resources and Energy); Arthur Mory (Geological Survey of Western Australia, John McKellar (Geological Survey Queensland); Liz Jagodzinski (South Australia Department for Manufacturing, Innovation, Trade, Resources and Energy); Mel Wilkinson and Geoff Wood (SANTOS); Malcolm Ives (Centennial Coal); Chris Knight (Muswellbrook Coal), and Malcolm Bocking (baCBM).

The future of CA-IDTIMS studies is only limited by the availability of new material to date. We are only scratching the surface of the potential of middle and upper Permian sediments. The early Permian record is virtually untouched. The Jurassic has only been discussed and only preliminary analyses have been conducted in the Triassic sequences. Felsic volcanics are common in the Lachlan Fold Belt of Eastern Australia and Liz Jagodzinski’s early sampling is opening the window on the Cambrian in South Australia. This work will greatly improve local and regional correlation, within and between basins. Additionally, the well-constrained revisions to biozones in dated basins have implications for the revision of stratigraphic time sequences in basins without tuff beds.

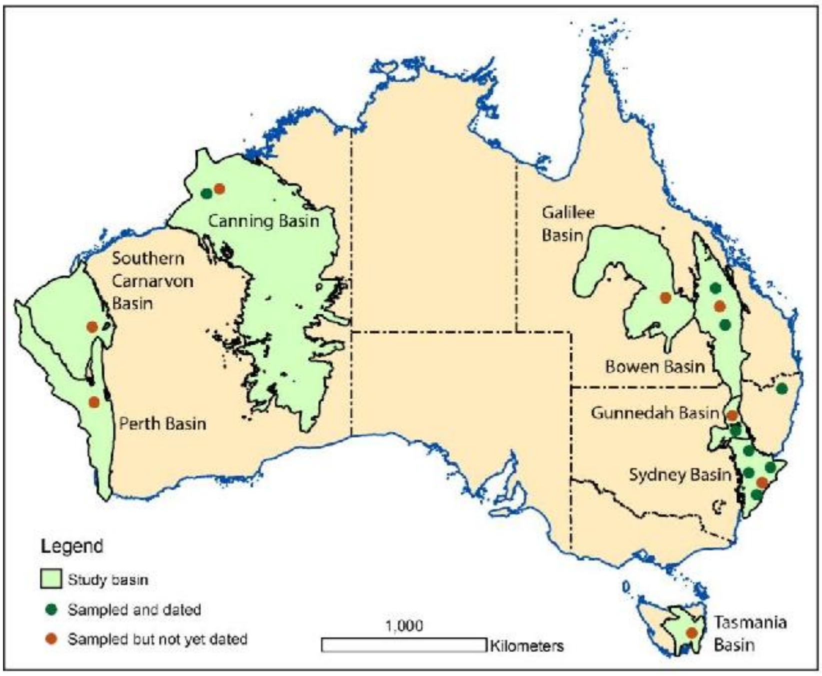

Figure 1: Map showing study sample locations

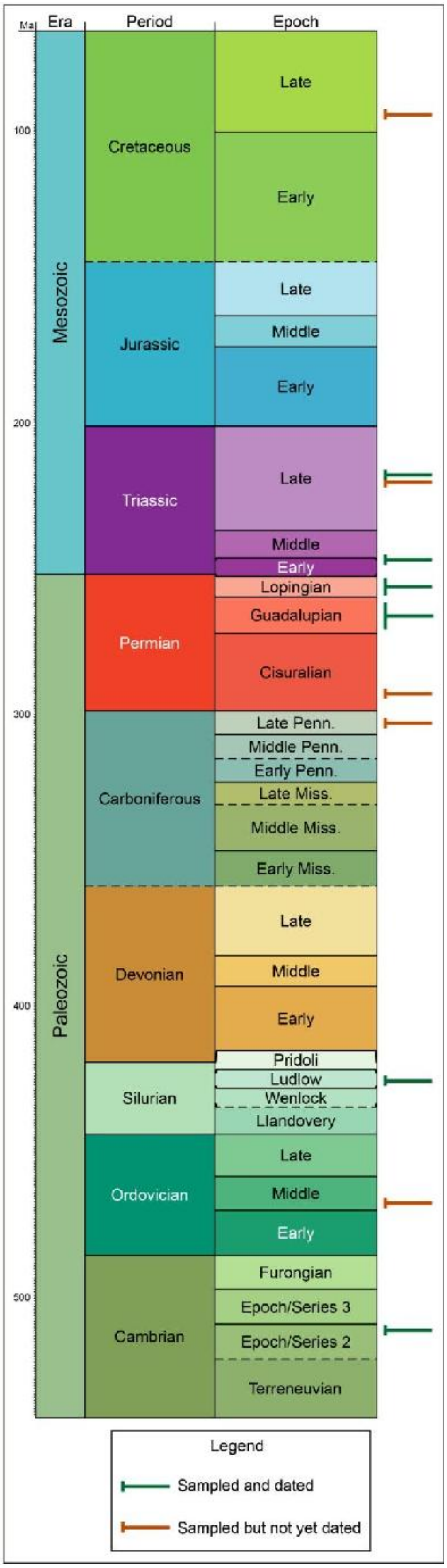

Figure 2: Chronostratigraphic levels of sampled study material

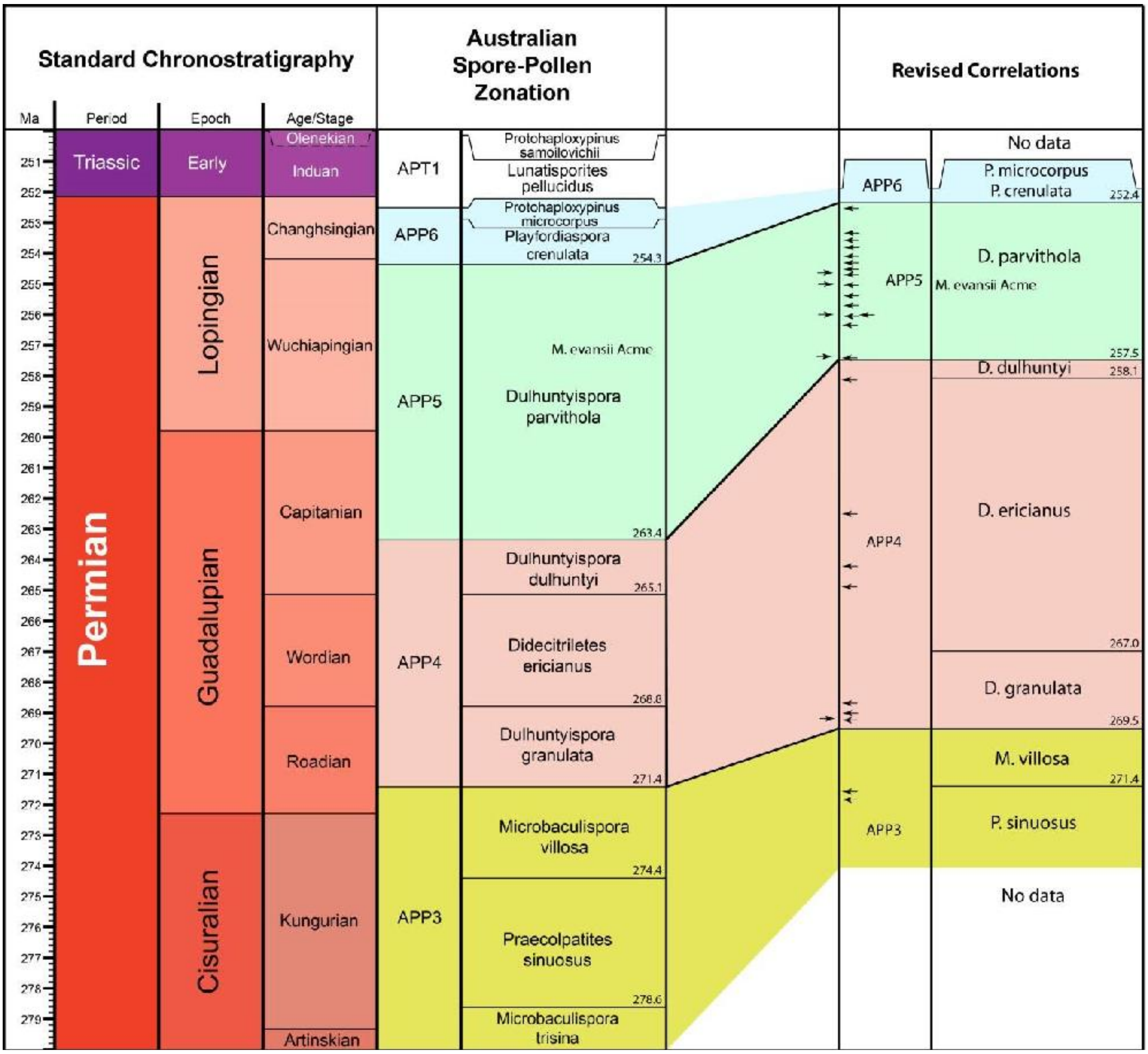

Figure 3. Revisions to calibration of part of the Permian palynostratigraphic scheme of Price (1997). To the left is the Permian timescale of Henderson *et al.* (2012); in the middle is the calibration of the palynostratigraphy by Mantle *et al.* (2010) and to the right is the new calibration based on CA-IDTIMS dates obtained in this study. Arrows along the left margin of this column represent individual CA-IDTIMS dates.

01SBC-02. REVISING STRATIGRAPHIC CORRELATIONS IN THE SYDNEY-GUNNEDAH BASIN – DOES RECENT TUFF BED GEOCHRONOLOGICAL DATA JUSTIFY IT?

Kevin Ruming[1], Erin Holmes[1], Malcolm Bocking[2], Jim Crowley[3], Robert Nicoll[4], Roger Cameron[5], Malcolm Ives[6], Mel Wilkinson[7] & Sonja Zink[8]

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Approximately 373 samples have been collected for high precision U–Pb Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-IDTIMS) age analysis throughout the Sydney-Gunnedah Basin. The age dates are obtained by analysing Pb–U ratios of zircon grains extracted from tuff samples collected from core and outcrop.

Samples have been collected from throughout the basins and in all the major stratigraphic units from the Triassic to early Permian. Over 80 samples have been analysed and approximately another 100 are in progress.

Stratigraphic correlations and terminology have been long established and debated for the basin. The latest revisions were ratified by the Coalfield Geology Council in 1999. These new data provide the opportunity to review existing correlations within and between the different coalfields.

Relationships between the stratigraphic units throughout the basin and across the coalfields are best illustrated using a 3D 'fence' diagram. A revised fence diagram, incorporating these new age determinations, shows that the majority of the previous correlations are supported by the new data. The new data also show that some previous correlations are incorrect. The new dates also allow us to apply a rigorous time framework to depositional rates in coal beds and associated clastic sediments.

Analysis of these new data will require making clear distinctions between chronostratigraphic and lithostratigraphic units. The tuff layers can be considered geologically instantaneous, whereas the basin-wide regressive–transgressive episodes may have spanned timeframes of sufficient magnitude that some of the tuff layers (chronostratigraphic units) cut across some of the lithostratigraphic units. These new data warrant additional discussion and possible revision of the currently accepted stratigraphic correlations and terminology of the Sydney-Gunnedah Basin.

01SBC-03. PERMIAN STRATIGRAPHY AND TUFF BED GEOCHRONOLOGY OF THE SOUTHERN SYDNEY BASIN

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Approximately 15 high precision U–Pb CA-IDTIMS dates have been obtained from various stratigraphic units of the Southern Coalfield of the Sydney Basin. Dated samples have been collected from various geographic locations, covering a range of stratigraphic units from Triassic Narrabeen Group units through to Permian Shoalhaven Group units. The dates range between approximately 247 and 264 Ma.

The stratigraphy and terminology of the Southern Coalfield has long been established, with the last revision ratified by the Coalfield Geology Council in 1999. The new CA-IDTIMS dates allow a chronologic revision of the Southern Coalfield stratigraphy, and also provide preliminary definitions of depositional rates for the sedimentary sequences. The dates furthermore have allowed preliminary correlations between particular Southern Coalfield units and similar aged units of the Western, Hunter and Newcastle Coalfields.

Some of the most significant findings are reflected in the dates of the upper units of the Sydney Subgroup and the lower Narrabeen Group. It is proposed that the top of the Permian is in fact stratigraphically higher than previously thought, and as a result it is proposed that the stratigraphy of the Sydney Subgroup and the Narrabeen Group need to be redefined.

01SBC-04. FROM WHENCE COMETH THE RAIN: SOURCE OF THE MIDDLE TO LATE PERMIAN ASHFALL TUFFS OF THE SYDNEY AND GUNNEDAH BASINS

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The late Permian Wandsworth Volcanic Group (WVG) in the southern New England Orogen (SNEO) is dominated by a monotonous series of amalgamated rhyodacitic to felsic eruptive facies, with minor interbedded flows, intrusions and sedimentary rocks. The area enclosing known exposures of the WVG covers more than 30 000 km^2, with a minimum thickness of 2 km. The top of the succession, as well as the vast majority of the pile representing non-welded material, has not been preserved. Field relationships indicate a broadly contemporaneous (though not necessarily genetic) relationship with late Permian granite magmatism, while Triassic plutons (typically in the range 246–243 Ma) intrude the WVG. SHRIMP U–Pb zircon dating indicates ages around 256.4 ± 1.6 Ma for basal units of the WVG, and 254.1 ± 2.2 Ma for the youngest preserved member of the WVG (Dundee Rhyodacite), defining a short period of substantial intermediate to acid eruptive volcanism. The compositionally primitive Drake Volcanics to the northeast is older (264.4 ± 2.5 Ma) and at Halls Peak is older still (early Permian). Granites of the I-type Moonbi Supersuite and Uralla Supersuite are dominantly 256–251 Ma, and thus overlap in timing (and space) with the WVG event. Interestingly, many mineralised leucogranites (e.g. Parlour Mountain, Oban River, Gilgai), which were formerly regarded as Triassic, are now established as synchronous with the Moonbi and Uralla supersuites and the WVG. The age range of eruption of the WVG permitted by the SHRIMP results (*ca* 6 Ma) has been further constrained by CA-ID-TIMS U–Pb zircon analysis, which yielded oldest and youngest ages of 255.54 ± 0.16 Ma and 253.26 ± 0.15 Ma respectively, indicating a maximum eruptive time range of *ca* 2 Ma for the preserved pile. Our new results coincide with those determined from CA-ID-TIMS dating of tuffs in the Sydney Basin and Gunnedah Basin. WVG exposures at Attunga are exactly (within *ca* 0.1 Ma) coincident with the age of tuffs within the Trinkey

Formation located in the Gunnedah Basin to the west. The Dundee Rhyodacite is similarly closely matched to the thick Awaba Tuff in the Sydney Basin. Notably, much of the late Permian volcanic and plutonic magmatism in the SNEO is restricted to a remarkably small time range, which coincides exactly with the range of ash fall events in the Sydney and Gunnedah basins, and possibly further afield. This suggests that the SNEO, and the WVG in particular, was the dominant source of volcanic material erupted into these adjacent basins. Furthermore, the adjacent basins may provide a more complete record of Permo-Triassic magmatism in the SNEO than currently preserved within the orogen itself.

01SBD - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

01SBD-01. PHYSICAL VOLCANOLOGY AND XENOLITH PETROLOGY OF A DYKE INTRUDING THE GERRINGONG VOLCANICS, SOUTHERN SYDNEY BASIN: ASSOCIATED WITH PROXIMAL MID PERMIAN VOLCANOES

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The mid Permian Gerringong Volcanics (GV), southern Sydney Basin, outcrop along the coast between the Shoalhaven River in the south and Wollongong in the north. A series of mafic extrusions are interbedded with fossiliferous volcaniclastic shallow marine sediments. Numerous mafic dykes along the coast, which intrude both the sedimentary and igneous rocks, have been reported as being generally Jurassic to Cenozoic in age.

This research describes the physical volcanology of a mafic dyke and petrology of xenoliths found within, intruding the Westley Park Sandstone Member of the GV, on a coastal rock platform near Gerringong. Cylindrical flow structures, or lobes, within the dyke have incorporated the surrounding wet, soft, unconsolidated sediments during intrusion. Other syndepositional features include contact metamorphism and pepperite formation at the contact.

The dyke contains abundant (in places, up to 50 volume% of the dyke) metasedimentary xenoliths, largely confined to the centre of a few lobes at one end, and rare K-feldspar megacrysts. Quartz-rich metasedimentary xenoliths (rarely >95% quartz) predominate (GB1), followed by quartzo-feldspathic metasedimentary xenoliths (GB2). These xenoliths have a pronounced equigranular-texture, are largely massive and vary from fine to medium grained. Rare fine-grained metasedimentary xenoliths have pronounced relict fine laminations.

Quantitative X-ray diffraction analysis revealed that GB1 contains quartz (35%), albite (40%) and K-feldspar (25%) while GB2 contains quartz (27%), albite (30%), K-feldspar (33%), chlorite (8%) and diopside (2%). This is also shown by the major element chemistry through semi-quantitative XRF with GB2 containing more iron, potassium, and calcium compared to GB1. Some of the xenoliths also contain rare disseminated pyrite. In terms of trace element chemistry, both metasedimentary types are similar in Rb (104, 118), Sr (529, 521), and Ba (971, 1174) but differ in Zr (110, 374), Nb (4, 21), Cr (bdl, 19) and Ni (bdl, 46). These differences most likely reflect differing abundances of detrital grains of zircon, spinels and ferromagnesium phases.

The host basaltic dyke largely comprises chamosite, Ca-plagioclase, K-feldspar and clinopyroxene. This would reflect an initial primary mineralogy of olivine, anorthite, sanidine, and clinopyroxene, akin to the primary shoshonitic assemblage ascribed to the upper Permian volcanics of the southern Sydney Basin.

There is a complete lack of any reaction rims between the quartz-rich metasedimentary xenoliths and host shoshonitic basalt, suggesting derivation of the xenoliths from shallow depths. At this stage, the metasedimentary xenoliths may represent contact metamorphosed pebbly sandstones and siltstones of the immediately underlying units, possibly the quartz rich Snapper Point or Nowra sandstones.

At least four intrusions along the coast have been located that exhibit classic features associated with syndepositional sediment intrusion. This includes magma/sediment mixing at the contact, with pepperite, metamorphosed sediments at the contact, pillows, or small flow tubes and sediment liquefaction and slumping. Numerous others have also caused sediment slumping adjacent to the intrusions.

Evidence suggests that the sources for these intrusions were Permian volcanoes situated off the present-day coastline, associated with subduction and stress related foreland loading from the Currarong Orogen to the east, the southeasterly extension of the New England Orogen.

01SBD-02. RECALIBRATING THE PERMIAN PALYNOSTRATIGRAPHIC SCHEME VIA U–PB ZIRCON CA-IDTIMS DATING OF TUFFS IN EASTERN AUSTRALIAN BASINS

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Accurately recording a sequence of geological events requires precise determination of their relative ages, but understanding their duration or temporal separation of these events, requires accurate determination of their numerical ages. Accurately determining the numerical age of every lithological unit is still only a dream, but it is much closer than it was when the reality of radioisotopic dating dawned on the broader geological community just over a century ago with the publication of the overview by Holmes (1913). Here we report on the application of one of the more recently developed techniques: Chemical Abrasion-Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-IDTIMS). This technique (Mattinson 2005) utilises the U–Pb system in zircon, and features sample preparation procedures that dissolve and leach zircon domains affected by isotopic leakage (‘chemical abrasion’). Zircon that survives this process tends to preserve U–Pb systems unaffected by post-crystallisation disturbance, which results in a high degree of isotopic uniformity in rocks characterised by a simple magmatic crystallisation history. The technique is capable of delivering considerably more precise dates than has hitherto been possible, with 95% confidence intervals of the order of 0.1–0.2% routinely achieved on cogenetic populations of magmatic zircons.

Basins studied

Because this project derived from an investigation into the Permian–Triassic boundary in tuff-rich sequences in China, the natural progression was to examine a similar interval on this continent, where tuffs were known to exist in large numbers. The three eastern Australian coal basins (Sydney, Gunnedah and Bowen) were therefore the main focus. However, an opportunity to analyse samples from the Canning Basin was also taken. The Newcastle Coal Measures in the Lopingian of the Sydney Basin can be used as an example to illustrate the large number of tuff beds in these eastern Australian basin successions. It is a Lopingian group-level unit about 450 m thick, is divided into eight formations and contains over 140 recorded tuff beds. Of these, three are relatively thick (up to 30 m) and are formations in their own right. These are the Awaba, Warners Bay and Nobbys tuffs.

Previous dating

Previous U–Pb zircon dating of the Permian sequences of Australia has utilised the Sensitive High Resolution Ion Micro Probe (SHRIMP) (Roberts *et al.* 1995, 1996, 2006) or Thermal Ionisation Mass Spectrometry (TIMS) (Gulson *et al.* 1990). The early SHRIMP dates indicated some problems with the precision of the technique when ages obtained were compared with established dates from other methods. For example, a SHRIMP date of 250.1 ± 2.8 Ma (all dates quoted are $^{206}Pb/^{238}U$, with uncertainties at the 95% confidence level) for a tuff in the Black Alley Shale in the Bowen Basin indicated an earliest Triassic age for this unit and overlying *Glossopteris*-bearing coal measures (Roberts *et al.* 1996). This date is anomalous, however, considering that Early Triassic palynofloras first appear stratigraphically hundreds of metres above (Foster *et al.* 1997, 1998) and *Glossopteris* is known elsewhere only from rocks of Permian age. CA-IDTIMS data on single zircons from a volcanic ash layer underlying the Rewan Formation (Bowen Basin) yield a robust age of 252.2 ± 0.4 Ma (Mundil *et al.* 2006), indicating that the base of the Rewan Formation correlates with the P–T boundary interval in southern China (Shen *et al.* 2012; Burgess *et al.* 2014). This correlation is consistent with palynostratigraphic data (Foster 1982). However, it should be noted that this CA-IDTIMS date and its 95% confidence interval lie entirely within the 95% confidence interval of the SHRIMP date; a factor which should be taken into account when interpreting these dates.

The SHRIMP dates presented by Roberts *et al.* (1995, 1996) were calibrated using the reference zircon SL13, which is now known to be affected by heterogeneity in $^{206}Pb/^{238}U$ (Compston 1999). This, in combination with possible problems related to minor but undiagnosed loss of radiogenic Pb from both reference and sample zircons, and even potential matrix effects on the measured Pb/U, raised fears that the accuracy of Phanerozoic SHRIMP dates might be limited to about ± 2% (Black & Jagodzinski 2003). Subsequent use of carefully characterised reference zircons that are homogeneous in $^{206}Pb/^{238}U$ (such as TEMORA: Black *et al.* 2003, 2004) has since demonstrated that Paleozoic SHRIMP $^{206}Pb/^{238}U$ dates with uncertainties of ± 1% at the 95% confidence interval are usually within experimental error of CA-IDTIMS dates from the same rock (e.g. Bodorkos *et al.* 2012). Age resolution of 1% is not sufficient to distinguish between the numerous ashfall tuffs in the eastern Australian Permo-Triassic; however, some of the zircon populations selected for CA-IDTIMS analysis were first mounted, imaged using cathodoluminescence, and then analysed by SHRIMP. The images and isotopic data assisted in identifying any SHRIMP-resolvable inherited components (Bodorkos *et al.* 2012), thereby refining targeting of the CA-IDTIMS analyses.

Correlation to the timescale

The Permian portion of the International Geological Time Scale (Henderson *et al.* 2012; see Figure 1) has marine fossil zonations as its prime correlative tools. These comprise conodont, fusulinid and benthic foraminiferal, and ammonoid zonations. Each of the nine stages of the Permian time scale has, or will have, its base defined by a Global Stratotype Section and Point (GSSP). All of these are located in the northern hemisphere (USA, China, Russia or Kazakhstan), and were at low latitudes at the time of deposition. Because all of these Permian stage subdivisions were defined in marine successions and the Australian Permian was in high latitudes and largely non-marine, Permian successions in this continent are difficult to correlate globally. The most effective technique for correlating the mostly non-marine Permian–Triassic successions in eastern Australia is the spore-pollen zonation erected by Price (1997), which has been time-calibrated by Mantle *et al.* (2010; see Figure 1). However, this palynostratigraphic zonation is fairly broad — only 13 zones span the entire Permian — and correlating this zonation to the global geological timescale has proven difficult at best. The reasons for this are twofold. Firstly, conodonts and fusulinids have never been found in the eastern Australian successions, and ammonoids are very rare. Conodont faunas recovered from the Tethyan margin of Western Australia are scarce and mostly endemic (Nicoll & Metcalfe 1998). Secondly, the high latitude flora of the Permian and Triassic was largely endemic to the circumpolar Gondwanan continents, so precise correlation to the northern hemisphere is almost impossible.

Leonova (1998) attempted a broad, stage-based correlation of the Sakmarian to Roadian interval between Australia and Russia, based on the presence of ammonoid genera recorded from the Permian of Australia, most of which are from Western Australia. In their overview of the 'anchor points' for the Permian in Australia, Foster & Archbold (2001) reviewed and summarised the evidence for international correlation. They noted that palynomorphs are "the most widely used groups for local correlation within and between…basins" (Foster & Archbold 2001, p. 179), but that the macrofauna which have traditionally provided ties to the international scale are scarce or absent. Even correlation of the macrofauna between western and eastern Australia is hampered by substantial provincialism, because the western Australian margin opened onto the relatively warm Meso-Tethys Ocean and the eastern margin onto the high latitude cold water southern Panthalassic Ocean. Thus, correlation of palynozones defined in eastern Australia to the global timescale is based on extremely limited evidence. Below, we summarise new U–Pb zircon CA-IDTIMS data obtained from tuff layers with palynological control, and evaluate our results in terms of the numerical age constraints placed on the Australian palynostratigraphic zonation of the second half of the Permian. The preliminary CA-IDTIMS dates quoted below have been rounded, pending assessment of the systematic uncertainties prior to formal publication, but the 95% confidence intervals are generally less than 0.4 Ma.

Praecolpatites sinuosus **Zone (APP3.2):** One tuff sample from Muswellbrook Coal Sandy Creek DDH 32 from within the *P. sinuosus* Zone produced a CA-IDTIMS date of 271.6 Ma. Roberts *et al.* (1996) obtained a SHRIMP date of 268.9 ± 2.0 from a nearby outcrop sample (Z1842), and re-analysis of selected SHRIMPed grains using CA-IDTIMS yielded a date of at 271.9 Ma. Chris Knight (Muswellbrook Coal, pers. comm. 27 March 2014) maintains there is only one tuff bed in this part of the section, and thus that sample Z1842 and our sample from Sandy Creek DDH 32 are from the same stratigraphic level. The age of the base of the *P. sinuosus* Zone remains to be determined.

Microbaculispora villosa **Zone (APP3.3):** The *M. villosa* Zone has not been dated directly by CA-IDTIMS, but the zones above and below have been. Roberts *et al.* (1996, p. 412) obtained a SHRIMP date of 272.2 ± 3.2 Ma from a sample (Z2015) obtained probably from the *M. villosa* Zone. There is no associated palynology, so this zonal assessment is based on a probable correlation. The sample is awaiting analysis by CA-IDTIMS. In our interpretation, the base of the *M. villosa* Zone is probably slightly younger than the dates obtained from the *P. sinuosus* Zone and is placed at about 271.4 Ma (see Figure 1), which is considerably younger than the previous calibration of 274.4 Ma (Mantle *et al.* 2010).

Dulhuntyispora granulata **Zone (APP4.1):** No CA-IDTIMS dates have been obtained from the *D. granulata* Zone in eastern Australia, but four dates ranging from 268.8 Ma to 269.3 Ma have been obtained from tuffs in core from the Lightjack Formation in the Canning Basin of Western Australia. Palynological samples were assessed from the same core and all samples lie within the *D. granulata* Zone. We therefore tentatively place the base of the *D. granulata* Zone at about 269.5 Ma (see Figure 1), a little over two million years younger than the calibration of Mantle *et al.* (2010).

***Didecitriletes ericianus* Zone (APP4.2):** A sample obtained from a well near the boundary between the Sydney and Gunnedah basins (Brawboy 1) and lying within the *D. ericianus* Zone (Wood & Gallagher 2012) gave a CA-IDTIMS date of 262.5 Ma. Another three samples from other wells in the Gunnedah and northern Sydney basins, and all within the *D. ericianus* Zone, gave CA-IDTIMS dates of 258.1 Ma, 264.1 Ma and 264.9 Ma. These results indicate that the *D. ericianus* Zone is quite long, with its base tentatively placed at 267.0 Ma, about half way between the lowermost *D. ericianus* Zone date and the uppermost *D. granulata* Zone date (see Figure 1).

***Dulhuntyispora dulhuntyi* Zone (APP4.3):** No tuff beds from within this zone have been dated. However, based on the youngest dates associated with the underlying *D. ericianus* Zone (258.1 Ma) and the oldest dates of the overlying *D. parvithola* Zone (257.4 Ma), the *D. dulhuntyi* Zone comprises only a short interval, with its base probably at about 258.0 Ma (see Figure 1).

***Dulhuntyispora parvithola* Zone (APP5):** About 20 samples belonging to the *D. parvithola* Zone have been obtained from the Bowen, Gunnedah and Sydney basins and the CA-IDTIMS dates range from 257.4 Ma up to 252.5 Ma. Based on these dates, the base of the *D. parvithola* Zone is assigned an age of about 257.5 Ma (see Figure 1). This is almost six million years younger than the calibration of Mantle *et al.* (2010). Wood & Gallagher (2012) have also determined the position of the *Micrhystridium evansii* Acme in the well Brawboy 1. The nearest CA-IDTIMS date (255.7 Ma) obtained from this well is from about 19 m below *M. evansii*. The *M. evansii* Acme is therefore suggested to lie at about 255 Ma (see Figure 1). This confirms the conclusions independently drawn by Smith & Mantle (2013) on the age of the *M. evansii* Acme based on bracketing CA-IDTIMS and palynological data obtained from the well Meeleebee 5 in the Bowen Basin.

***Playfordiaspora crenulata* Zone (lower APP6):** No tuffs within this zone have been dated but dates obtained from the underlying *D. parvithola* Zone clearly indicate that the previous calibration of this zone (Mantle *et al.* 2010) requires revision. Mantle *et al.* (2010) specified a date of about 254.3 Ma for the base of this zone, whereas the youngest sample from the underlying *D. parvithola* Zone has a date of 252.5 Ma. As a consequence, a date of about 252.4 Ma seems more likely for the base of this zone (see Figure 1).

Conclusion

This study demonstrates the utility of high precision CA-IDTIMS in refining the correlation of endemic biostratigraphic schemes to the international timescale. In turn, this will have a major impact on the correlation within and between basins. This technique of calibrating palynozones to the timescale using CA-IDTIMS can be extended throughout the non-marine successions from the Devonian to the Cenozoic in the eastern half of Australia, as these successions are mostly correlated using palynostratigraphy and they are replete with tuff beds. To recalibrate this entire palynostratigraphic scheme will be the most significant advance in Phanerozoic palynostratigraphy since this scheme was erected.

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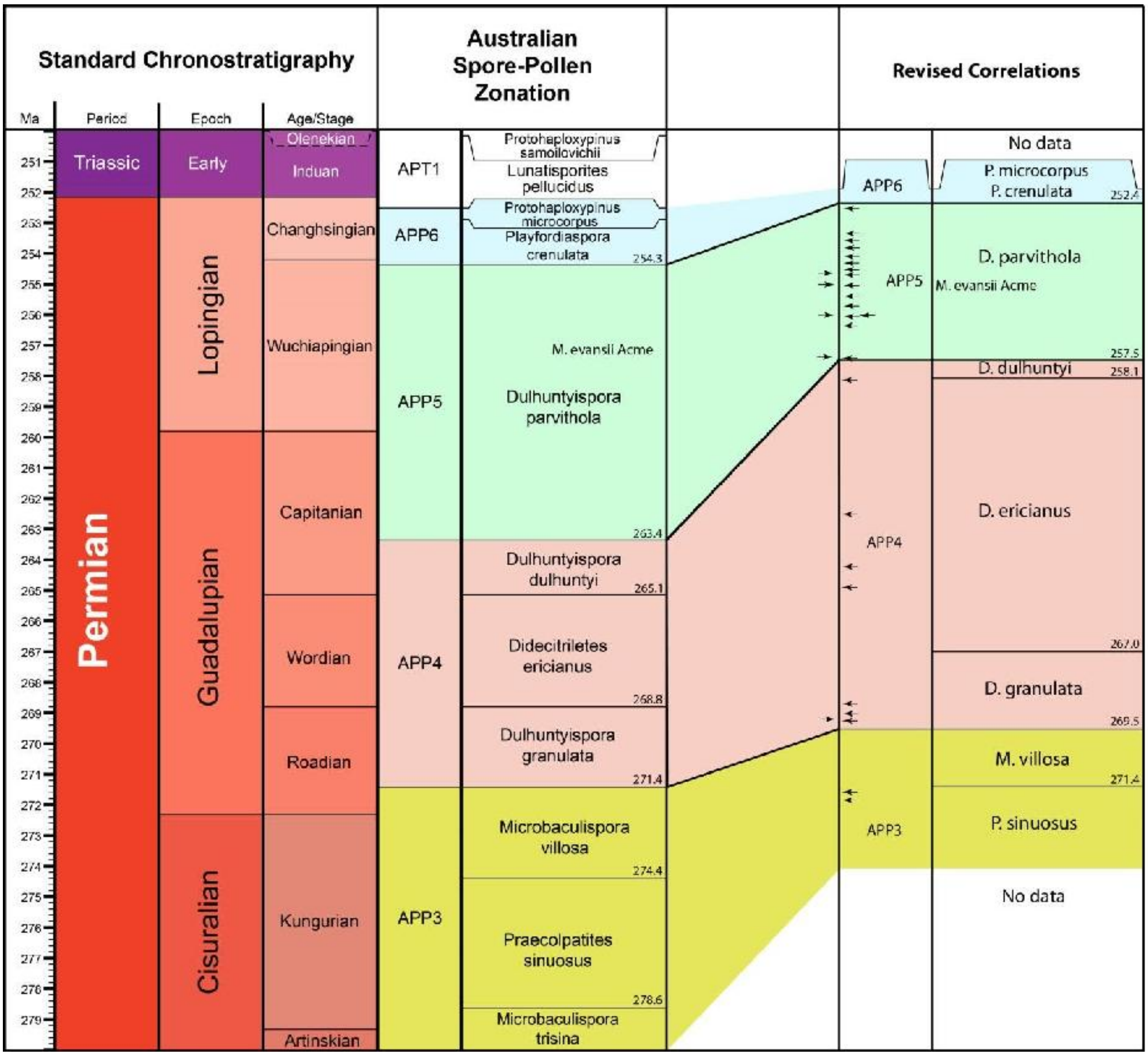

Figure 1. Figure showing revisions to calibration of part of the Permian palynostratigraphic scheme of Price (1997). To the left is the Permian timescale of Henderson *et al.* (2012); in the middle is the calibration of the palynostratigraphy by Mantle *et al.* (2010) and to the right is the new calibration based on CA IDTIMS dates obtained in this study. Arrows along the left margin of this column represent individual CA-IDTIMS dates.

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01SBD-03. AGE OF THE YARRABEE TUFF MEMBER AND ITS SIGNIFICANCE TOWARDS REGIONAL STRATIGRAPHY OF THE FORT COOPER COAL MEASURES

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The late Permian Fort Cooper and equivalent Coal Measures in the Bowen Basin host abundant tuffaceous horizons, one of which is the “Yarrabee Tuff Member”, which represents a series of discrete but closely spaced eruptive events. Commonly only one of these tuffs is tracked as a regional time marker, but this laterally consistent series of tuffaceous beds is used throughout the basin to distinguish the overlying Rangal (and equivalent) Coal Measures from the underlying Fort Cooper Coal Measures.

Seven hundred open file and proprietary wells were used to develop a regionally consistent stratigraphy across the basin. Samples of the Yarrabee tuffs from four different locations were collected and dated to verify the stratigraphic correlations and test the variability in age for this marker horizon. The U–Pb CA-IDTIMS zircon technique was used and has a precision of ± 0.05%. Early preliminary dates cover a range from 252.68 ± 0.20 to 253.22 ± 0.13 Ma. Variation has also been observed in previous dates of the Yarrabee Tuff, e.g. 252.49 ± 0.06 Ma from Yebna 1 well[1] and 252.54 ± 0.04 Ma from Meeleebee 5 well[2].

Variability in age dates of previous and current studies range from 0.05 my to 0.5 my, which is greater than the precision level of the dating technique. Such a wide variation within different parts of the Bowen Basin suggests either multiple eruptions of varying size from a volcanic arc or group of volcanoes, frequently erupting for a span of hundreds and thousands of years forming an incremental suite of sequential tuff layers constrained by a set of isochronous surfaces rather than a isochron. This may correlate with the massive volcanic eruptions interpreted to have occurred during the end of Permian time lasting for about less than 0.5 my. Volcaniclastics of such kind may assist in providing a high-resolution geochronology of the sequence and also help in unravelling the tectonic processes and impacts on sedimentation rates for peat and siliciclastics during Fort Cooper time.

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01SBD-04. DATING OF SHALLOW BRITTLE FAULTS WITHIN THE SYDNEY BASIN – NEW CONSTRAINTS ON THE BREAK UP OF GONDWANA

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Neotectonic brittle faults are associated with near-surface deformation. Displacement on the fault planes produces fault gouge composed of rock fragments and authigenic illite. Numerous studies have demonstrated that the absolute timing of brittle fault history can be determined using isotopic dating techniques of illite clay minerals. The understanding of the timing of clay-rich fault gouge formation is important for: (1) hydrocarbon exploration because faults may act as either a conduit or a seal for fluids and/or hydrocarbons; (2) civil engineering in the evaluation of earthquake hazards; and (3) ascertaining the suitability for waste storage. Several construction sites within the Sydney area and a cliff face and open cut in the Newcastle area, have enabled fresh exposures of brittle fault zones thus avoiding problems associated with surface weathering and contamination.

K–Ar data of authigenic illite from N–S, NNE and E–W trending faults within the Sydney Basin containing well-developed gouge will be presented. Results obtained from gouges are commonly difficult to interpret as clay minerals of detrital and/or authigenic origin, and detrital micas, can be present within the host rocks. Most of the investigated clay gouges comprise illite/smectite and kaolinite with distinct morphologies suggesting an *in-situ* authigenic origin. Four main groups of illite ages were obtained, namely: (1) ages from 272 to 281 Ma, that are older than most of the host sediments and interpreted to be of detrital origin; (2) ages from 235 to 245 Ma, which are believed to represent an early diagenetic overprint related to burial; (3) ages from 120 to 150 Ma that date brittle faulting, related to the break up of Gondwana and that occurred prior to the opening of the Tasman Sea; and (4) ages of *ca* 110 Ma in gouge and associated host rock in the Sydney area and West side open cut, south of Newcastle that record a distinct thermal overprinting event. The thermal event is interpreted to be related to the break-up of Gondwana and associated volcanism during the early Cretaceous.

The illite age data provide new insights into the timing of low temperature brittle deformation events in the Sydney Basin and thermal events associated with the rifting of eastern Gondwana in the Cretaceous. They provide absolute time constraints on the younger, neotectonic movements in eastern Australia.

TUESDAY 8 JULY

PLENARY

PLEN2-01. AUSTRALIA'S BIG CHALLENGES – THE ROLE OF GEOSCIENCE

Chris Pigram

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Australia as a very large but sparsely populated continent has always been shaped by its geology and geography. As the nation responds to the many challenges it faces at this time, Geoscience Australia (GA), as the Government's advisor on geoscience is focussing on three key challenges as the drivers for its work. These themes are future minerals and energy resources; community safety and environmental baselines, including groundwater; and change in the geographies of the nation.

In relation to the discovery of future minerals and energy supplies Australia has not been globally competitive for minerals exploration investment for over a decade and consequently requires new search areas if it is to regain its former standing as a desirable environment for mineral exploration activity. To help address this issue, GA in partnership with the State and Territory Geological Surveys, is undertaking a major program to reveal the basement geology and potential of Australia's covered terranes. In relation to energy resources GA has a three-pronged strategy designed to reveal the hydrocarbon potential of Australia's conventional and unconventional petroleum resources. This work involves basin analysis of offshore basins, regional studies and targeted petroleum systems studies for onshore basins.

GA has, or is undertaking, a wide range of groundwater studies to inform the management of issues like the water production from coal seam gas developments, new and future water supplies for remote communities, and strategic assessment of the potential groundwater resources in the arid regions of Australia.

Our Community Safety and Earth Monitoring program encompasses a wide range of natural hazards and their potential impact on communities both within Australia and in the region. This work includes the development of a flood portal to provide information to the community on flood risk and has led to the development of the first ever, national flood-water map of the entire continent. In addition, GA is involved through Australian aid activities in the provision of natural hazard risk and impact studies in Indonesia, the Philippines and PNG.

GA is building the next generation of positioning infrastructure, which will have a very wide range of industrial and business applications but will also enable major research into the deformation of the Australian continent from both natural and human activities. This work has the potential to inform the processes that drive intraplate earthquakes and provide a much-improved understanding of earthquake risk in Australia.

GA has, through a major program over the last few years, found a way to liberate our satellite imagery archive, rectify it and interrogate it so that it is now possible to examine change through time in the Australian landscape. This work provides, for example, a mechanism to establish robust environmental baselines, monitor water in the landscape and monitor vegetation health including crops and recovery of the landscape after major floods or fire.

The presentation will canvass these major challenges and present examples of the science that is being undertaken to help inform government decision makers.

ENVIRONMENT

02EVA – GROUNDWATER QUALITY IMPLICATIONS OF CHANGES IN PHYSICAL WATER MANAGEMENT

02EVA-01. GROUNDWATER QUALITY IN A COASTAL AQUIFER – A CASE STUDY OF WATER QUALITY CHANGES DUE TO THE DEGRADATION OF ORGANIC MATTER

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The impact of natural organic matter degradation on groundwater quality was studied in a freshwater coastal aquifer in Anna Bay, NSW. Fifteen piezometers, across 5 sites, were installed in a sand dune aquifer system along a 450 m transect located between a freshwater wetland and the Pacific Ocean.

Groundwater samples were collected from the piezometers and field parameters pH, EC, DO and alkalinity were analysed in the field. Subsequent lab analysis using ICPMS and ICP-OES was done to obtain the complete chemical composition. The results indicated that the dune aquifer system receives water from three sources: local rainwater infiltrating through the sand dunes, freshwater leakage from the wetland and deeper regional groundwater from underneath the wetland. Two dominant geochemical processes, the reduction of organic matter and the dissolution of calcium carbonate, were identified as controlling the water composition. The degradation of organic matter resulted in a general depletion of oxygen and the creation of anoxic conditions in the aquifer. The availability of redox sensitive species throughout the transect varied as the dominant organic matter degradation process changed. The medium to deep borehole samples indicated that sulfate reduction of organic matter was the prevalent process. The deepest borehole samples indicated that methanogenesis was the dominant redox process at depth, which resulted in increased carbon dioxide levels and the lowest pH.

The dissolved inorganic carbon (DIC) increased as more redox sensitive species were reduced along the flow paths. A peat layer located below the wetland provided a source of high organic matter concentrations and as a result all the oxygen, nitrate and sulfate was reduced and the highest DIC concentrations were found in the groundwater near the wetland.

The availability of calcium carbonate minerals, presumably as shell fragments, influenced the water quality, especially in the upper part of the aquifer system. In this part the pH and the Ca^{2+} concentration was higher than in the deeper parts of the aquifer. The high turnover of organic matter appears to enhance the dissolution of carbonate minerals. The understanding of these geochemical processes, and their distribution and controls within coastal aquifers, is critical to creating sound and sustainable groundwater management and abstraction systems where the water quality is not compromised and degraded. The inclusion of a conceptual geochemical understanding in the management of coastal aquifers is important as demands for alternative local water sources increase with the increase in coastal populations and frequency of droughts.

02EVA-02. MANAGED AQUIFER RECHARGE AND STRATEGIC AQUIFER STORAGE IN NORTHERN AUSTRALIA: CHALLENGES AND OPPORTUNITIES

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A critical factor in the development of the energy, minerals and agriculture sectors in northern Australia is the availability of adequate water resources and supporting infrastructure. There are limited areas where rainfall is sufficient to underpin agricultural development, however even in these areas there will be a need for additional water sources and storage due to the unreliability of seasonal rainfall. The development of energy and mineral resources also requires water for production and processing, while Indigenous community health could also be improved through provision of more suitable water supplies. Considering the high seasonal rainfall variability and evaporation rates across northern Australia, managed aquifer recharge (MAR) becomes an attractive adjunct or alternative to surface water storage.

At present, strategic development decisions across many parts of northern Australia are hindered by the lack of relevant hydrological datasets and knowledge at appropriate scales. Surface water availability limits opportunities for MAR and strategic aquifer storage across much of the arid and semi-arid northern inland. However, new mining and energy developments have potentially increased available source waters, while recent studies of wetter climate zones have also shown greater potential for enhanced recharge than previously realised. In deeper confined brackish–saline aquifers there is also the potential to develop fresher zones where low-salinity source waters are available.

Economic factors often limit MAR options to the near-surface environment (<200 m depths), where strategic aquifer storage opportunities lie largely in shallow paleovalley and alluvial fan systems, as well as in some karst aquifers. Sands deposited in marine environments have a more restricted distribution, but generally have more consistent hydraulic properties.

Some of the challenges for MAR projects in northern Australia include:

- A general paucity of relevant spatial and temporal baseline geoscience and hydrological data.
- Hydrogeological and hydrogeochemical processes in Australia's shallow aquifer systems are generally poorly understood at all scales relevant to MAR assessments.
- Many of Australia's inland depositional landscapes are characterised by fining-upwards sediment sequences, which limits surface infiltration options.
- Paleovalley systems are difficult investigative targets, with highly variable hydraulic properties.
- Confining aquitards can have a restricted or variable distribution, and are poorly understood.
- Post-depositional weathering of sedimentary sequences is significant but highly variable, modifying hydraulic and geochemical properties, with implications for aquifer clogging potential.
- Faults in sediments and geological basement may influence MAR viability and/or play a role in recharge, but their distribution and hydraulic properties are poorly understood.
- Groundwater quality in aquifers (e.g. salinities and trace metals), important for MAR recovery efficiencies, is poorly characterised.

Despite these challenges, recent studies have demonstrated that new rapid landscape mapping and basin analysis methods, combined with phased data acquisition, can be used to efficiently identify and assess potential MAR targets across large areas. Mapping derived from Landsat time-series statistics can be used to identify areas of potential water capture and storage (both surface and underground). Combined with DEM processing and basin analysis approaches enables the targeting of more intensive multi-disciplinary geoscience, hydrogeophysical and hydrogeological investigations.

02EVA-03. INVESTIGATING THE ORIGIN OF SALINITY AND AQUIFER INTERACTION IN A SEASONALLY PUMPED CONFINED AQUIFER SYSTEM IN SOUTHEAST AUSTRALIA (WESTERN PORT BASIN)

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This ongoing study aims to identify the different sources of fresh/saline water, pathways, mechanisms of groundwater salinisation, and factors controlling salt-water intrusion in the Western Port Basin aquifer (Victoria, Australia). The multi-layered aquifer is characterised by variable distributions of fresh and saline groundwater at the coastline, which are speculated to result due to geological heterogeneity, and the influence of past sea levels. The spatial salinity distribution observed indicates that the typical situation of a dense saltwater wedge underlying fresh groundwater does not apply. Further to natural drivers, an understanding of the potential short and long term effects of seasonal pumping for irrigation in the basin is desired, particularly whether it induces migration of water from other areas in the basin or causes leakage from low-permeability horizons.

The impact of seasonal pumping on the variation and distribution of salinity was examined at a nested bore site 500 m from the coast. Analyses of chloride concentration and $\delta^{18}O$ in groundwater indicate various degrees of mixing between seawater and fresh meteoric groundwater. Multi-depth sampling in the upper aquifer, identified high salinity water with ~19% seawater mixture above slightly less saline water – with ~17% seawater; while samples from the lower aquifer yielded significantly fresher groundwater (~4 to 7% seawater). This is likely to be due to the relatively good connection between the upper aquifer and the ocean, and low-permeability material separating the shallow and deeper aquifers. Seasonal salinity changes were observed as a response to pumping, with salinity in the upper aquifer decreased by ~15.5% at the onset of pumping, and salinisation gradually increased once pumping ceased by ~22%.

Recent ^{14}C dating of groundwater in the proximity of the pumping area revealed low radiocarbon activities (<25 pMC) and a lack of tritium, which rules out the possibility of modern recharge reaching the pumping area. A thick Holocene clay cap (ranging from 10 to 30 m) covering significant areas and extending beneath the bay, limits rainfall recharge to the basin margins where the aquifers outcrop. Beneath the shallow bay a paleoriver channel incised deep into the bay floor sediments expose the aquifer to potential vertical and horizontal input from modern seawater. However, the lack of long-term salinisation despite decades of pumping, and the relatively old groundwater ages, imply buffering against saline intrusion by stores of relict fresh water. Incorporation of these results into a conceptual model will contribute to an improved understanding of the groundwater flow system and the long-term implications of pumping on future groundwater sustainability in the Western Port Basin.

02EVB – SCIENTIFIC RESULTS OF THE INTEGRATED OCEAN DRILLING PROGRAM (IODP)

02EVB-01. THE AUSTRALIAN AND NEW ZEALAND ROLE IN SCIENTIFIC OCEAN DRILLING

Neville Exon

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Australian and New Zealand scientists have been involved in scientific ocean drilling for more than 40 years, and have made vital contributions to the ~35 expeditions in our region, often as co-chief scientists. Our Southern Hemisphere scientific skills and data sets give us a considerable advantage in writing proposals for a global scientific program.

Our two countries joined IODP as ANZIC in 2008, and that has involved four expeditions in the region. A particularly exciting activity was the Great Barrier Reef paleoenvironmental Expedition 325, which helps us understand the history of the reef in the last 30 000 years and also helps construct a better global sea level rise curve. Our scientists have been on 25 expeditions from 2008 to 2013. Most were two-month expeditions on the non-riser American-funded vessel *JOIDES Resolution*, but some were on the deep-drilling, riser-equipped Japanese vessel *Chikyu*, and some on alternative platforms.

A new phase of IODP, the International Ocean Discovery Program, began in October 2013 and we have new funding for 2014 and 2015. ANZIC continues as an entity, and nearly all the likely Australian and New Zealand research institutions are involved. This phase is addressing the fields of climate and ocean change; biosphere frontiers including the sensitivity of marine organisms to environmental change; the nature of subseafloor microbial communities; the deep processes of the Earth; and the processes and hazards that affect humanity.

The *JOIDES Resolution* is operating north of Australia this year and in the Indian Ocean next year, and two Australian co-chief scientists will be involved. The vessel is expected to drill in the Southwest Pacific Ocean and on the Antarctic margin in 2016 and 2017. The *Chikyu* and alternative platforms may also come into our region within the next five years.

Eight mature proposals for *JOIDES Resolution* in the Southwest Pacific are with IODP and a number of these will be drilled, and others are in the pipeline. A highly rated proposal is to use *Chikyu* to drill and monitor the subduction zone east of New Zealand, helping to understand the associated earthquakes and tsunamis. A European seabed drilling system may drill drowned reefs off Hawaii to elucidate the sea level history over the last 500 000 years, and may also drill the Cenozoic sequences on the Antarctic margin.

More of our scientists should get involved in ocean geoscience and microbiology using IODP as a tool. As we know, ocean tectonics controls the distribution and physical nature of our continents, and ocean processes drive our weather patterns and rainfall. IODP is helping to explain how the Earth has worked in the past and how it works now, and can provide insights into how it may work in the future. We need local and foreign scientists to get involved in planning IODP expeditions, gathering data to underpin such expeditions, and writing proposals for research drilling around the world and in our region. This is the world's largest geoscience research project and it brings huge scientific benefits, especially to those involved.

02EVB-02. A 5 MILLION YEAR HISTORY OF REEFS, OCEAN AND CLIMATE ON THE NORTHWEST SHELF OF AUSTRALIA: INTERNATIONAL OCEAN DISCOVERY PROGRAM EXPEDITION 356 (2015)

Stephen Gallagher[1], Craig Fulthorpe[2], Andrew Heap[3], Christian Heine[4], Karol Czarnota[3], Neville Exon[5], David Greenwood[6], Nicholas Herold[7], Yasufumi Iryu[8], Willem Renema[9], Yair Rosenthal[10], Tokiyuki Sato[11], Kale Sniderman[1], Asrar Taluker[12], Barbara Wagstaff[1], Malcolm Wallace[1] & Matthew England[13]

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The Indonesian Throughflow (ITF) is a critical part of the global thermohaline conveyor. It plays a key role in transporting heat from the equatorial Pacific (the Indo-Pacific Warm Pool, IPWP) to the Indian Ocean and exerts a major control on global climate. The complex tectonic history of the Indonesian Archipelago due to the continued northward motion and impingement of the Australasian Plate into the SE Asian part of the Eurasian plate makes long-term (million year) reconstructions of ITF history difficult. The best areas in the Indian Ocean to determine ITF history are either in the deep ocean away from strong tectonic deformation or along proximal passive margin regions that are directly under the influence of the ITF. While previous deep-water cores in the Indian Ocean have been used to chart IPWP influence (and by proxy ITF variability), these sections lack direct biogeographic and sedimentological evidence of the ITF. The IODP (International Ocean Discovery Program) will drill a transect of shelf-to-shelf margin cores in September to August 2015, over 10° latitude in the Northwest Shelf (NWS) of Australia to obtain a five million year record of ITF, IPWP and climate evolution that has the potential to match orbital scale deep sea records in its resolution. Drilling the Northwest Shelf will reveal a detailed shallow water history of ITF variability and its relationship to climate. It will allow us to understand the history of the Australian monsoon and its variability, a system whose genesis is thought to be related to the initiation of the East Asian monsoon and which is hypothesised to have been in place perhaps since the Pliocene or earlier. It will also lead to a better understanding of the nature and timing of the development of aridity on the Australian continent.

Detailed paleobathymetric and stratigraphic data from the transect will also allow us to construct subsidence curves to constrain the spatial and temporal pattern of vertical motions caused by the interaction between plate motion and convection within the Earth's mantle, known as dynamic topography. The NWS is in an ideal location to study this phenomenon since it is positioned on the fastest moving continent since the Eocene, on the edge of the degree two geoid anomaly. Accurate subsidence analysis over 10° of latitude will resolve whether northern Australia is moving with/over a time transient or long term stationary downwelling within the mantle, thereby vastly improving our understanding of the dynamics of deep Earth processes.

02EVB-03. GEOCHEMISTRY AND SOURCE OF ASH LAYERS IN BERING SEA SEDIMENT AT IODP SITE 323-U1341

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IODP Expedition 323 to the Bering Sea drilled seven sites (U1339–U1345) with the aim of collecting high-resolution ocean and climate data 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. Sediment cores recovered during IODP Expedition 323 contained numerous volcanic ash layers.

This study concentrates on ash layers in Hole U1341B on the Bowers Ridge. This hole was about 600 m deep corresponding to an age at the bottom of the hole of approximately 3.9 Ma. Ash from U1341B was analysed for major and trace elements and the results compared with ash from surrounding volcanic sources and ash layers intersected in other drill holes in the region. The ash at Site U1341 varies in composition from felsic to mafic with a silica range from 40.35% to 79.90%. The high silica ashes cannot be matched with sources in Alaska or the Aleutians.

While most siliceous ash from Japan has lower TiO_2, there are some ash layers that do overlap with the U1341B compositions, for example the Ah ash from Kikai caldera south of Kyushu.

Basaltic and andesitic ash layers from U1341 are compared with volcanic ash analyses from the Aleutians, Alaska, Kamchatka and Japan. Some analyses overlap with analyses from Unimak Island in the Aleutians. Most analyses of Bering Sea ash have slightly higher TiO_2, FeO, and lower MgO compared to ash from nearby arc volcanoes.

02EVC – SCIENTIFIC RESULTS OF THE INTEGRATED OCEAN DRILLING PROGRAM (IODP)

02EVC-01. "CHIKYU" RISER DRILLING RESULTS AND HER FUTURE CHALLENGES

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Integrated Ocean Drilling Program (IODP) <www.iodp.org> is an international marine scientific drilling program that explores the Earth's history and structure as recorded in seafloor sediments and rocks, and monitors subseafloor environments. Japan's contribution to the international scientific ocean drilling, riser equipped advanced drilling vessel – CHIKYU, began operations in 2005 with the aim to reach the challenging targets at depth, like dynamic faults, continent formation and mantle, sediment secrets and deep biosphere.

Since 2007, Chikyu's challenges began with the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) by drilling, sampling and monitoring at extensive shallow holes transecting across the subduction, and continues deepening the primary riser hole to reach the mega-splay fault as deep as 7 km below sea level. Various challenges forced multiple delays during the operations, from strong current, difficult formation from the tectonically active faulting environment, typhoon and winter cold fronts, to the mechanical failures related to those natural challenges. After barely escaping the tsunami during the March 11 Tohoku-oki earthquake (M9.0) with some damage, scientists from continental and ocean drilling operations organised the successful drilling, sampling and monitoring of the shallow, active slip zone at the 7 km water depth in a surprisingly short period of preparations. This expedition found a fundamental mechanism of large slip of thin and weak fault near the Japan Trench axis during the earthquake.

In regard to the deep and extreme biosphere studies, two expeditions investigated the hydrothermal environment in Okinawa and deep coal-bed biosphere in Shimokita. Scientific drilling's most extensive wireline logging was carried out to identify, evaluate and analyse the coal-bed and to sample the least contaminated fluid samples for geochemical and biological studies. More drilling may followup in the near future to understand the biosphere at deeper and more extreme environments.

Scientific ocean drilling's ultimate target from its beginning in the '60s was drilling into the mantle. The technical feasibility studiOcean es began in 2010, and planning for site surveys at three potential locations in the Pacific will start this year. Geotechnical analyses and various feasibility studies are being carryied out for two highly ranked riser projects, Izu-Bonin-Mariana (IBM) and Costa Rica Seismogenesis Project (CRISP).

To plan for the next 10 years, the Chikyu+10 workshop was held in April 2013 with a gathering of 397 scientists from 21 countries during which 127 proposals were reviewed and categorised projects for the future development (see http://www.jamstec.go.jp/chikyu+10/).

02EVC-02. EXPLORATION OF MIOCENE BIOMARKERS IN CORED SEDIMENTARY ROCKS FROM IODP EXPEDITION 317, CANTERBURY BASIN, NEW ZEALAND

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Integrated Ocean Drilling Program (IODP) Expedition 317 to the Canterbury Basin, on the eastern margin of the South Island of New Zealand, provided the opportunity to study sediment geochemistry in contrasting depositional settings, from mid-shelf to upper slope sedimentary rocks. The expedition recovered sediments from the Eocene to the Holocene. A particular research focus was on the sequence stratigraphy of the sedimentary package, which recorded a time when global sea level change was dominated by glacioeustasy. The main goal of this research was to provide the first organic geochemistry results for the cored Miocene sediments from this expedition.

The comprehensive biomarker picture from these cores enables a better understanding of the organic matter origin in the Canterbury Basin, as well as the depositional and post-depositional processes involved.

Upper Miocene to Holocene sedimentary sequences were cored in a transect of three drilling sites on the continental shelf (Sites U1354 and U1351) and one on the continental slope (Site U1352). Overall, 72 samples were recovered from Miocene sediments in U1351 and U1352 for geochemical analysis including biomarker research. Thirteen of these were squeeze cakes, and the rest were cut spot samples. Total organic carbon content for these samples is generally low (<1 wt %), with only a few spot samples in U1352 having higher values.

To determine the origin of the organic material, as well as the thermal maturity gradients in these three sites, hydrocarbons and biomarkers were extracted from 40 samples. Relatively low amounts of extractable organic matter (OM) were detected. There is good preservation of C_{11} to C_{34} alkanes, with a slight–moderate predominance of odd-over-even chain length for long-chain n-alkanes – the $CPI_{22–32}$ values are mainly between 1.09 and 1.77.

The Pr/Ph ratios (0.58–2.14) for all three cores indicate variable oxygenation from anoxic to suboxic conditions. Thermal maturities of the U1351 and U1352 core sediments were calculated using Pr/n-C_{17} (0.58–3.06) and Ph/n-C_{18} (0.3–1.9) ratios. These data indicate increasing thermal maturity with depth, as well as some possible biodegradation of the OM. Depositional environment can also be determined by the abundance of C_{27}–C_{29} regular steranes in the samples, as well as the C_{30} sterane index and the C_{31}/C_{30} hopane ratio.

Varying inputs of organic matter were identified for the Miocene sediments in the cores. Acyclic biomarkers indicate probable marine biological input for the middle Miocene samples. Upper Miocene samples predominantly were defined by high terrigenous input. In addition, calculated wax indices for the Miocene sediments were between 0.09–0.54 for n-alkanes. These ratios suggest a primary marine depositional environment for all the sediments, although the type of organic matter was likely often of terrestrial origin. The amount and distribution of the aromatic hydrocarbons suggest numerous origins of the organic matter, as well as diverse levels of biodegradation.

02EVC-03. HIGHLIGHTS OF IODP RESEARCH AND FUTURE OUTLOOK

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The IODP is the largest scientific Earth Science program in the world. Drilling missions are executed by three unique drilling platforms in all ocean basins, including the drilling vessels *Chikyu* and *JOIDES*

Resolution, and *ad hoc* Mission Specific Platforms. The impact of this drilling program has implications for a wide variety of societal issues, and has just entered a new five year phase.

Examples of IODP research areas are global warming and past oceans, ocean circulation, geohazards, gas hydrates, rifting, the architecture of the lower crust, and others. My presentation will focus on highlights of past IODP drilling, specifically in the Climate and Ocean area, and on promising projects in the future.

My career is marked by continuous involvement in the study of past Climates and Oceans within the context of the International Ocean Drilling (IODP) program. I have participated in five cruises, and I am currently the chair of the IODP Panel that evaluates the proposals.

02EVD – SCIENTIFIC RESULTS OF THE INTEGRATED OCEAN DRILLING PROGRAM (IODP)

02EVD-01. IODP EXPEDITIONS 343 AND 343T, THE JAPAN TRENCH RAPID DRILLING PROJECT (J-FAST) YIELD NEW INSIGHTS INTO THE MECHANICS AND STRUCTURE OF SUBDUCTION THRUST FAULTS

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The Mw = 9 2011 Tohoku-oki earthquake ruptured to the Japan Trench, with very large coseismic slip occurring on the shallow part of the décollement. A significant consequence of the large slip was generation of a devastating tsunami. To better understand the controls on rupture propagation and slip, the plate boundary décollement, and over-riding and subducting plate materials near the trench were investigated by downhole logging and coring, and a temperature observatory was installed, during Integrated Ocean Drilling Project (IODP) Expeditions 343 and 343T (the J-FAST project) from May–July 2011.

Analysis of samples and data arising from these expeditions has already yielded new insights into subduction thrust mechanics. In particular, the very smectite-rich shallow décollement materials are demonstrated experimentally, and by the very small temperature anomaly generated during slip, to be extremely frictionally weak (? ~0.05–1.0). They could also have experienced thermal pressurisation resulting in additional coseismic weakening. These properties allowed an energetic rupture that had initiated deeper on the subduction thrust to accomplish very large slip in the surface during a near total stress drop earthquake!

Examination of the structure of the décollement materials reveals a range of fabrics exhibiting evidence that shear was localised in zones ranging from 5 m to <<1 mm in thickness. The range of fabrics is tentatively interpreted to have developed at a range of strain rates, from creep to seismic slip.

I will discuss these overarching scientific findings, and outline how NZ-based research is helping to characterise the structure of the wedge, décollement, and subducting plate.

This research used samples provided by the Integrated Ocean Drilling Program (IODP). Additional funding was provided by the Australian–New Zealand IODP Consortium (ANZIC).

02EVD-02. INSIGHT INTO THE EOCENE: MARINE SEDIMENTARY SEQUENCES FROM IODP EXPEDITION 342

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Foraminiferal stable isotope analysis has allowed us to develop a remarkably coherent picture of the earth's climate over the past 65 million years. Expedition 342 of the International Ocean Drilling Program (IODP) recovered nearly 5.5 km of sediment core from 5 locations on South East Newfoundland and 3 locations on J-Anomaly Ridge, off the coast of Newfoundland in the western North Atlantic. Cores recovered from these locations are characterised by high clay content, high sedimentation rates, good stratigraphic controls and often 'glassy' microfossil preservation. As such these cores present an opportunity to produce a continuous, high-resolution paleo-oceanographic record from the earliest Eocene to the Oligocene, covering major climate events such as the Mid Eocene Climatic Optimum and Eocene/Oligocene Boundary.

The late Eocene represents the descent from the balmy greenhouse climate of the Paleocene to the cool change at the Eocene–Oligocene boundary that brought about glaciation and conditions that resemble our modern climate. This change is thought to be a result of declining global temperatures driven by declining atmospheric CO_2 allowing for the eventual development of large-scale ice sheets in Antarctica. These sequences present a unique opportunity to investigate climatic drivers and responses, namely carbon cycle dynamics, ocean circulation, atmospheric CO_2 and climate sensitivity.

We currently lack an astronomically tuned time scale for a large portion of the middle Eocene because many of the current records suffer from modest resolution or hiatuses, leaving the earlier Paleogene chronologies 'floating'. Closing this gap is critical to paleoclimate reconstructions to accurately constrain the dating of globally disparate records and understand climate dynamics and evolution.

Our study takes advantage of exceptional marine sedimentary sequences spanning the late Eocene to produce a detailed stable isotope record from well-preserved benthic foraminifera. This will contribute to producing an astronomically tuned deep-sea age model and a continuous, high-resolution paleoclimate record. These results will play a part in a global effort to analyse Eocene climate sensitivity and dynamics under high atmospheric CO_2 and allow us to address a suite of interrelated questions regarding the evolution of earth's climate.

Preliminary observations of initial isotope data from our sediment cores in combination with ship-board stratigraphic data suggests the record is of a very high resolution, <2 Ka. Spectral analysis of the isotope data further suggests the presence of orbital pacing. This gives us hope that these records will help meet the goals of nearly 30 years of Ocean Drilling.

02EVD-03. SLOW SLIDING OF GAS-HYDRATE-BEARING LANDSLIDES ON THE HIKURANGI MARGIN, NEW ZEALAND

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It has long been hypothesized that gas hydrates facilitate submarine landslides. Solid and potentially cementing gas hydrate is generally thought to increase sediment strength. The driving factor for gas hydrate-related slope instability has thus been assumed to be hydrate dissociation causing sediment weakening and overpressure. However, clear evidence for this process has yet to be found. Analysis of seismic data from the Tuaheni Landslide Complex (TLC) east of New Zealand's North Island, suggests that gas hydrate itself may lead to seafloor weakening. This appears to occur in the form of plastic, creeping seafloor deformation rather than the catastrophic events typical of submarine slides. This observation could have wide-ranging implications for assessment of the hazard posed by hydrate-bearing submarine slides as well as more generally, for seafloor morphological processes.

The TLC displays morphological features that are typical of active, creeping terrestrial slides. The TLC is underlain by bottom simulating reflections (BSRs), free gas at the base of gas hydrate stability (BGHS) and indicative of a presence of gas hydrates. Crucially, the upper limit of creeping coincides with the pinchout of the BGHS at the seafloor. We thus hypothesize that slow sliding is related to gas hydrate. Out of several possible processes that may link gas hydrates to seafloor "creeping", we consider the most likely mechanism that interstitial gas hydrate, like ice, may exhibit plastic behaviour leading to slow deformation, similar to that of terrestrial rock glaciers. Our presentation will focus on analyses of data from several 2-D seismic surveys combined with bathymetric data and gas-hydrate-related modelling. We will also present first results from a 3-D seismic survey planned for April-May 2014. These studies ultimately underpin plans for drilling: Our efforts dovetail with a planned remotely operated seafloor drilling expedition using the MeBo system in 2016 for sediment coring. Proposed IODP drilling with the D/V JOIDES Resolution, if approved, will then focus on logging-while-drilling and retrieval of pressure core samples for shore-based analyses.

02EVD-04. A COMPARATIVE MULTIPROXY APPROACH TO ADDRESS PALEO-REDOX CHANGE AT THE PALEOCENE-EOCENE BOUNDARY, NEW JERSEY CONTINENTAL MARGIN

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Superimposed on the gradual warming trend from the late Paleocene to Early Eocene Climatic Optimum (EECO; ~53.5 Ma) are pulses of short duration hyperthermals. Among them, the Paleocene-Eocene Thermal Maximum (PETM; ~55.8 Ma) has arguably received the most attention. Investigations thus far have revealed warming on a global scale with an associated negative carbon isotopic excursion (CIE). Both the source of the light carbon required for the observed several per-mil CIE and the rate of its release are hotly debated. The proposed time frame for the latter ranges from instantaneous (13 years; Wright and Schaller, 2013) to hundreds [Röhl et al. 2007] or tens of thousands of years [Murphy et al. 2010]. The shortest proposed time frame has been invoked to limit the number of plausible causes operating on processes that could conceivably result in the requisite amount of light carbon being released into the atmospheric-ocean circulation, namely contact metamorphism-induced thermogenic methane and/or CO2 from large igneous province intrusion and cometary carbon (δ13C ~ -45 ‰). Cited as support for a comet impact is a recent study by Wang et al. [2013] that claimed the existence of abundant isolated single-domain magnetic particles, whose origin remain unknown, in the Marlboro Clay recovered from the New Jersey continental margin coincident with the CIE. Here we present new results from the Marlboro Clay recovered from the Millville site by ODP/CPDP Leg 174AX. Our initial intention was to use magnetic, inorganic and organic geochemical proxies, and pyrite texture to reconstruct paleo-redox changes at this locality. Unexpectedly, we found evidence suggestive of the magnetic mineral greigite (Fe3S4) that can account for the supposed isolated single-domain magnetic particles. These greigite particles are known to form diagenetically during organoclastic sulphate reduction, and as such, are not derivatives of comet impact plume condensate.

To reconstruct paleo-redox using magnetofossil abundance, we measured and modelled the remanent magnetization curves. We found particularly high abundance of a magnetic component attributable to the nanocrystals genetically engineered by magnetotactic bacteria that are ubiquitous around the oxic-anoxic interface in aquatic environments. The sequential Fe extraction method of Poulton and Canfield [2005] was followed to determine iron fractionation and to calculate the degree-of-pyritization (DOP). The deduced DOP pre-CIE is 0.096 on average, considerably lower than the syn-CIE of 0.215 on average. Using electron microscopy, we observed variations in the pyrite texture. Patches of pyrite crystal aggregates are commonplace in the bioturbated, silty-clay Vincentown Formation in the upper Paleocene. In contrast, pyrite framboids, single and clustered euhedral crystals are observed from the CIE clay interval. We also solvent extracted samples spanning the pre-, syn-, and post-CIE period for redox-sensitive lipid biomarkers and will be presenting our results. Overall, results from our combined proxy approach suggest that deoxygenation did indeed occur at the New Jersey margin, although the stratification was not severe and euxinia did not take place or was not sustained. Such loss in oxygenation can be attributed to a combination of warming-induced decrease in gas solubility, increased productivity, and freshening of the surface water.

ENERGY

02EGA – CO_2 GEOLOGICAL STORAGE – LOCKED IN FOR THE LONG-TERM

02EGA-01. GEOLOGICAL CO_2 STORAGE – A SOLUTION FOR DEEP EMISSION CUTS IN AUSTRALIA?

Matthias Raab

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Australia is one of the largest consumers of fossil fuels per capita in the world. To meet global expectations in emission targets, Australia needs to manage its existing energy generation from fossil fuels in an environmentally sustainable manner. According to the World Resources Institute, almost 1200 large new coal facilities in 59 countries are proposed for construction. The developing world in particular has massively increased its use of coal, with every indication that this trend is likely to continue. Coal is too abundant and too cheaply available from reliable sources to be ignored as substantial generator of electricity.

This presents a strong case for CCS, involving the geological storage of carbon dioxide, to become an integral part of Australia's and the world's energy industry. CCS is a readily available transition technology that can have more impact than any renewable-energy technology for several decades to come. While there are globally only a limited number of projects which are injecting CO_2 solely for storage, Australia is a global forerunner demonstrating storage technologies from small/research scale (CO2CRC Otway Project, >65kt) to medium scale from LNG processing (Chevron's Gorgon Project, >3Mt/a, starting 2015), to full industrial scale through the Federal CCS Flagship program in the long term.

Storage in geological formations is one of the most effective technologies for dealing with industrial CO_2 quantities (Gt/a) in a permanent safe and secure way. The CO_2 behaviour in the subsurface is conducive for secure storage. Once injected, the CO_2 will residually trap, dissolve in formation water, and mineralise within the lithology of the storage formation. This further enhances the security of permanent storage. The potential for enhanced mineral trapping, forming carbon-bearing minerals, depends on the composition of the reservoir rock, the temperature and pressure of the rock, the chemical composition of the water, the water/rock contact area, and the rate of fluid flow through the rock minerals, over geological time scales. Australia's extensive sedimentary basins provide ample capacity for permanent and large-scale geological storage of CO_2.

Projects storing CO_2 are being regulated by legal frameworks ensuring environmentally safe geological storage. A storage site can only be selected for use if a prior analysis shows that, under the proposed conditions of use, there is no significant risk of leakage or damage to human health or the environment. R&D continues to reduce the costs and improve the capabilities for appraisal and monitoring technologies ensuring safe storage. Advanced R&D in Australia will further bridge technical capabilities with regulatory needs and ultimately gaining public acceptance. This presentation will address key aspects of safe geological carbon storage and the opportunity in Australia to significantly reduce the carbon emissions footprint.

02EGA-02. MULTI-SCALE IMAING OF PRECIPICE SANDSTONE CORE PLUGS AND CROSS PROPERTY CORRELATIONS

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Digital 3D image data from X-ray micro-CT (μCT), in combination with simulation software, allow for the measurement and calculation of geological and petrophysical reservoir rock properties. Similar to conventional core analysis, data obtained through digital image analysis may be used in the construction of geological models, which require upscaling for use in dynamic simulation of the behaviour of fluids like oil and CO_2. This paper presents some steps towards a workflow to determine core-plug scale properties through the use of μCT imagery.

μCT enables the characterisation of lithological attributes in core samples over a wide range of length scales, presenting new possibilities for property prediction. A single μCT image is capable of capturing data for length scales covering approximately three orders of magnitude (μm, mm, and cm); additionally, one can acquire multiple images at different resolutions to improve data accuracy at different length scales.

In this work, 100 mm tall and 25 mm diameter core-plugs from the Precipice Sandstone, consisting of fine- to coarse-grained bands ranging from mm to cm in thickness, were imaged using μCT at 16 μm/voxel resolution. The essential stages in the data analysis workflow involve: (1) Plug Unitisation: automated identification of geological rock units through the analysis of grain size and porosity logs using instantaneous rate of change; (2) Geological Characterisation: measuring the phase proportions, grain and pore size, and grain sorting of the rock units; and (3) Petrophysical Characterisation: measuring rock unit permeability and conductivity using digital simulation software. μCT Images of the 25 mm diameter core-plugs have insufficient resolution to capture fine-scale features such as pore throats or clay-bound porosity; therefore, additional fine-scale data are collected in step (4) Sub-plug Imaging and Characterisation: a series of sub-plugs (typically 25 mm tall x 8 mm diameter) are collected from the original core-plugs, imaged at approximately 5 μm/voxel resolution, and analysed in a similar way as the 25 mm diameter datasets. An associated experimental program is also underway on the same samples that will link the digital core data with results from routine and special core analysis.

Results indicate linearity between grain and pore size; however, there is no clear correlation between grain size and other macro properties such as porosity and the proportion of clay minerals. With specific analytical parameters, modelled horizontal and vertical permeabilities correlate linearly with the average pore body size after log transformation of both properties, suggesting a potential methodology for property prediction using a combination of core-plug and sub-plug scale data.

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02EGB-01. MINERAL CHARACTER OF SEDIMENTARY FACIES ASSOCIATIONS, LOWER JURASSIC, SURAT BASIN, QUEENSLAND

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The Carbon Geostorage Initiative (CGI, funded by industry and the local and federal governments) commissioned the sequence stratigraphic study of the Lower Jurassic formations in the Surat Basin, with the aim of assessing their suitability for safe geostorage of carbon dioxide. The findings of this study will soon be published in the Geological Survey of Queensland Review Series.

A concurrent project funded by industry (Australian National Low Emissions Coal Research and Development) and the federal government (CO2CRC) has focused on the geochemical impact of carbon dioxide storage in low salinity aquifers. This research project is currently undertaken by several research organisations and has employed a multitude of methods (X-ray diffraction, X-ray fluorescence, electron microscopy, geochemical reactor tests and geochemical modelling).

This presentation summarises the findings of the sequence stratigraphy study conducted by CGI and describes the mineral character of the Lower Jurassic sedimentary facies associations (specifically the Precipice Sandstone and the

Evergreen Formation with its two members) as determined by the CO2CRC-funded project. GSQ Chinchilla 4 is the study drill hole that has been stratigraphically logged and concurrently sampled for mineralogical analysis.

Sequence boundary 1 represents the widespread unconformity at the base of Surat Basin. Sequence 1 includes the Precipice Sandstone and represents the transition from braided fluvial channel deposits to lower energy meandering depositional systems. Sequence boundary 2 is placed at the base of the Boxvale Sandstone Member in GSQ Chinchilla 4, although this member has not been identified throughout the basin. Sequences 2 and 3 are part of the Evergreen Formation and include lacustrine and swamp sediments. The Westgrove Ironstone Member (Sequence 2) is widely spread in the basin and correlates with the early Toarcian eustatic sea level rise linked to a global mass extinction. Sequence boundary 4 is a sharp erosive surface, which defines the shift to the fluvial sedimentation of the overlying Hutton Sandstone.

Overall, the Lower Jurassic sediments consist of quartz, plagioclase, K-feldspars, kaolinite, micas and occasional siderite, smectite–illite mixed layer clays, chlorite and calcite.

The stacked channels of the lower Precipice Sandstone (Sequence 1) contain high concentrations of quartz (>90%), except when siltstone clasts are present. The upper Precipice Sandstone fluvial channel sediments (Sequence 1) contain less quartz (35–75%) and more feldspar, dominantly K-feldspars (10–20%).

The overlying sequences are indicative of lower depositional energy and include lacustrine shoreface, swamp and offshore facies. Quartz concentrations can vary significantly (20–60%), while the dominant feldspars are plagioclase (up to 25%). Kaolinite remains the dominant clay mineral (up to 40% in distal offshore lacustrine sediments), although micas (illite and/or muscovite) may reach 20%.

Of note is the shift from the K-feldspar character of the Sequence 1 to plagioclase dominance in the younger stratigraphic sequences. The Boxvale Sandstone Member consists of mouth bar to river mouth facies and has a unique mineral character, with 30–45% feldspars, mainly plagioclase. The Westgrove Ironstone Member, which is associated with a global sea level rise, it is kaolinitic and may have up to 50% siderite.

02EGB-02. TIME SERIES IMAGING AND CONVENTIONAL EXPERIMENTAL STUDIES OF CHINCHILLA-4 WELL SAMPLES TO MEASURE GEOCHEMICAL REACTIVITY AND DISSOLUTION TRAPPING CAPACITY OF CORE MATERIAL USING SUPERCRITICAL CO_2

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In this study 3D Digital Core Analysis (DCA), Scanning Electron Microscope (SEM) imaging and mineral mapping by automated quantified SEM-EDS (QEMSCAN™) were combined with conventional oil industry, best-practice core analyses to fully characterise a suite of five samples from the Chinchilla-4 well (Surat Basin). On these samples, which include reservoir, seal and overburden rock types, 4D (time series) multi-resolution imaging studies were conducted to explore their geochemical reactivity and trapping capacity in order to assess their potential as a CO_2 storage site.

Micro-computed tomography (µCT) 3D images have been acquired on sub-plugs extracted from Precipice Sandstone (reservoir), Evergreen Formation (seal) and Hutton Sandstone (overburden) core plugs in their native state and then again after the sub-plugs were reacted with artificial formation water and supercritical CO_2 at 70°C and 200 bars, which is representative of *in-situ* conditions for potential storage sites in the Surat Basin. For each of the five sub-plugs, SEM and QEMSCAN™ images were also acquired, before and after reaction states, on polished sections created on a nominated plane of interest within the field of view of the tomograms.

The before and after reaction 3D tomograms have then been registered into perfect geometric realignment (3D–3D registration), and the SEM and QEMSCAN™ images have also been registered into the tomograms (2D–3D registration). Comparison between registered before and after reaction images highlighted the pore scale effects of water–CO_2–rock reactions and allowed to investigate and quantify in 3D changes due to loss (dissolution) or gain (precipitation) of matter during the geochemical reactions of the carbonic acid formed in the reaction vessel and their likely impact on storage volumes, injectivity and seal effectiveness.

02EGB-03. CO_2–WATER–ROCK INTERACTIONS: MINERAL REACTIVITY UNDER CO_2 STORAGE CONDITIONS

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The implementation of carbon capture and storage technology will rely on the characterisation of suitable sedimentary basin reservoirs for its storage, and as part of that process an understanding of how reactive CO_2 is under reservoir conditions.

This presentation will review the principle CO_2–water–rock interactions by focusing on the following processes. Injecting CO_2 into geologic formations under high pressures and temperatures leads to an increase in the solubility of CO_2 in local formation waters, with the dissolution of CO_2 being a significant long term trapping mechanism for its storage. The CO_2 plume itself can act as a solvent, but its properties lead to a low solubility of water in the CO_2 phase. However, organic compounds in a reservoir may be dissolved in the CO_2 plume and even a small amount of water can lead to an increased reactivity between the wet-CO_2 phase and specific mineral phases.

The dissolution of CO_2 in formation waters leads to their acidification as CO_2 reacts with water to form carbonic acid. This increase in acidity enhances rates of mineral dissolution with different mineral phases exhibiting a wide range in their relative reactivity.

Carbonate phases are particularly reactive, but have the added effect of buffering solution pH as the concentration of dissolved carbonate species increases. Thus, target reservoirs with some carbonate content have an increased mineral buffering capacity to counteract any acid generated by the dissolution of CO_2 or other reactive co-contaminants in the gas phase.

Aluminosilicate phases, such as feldspars and clays, present as the primary minerals in siliciclastic reservoirs do not react as rapidly as carbonate phases, but their dissolution is an important source of dissolved solids. An increase in the dissolved solid load in formation waters may lead to the precipitation of new mineral phases over time.

Modelling the rate at which these mineral dissolution and precipitation reactions proceed under CO_2 storage conditions is critical to predicting how the geochemistry of a CO_2 storage reservoir will evolve and subsequent effects this may have on the petrophysical properties of a reservoir. Fits of empirical rate laws to experimental data sets have been compiled to describe the reactivity of a number of minerals relevant to sedimentary basins. Often these experiments are conducted under ambient conditions, and the rate law is used to extrapolate reaction rates to reservoir conditions. Here we present a quantitative comparison of the reaction rates of various mineral phases under CO_2 storage conditions, highlighting how sensitive the models are to temperature and pH.

02EGB-04. SELECTION OF POTENTIAL SITES FOR THE GEOLOGICAL STORAGE OF CO_2 IN THE OFFSHORE VLAMING SUB-BASIN, SOUTHERN PERTH BASIN

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In 2011, as part of the national carbon infrastructure plan, the offshore Vlaming Sub-basin located in the southern part of the Perth Basin, was identified for a detailed study of the CO_2 storage potential. During the two year study undertaken by Geoscience Australia new datasets were collected and a range of methodologies and screening techniques were applied to achieve an improved prospectivity assessment of this basin. The new datasets used in the study included updated biostratigraphy, swath bathymetry, detailed geochemical data and results from specialised petrophysical core analysis for the stratigraphic interval of interest.

In the offshore Vlaming Sub-basin the main reservoir–seal pair considered for CO_2 storage is the Lower Cretaceous gage sandstone and the overlying south Perth Shale (SPS). The Gage Sandstone was deposited in paleotopographic lows of the Valanginian breakup unconformity as a large submarine fan system. Filling of the sub-basin continued with deposition of a thick deltaic to shallow marine succession of the SPS. New biostratigraphy was used to revise the sequence-stratigraphic framework and reconstruct paleodepositional environments for the period corresponding to the deposition of the main reservoir and seal. This work provided key information on depositional facies distribution, which enabled mapping of the lateral changes in the reservoir and seal properties. A detailed investigation of the SPS has shown that it comprises highly diverse lithologies ranging from pro-delta shales to sandier facies in the middle to upper part of the deltaic succession. While pro-delta shales provide an effective seal to the underlying Gage reservoir, the sandier facies cannot be classified as a seal, which makes the containment uncertain. The effective seal was mapped throughout the study area and it is used as one of the main constraints for the site selection.

The storage site selection was guided by the location of significant volumes of high porosity and permeability facies within the Gage reservoir, the presence of the effective seal, predicted migration paths for the injected CO_2 and the location of structural closures identified by the fill–spill analysis carried out using Permedia™ software. In addition to the identified heterogeneity of the SPS, the study found some evidence of recent fault reactivation, which creates uncertainty over the seal integrity. An in-depth analysis of the fault reactivation, combined with modelling of fault behaviour after the injection of CO_2, provided additional constraints for selection of the suitable storage sites. An integrated approach to acquiring and analysing datasets in the structurally complex and relatively data poor offshore Vlaming Sub-basin helped to develop a better understanding of the reservoir and seal properties and achieve a more accurate estimate of the CO_2 storage capacity and helped to select potential storage sites.

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02EGC-01. AUTHIGENIC CARBONATES IN THE GREAT ARTESIAN BASIN AS NATURAL ANALOGUES OF MINERALISATION TRAPPING IN CO_2 SEQUESTRATION

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Precipitation of carbonate minerals within the pore space of the storage reservoir provides the greatest certainty of long-term storage and eliminates the risk of CO_2 leakage. Modelling studies suggest that significant CO_2 could be sequestered by carbonate formation when CO_2 is injected into sandstone formations with trapping capacity determined largely by cation availability. On the other hand, zones of significant carbonate cementation have also been identified in shallow clastic aquifers where CO_2 associated with and likely derived from oxidation of hydrocarbons migrating vertically from deeper source rocks or leaky hydrocarbon traps mixed with local formation water. These carbonates formed close to the naturally occurring point of shallow subsurface leakage (often a fault) that suggests mineralisation has been rapid relative to the movement of groundwater. Similarly, massive significant scaling of oil wells by calcite precipitation demonstrates that the authigenesis may occur within acceptable time frames for engineered authigenesis. The main parameters determining the extent of mineral trapping in sedimentary formations are host mineralogy, pH and ρCO_2, brine chemistry and temperature. In natural systems, pH is strongly affected by ρCO_2 and the combination of high pH and alkalinity favour carbonate precipitation. The mixing of solutions with different chemical compositions can produce undersaturated or supersaturated conditions for a particular mineral depending on the original compositions and temperatures even where the original ground waters were saturated with the mineral in question. The system may also evolve with time and the degree of mixing such that undersaturation prevails in more acidic and saline parts of the system and supersaturation in the more basic and dilute region of the system. Central to any attempt to engineer accelerated mineralisation for sequestration of CO_2 is an understanding of the conditions under which relatively rapid carbonate mineralisation has formed both in present hydrocarbon extraction activities and in the geological past. In this context, Surat Basin carbonate cements exhibit a range of $\delta^{18}O$ values from 4.6 to 17.0 ‰ (n = 25), with the exception of a heavily carbonate-cemented Hutton Sandstone sample that has a $\delta^{18}O$ value of 24.7 ‰. The Surat Basin cements exhibit a range of $\delta^{13}C$ from –11.1 to 3.0 ‰ (n = 26). Eromanga Basin cements and fault veins have an overlapping range of $\delta^{18}O$ and $\delta^{13}C$ values from 6.6 to 22.3 ‰ and –15.9 to 0.0 ‰ (n = 20), respectively. Modelled fluid oxygen isotope compositions indicate the calcite cements likely precipitated in the temperature range of 80°C to 120°C across both basins, which is supported by burial history modelling and preliminary fluid inclusion data. The carbonate cements with the most depleted $\delta^{13}C$ values are from wells located adjacent to major faults that supports the proposal that significant carbonate cementation may form where hydrocarbons and associated CO_2 migrate up leaking faults and emerge in a shallow aquifer system. Mixing between low salinity ground waters of meteoric origin and evolved basinal brines across a range of temperatures may explain the wide range of calculated oxygen isotope compositions from –17.0 to 7.9 ‰ of fluids precipitating carbonate cements and fault veins in Great Artesian Basin sediments.

02EGC-02. MINERAL TRAPPING CAPACITY IN RESERVOIRS WITH VARIABLE MINERALOGIES: A MASS BALANCE APPROACH

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Estimating changes in structural, fluid, residual and mineral trapping capacity over time is an important aspect of the CO_2 storage site characterisation. It contributes to understanding the long-term fate of CO_2 under storage conditions and associated risks. The precipitation of carbonate minerals from injected CO_2 is referred to as mineral trapping and is considered the safest trapping mechanism. Determining the mineral trapping capacity requires accurate prediction of the fluid–rock reaction pathways and rates, which depend on the fluid composition, the mineralogy and kinetic properties including the mineral specific reactive surface area.

Predicting the dynamics of CO_2 trapping through the different trapping mechanisms for a CO_2 storage site requires reactive transport modelling at reservoir scale. The model results are inherently dependent on the representation of reservoir heterogeneity in terms of petrophysical properties such as permeability and mineralogy and the chosen operational conditions such as grid size. Independently, the scope of this study is limited to the role of the reservoir mineralogy in determining the mineral trapping capacity.

Here we take a mass balance approach for carbon present in the form of supercritical (residual) CO_2 (sc-CO_2), dissolved inorganic carbon (DIC) and mineral-bound carbon (min-C) and assess the abundance of carbon within the different fractions over time for different reservoir mineralogies. This situation applies to the part of the reservoir, which is water saturated and contains residual CO_2 after the termination of CO_2 injection. Initial conditions include the estimate of sc-CO_2, DIC controlled by the CO_2 saturation concentration and min-C given by the reservoir mineralogy. Dissolution and precipitation reactions are predicted using a kinetic reaction path modelling approach using The Geochemist Workbench™ software.

In order to elucidate differences in model outcomes solely controlled by differences in the mineralogy, a generic formation water, analogous to the Utsira Formation water composition at the Sleipner site, was used. Equally the same porosity and kinetic properties were chosen for each scenario. The following three reservoirs with distinctively different mineral compositions were chosen: (1) the Precipice Sandstone, Surat Basin (Queensland, Australia); (2) the Pretty Hill Formation, Otway Basin (Victoria / South Australia, Australia); and (3) an andesitic reservoir rock motivated by the Japanese demonstration project at the Tomakomai site.

Differences in sc-CO_2, DIC and min-C over time will be presented for the three reservoirs and the results will be discussed in terms of the role of reservoir mineralogies. Overall, this study illustrates large differences in CO_2 mineral trapping capacity as a function of reservoir mineralogy. The abundance and reactivity of Ca-, Mg-, and Fe-bearing silicate minerals together with the presence of (minor amounts of) calcite buffering the pH in solution are the primary factors controlling the mineral trapping capacity.

02EGC-03. CHARACTERISATION OF POTENTIAL CO_2–WATER–ROCK DYNAMICS DURING GEOLOGICAL SEQUESTRATION IN A LOW SALINITY, SILICATE RESERVOIR SYSTEM

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Carbon Capture and Storage (CCS) is a technique for mitigating anthropogenic climate change by separating CO_2 from industrial flue gas, transporting it to and storing it in a subsurface geological storage reservoir. The low-salinity (TDS <3000 mg/L) Jurassic sandstone formations in Australia's Surat Basin have been identified as a potential reservoir system for geological CO_2 sequestration. However, given the prevailing use of saline reservoirs in CCS projects elsewhere, limited data are available on CO_2–water–rock dynamics during geological CO_2 sequestration in such low-salinity formations.

Here, a combined batch experiment and numerical modelling approach is used to characterise potential CO_2–water–rock reaction pathways, to assess potential impacts of CCS on groundwater chemistry, and to identify geochemical tracers of inter- and intra-formational CO_2 migration during geological CO_2 sequestration within the Jurassic sandstones. Mineralogy and physical properties of the prospective reservoir are characterised for 66 core samples from stratigraphic well GSQ Chinchilla 4. Representative samples are reacted with synthetic formation water and high-purity CO_2 for up to 27 days at a range of pressures to simulate conditions during carbon sequestration in the Jurassic sandstones.

Results show the low formation water salinity, temperature and mineralisation in the reservoirs, yield high solubility trapping capacity (1.18 mol/L at 45°C, 100 bar), while the paucity of divalent cations in groundwater and the silicate reservoir matrix result in very low mineral trapping capacity within the footprint of the supercritical CO_2 ($scCO_2$) plume. Though alkalinity buffers formation water pH under elevated CO_2 pressure, the acidic pH significantly enhances mineral dissolution in reactors with heterogeneous Hutton and Boxvale Sandstone samples. Smaller TDS changes are observed for samples of the mature Precipice Sandstone than for the other formations. Non-radiogenic, regional groundwater-like $^{87}Sr/^{86}Sr$ values (0.704845–0.706600) in batch reactors indicate carbonate and authigenic clay dissolution as the primary reaction pathways regulating solution composition in all formations during geological CO_2 sequestration. Slightly higher Sr isotope ratios in felsic samples than in calcitic samples, and dissolved Si concentrations in mature Precipice Sandstone reactors show detrital silicate dissolution to be an ancillary process.

Batch reactor degassing at the end of the incubation period was simulated to assess geochemical changes in formation waters during transport away from a $scCO_2$ plume. Model results suggest geological CO_2 sequestration in the Jurassic sandstone formations would increase regional ground-water alkalinity and redistribute carbonate minerals outside the $scCO_2$ footprint, but are unlikely to result in net mineral trapping of CO_2. Several elements are mobilised in concentrations greater than found in regional groundwater, making them viable tracers of CO_2 migration. Most notable is cobalt, concentrations of which are significantly elevated regardless of CO_2 pressure or sample mineralogy. Experimental results indicate manganese and cadmium concentrations may locally exceed drinking water quality guidelines, but further modelling of intra-aquifer mixing is required to quantify the potential risk to regional groundwaters from trace element mobilisation.

02EGC-04. ASSESSMENT FRAMEWORK FOR THE INTERACTION BETWEEN CO_2 GEOLOGICAL STORAGE AND EARTH RESOURCES IN AUSTRALIAN SEDIMENTARY BASINS

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Geological carbon dioxide storage (GCS) has been identified as an important element of greenhouse gas reduction strategies. The Carbon Capture and Storage Flagship program of the Australian Government currently funds two demonstration projects in Western Australia and Victoria. In addition, the Gorgon Project is scheduled to commence in 2014 and includes industrial-scale injection of CO_2 from gas processing on Barrow Island in Western Australia. All of these projects are located in resource-rich sedimentary basins, which contain varying degrees of groundwater, hydrocarbons, unconventional gas, coal, and geothermal energy. In many basins there is a geographic overlap between regions with resource potential and areas prospective for GCS. The concurrent large-scale development of multiple resources may result in complex interactions affecting a basin's fluid dynamics, *in-situ* stress, and geomechanics, which ultimately influence the capability to produce particular resources. A resource management system is helpful to optimise these multiple uses of the pore space ensuring they can sustainably co-exist. This study proposes a framework for the assessment of potential interactions between GCS and other basin resources at the basin- and at the site-scale.

Basin-wide impact assessment is based largely on the geographic overlap between various resources providing a first-order identification of areas with high, medium or low potential of the resources' interaction with GCS. It also maps known or suspected areas of weakness in the geological framework (i.e. faults, improperly abandoned wells) that may form potential leakage pathways for the injected CO_2. This can be used to guide the selection process for a GCS site, inform the data collection strategy for subsequent site characterisation and identify monitoring targets. It does not, however, indicate the specific risk of any resource interaction.

For project specific assessments, this study sets forth a process to qualitatively determine the potential positive or negative impacts of a GCS project on other basin resources following the US EPA's Vulnerability Evaluation Framework for Geological Sequestration. It is composed of: 1) identification of potential impacts of GCS on a specific resource, 2) assessment of impact risks, 3) assessment of options for detection and monitoring, and 4) definition of resource-specific mitigation, optimisation or management schemes.

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02EGD-01. SEABED STRUCTURES, SEDIMENTS AND HABITATS IN JOSEPH BONAPARTE GULF, NORTHERN AUSTRALIA: SEABED MAPPING IN SUPPORT OF POTENTIAL OFFSHORE CO_2 STORAGE OPTIONS

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Geoscience Australia is investigating the suitability of offshore sedimentary basins on the Australian margin as potential CO_2 storage sites. In May 2012 a seabed survey (GA0335/SOL5463) was undertaken in collaboration with the Australian Institute of Marine Science to acquire baseline marine data in the Petrel Sub-basin, Joseph Bonaparte Gulf. This aimed to collect information on possible connections between the seabed and key basin units (e.g. *via* faults and fluid pathways), and characterise seabed habitats and biota. Two areas were surveyed (Area 1: 471 km^2, depth ~80–100 m; Area 2: 181 km^2, depth ~30–70 m), chosen to investigate the seabed over the potential supercritical CO_2 boundary (Area 1) and the basin margin (Area 2), with Area 2 located around Flat Top 1 Well. Data analysed include multibeam sonar bathymetry and backscatter, seabed samples and their geochemical and biological properties, video footage and still images of seabed habitats and biota, and acoustic sub-bottom profiles.

Pockmarks, providing evidence for fluid release, are present on the seabed, and are particularly numerous in Area 1. Area 1 is part of a sediment-starved, low-relief section of shelf characterised by seabed plains, relict estuarine paleochannels, and low-lying ridges. Facies analysis and radiocarbon dating of relict coastal plain sediment indicates Area 1 was a mangrove-rich environment around 15,500 years ago, transgressed near the end of the Last Glacial period (Meltwater Pulse 1A). Modern seabed habitats have developed on these relict geomorphic features, which have been little modified by recent seabed processes. Seabed habitats include areas of barren and bioturbated sediments, and mixed patches of sponges and octocorals on hardgrounds. In the subsurface, stacked sequences of northwest-dipping, well-stratified sediments, variably incised by paleochannels characterise the shallow subsurface geology. Shallow faulting through these deposits was noted, but direct linkages between seabed features and deep-seated faults were not observed.

Area 2 is dominated by carbonate banks and ridges. Low-lying ridges, terraces and plains are commonly overlain by hummocky sediment of uncertain origin. Pockmarks occur on the margins of banks and on and adjacent to ridges. Despite the colocation of banks and ridges with major faults at depth (visible in the basin seismic profiles), there is a lack of direct evidence for structural connectivity in the acquired acoustic sub-bottom profiles because of significant acoustic masking. However, some faults extend through the upper basin units towards the seabed on the margin of Area 2.

No evidence was detected at the seabed for the presence of thermogenic hydrocarbons sourced from the basin, nor for fluids from strata beneath the CO_2 supercritical boundary. The source of fluids driving pockmark formation in Area 1 is most likely decomposing mangrove-rich organic matter within upper Pleistocene estuarine sediments. The gas generated is dominated by CO_2. Additional fluids are potentially derived from sediment compaction and dewatering. Conceptual models derived from this seabed research are being used to inform regional-scale assessments of CO_2 storage prospectivity in the Petrel Sub-basin.

02EGD-02. IMPURITY EFFECTS IN O_2–SO_2–CO_2–WATER–ROCK REACTIONS RELEVENT TO CO_2 STORAGE IN THE SURAT BASIN

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Industrial CO_2 streams from oxyfuel firing and coal combustion will contain impurities including O_2, SO_X and NO_X that may be stored together with CO_2 in geological formations. Carbon dioxide dissolves into formation water subsurface (dissolution trapping) causing acidification and subsequent dissolution of carbonate and silicate minerals. The release of divalent cations into solution stabilises bicarbonate anions (ionic trapping) and may eventually lead to carbonate formation (mineral trapping). However, CO_2–water–rock interactions have implications for water quality changes, and storage integrity, hence each potential storage site must be assessed.

The majority of experimental and modelling studies of CO_2–water–rock interactions have focussed on pure (food grade) CO_2 effects. However, this level of gas purification during carbon capture and storage is unrealistic. The co-injection of SO_2 has previously been observed to enhance silicate dissolution, or in the presence of significant calcite, result in gypsum formation. (1) Impurity gases, especially O_2, affect the system redox, and mobilisation of redox sensitive elements (such as Fe, As, Cr, U) into formation water may be enhanced or reduced. (2) In the presence of oxygen, subsequent formation of Fe oxides and sulfates may immobilise trace elements, as has been observed in a natural analogue study.

O_2–SO_2–CO_2–water–rock laboratory experiments have been performed on a potential storage site reservoir and cap-rock core at *in-situ* reservoir conditions. Enhanced mobilisation of major elements into solution from dissolution of reactive silicates and carbonates in reservoir and cap-rock was observed. This has been attributed to sulfuric acid generation, with a low fluid pH ~1–2. Elevated concentrations of dissolved di-cations including Fe (up to ~1000 mg/kg) and Ca showed enhanced potential for ionic and mineral trapping of CO_2 as calcite, ankerite, and siderite. Secondary iron oxide and sulfate precipitated on cap-rock core in experiments, additionally predicted in preliminary geochemical modelling. Mobilisation of trace elements including U and As were observed at low concentrations, with U within EPA recommended levels. Concentration of As was observed to decrease (to ~3 ppb) in the experiment where iron oxide was precipitated suggesting its incorporation into the newly formed phase.

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02EGD-03. EDDY COVARIANCE'S ROLE AS A MONITORING TECHNIQUE FOR GEOLOGICAL STORAGE OF CO_2

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Geological storage of CO_2 is a leading strategy for large-scale greenhouse gas emission mitigation. Monitoring and verification is important for assuring that CO_2 storage poses minimal risk to people's health and the environment, and that it is effective at reducing anthropogenic CO_2 emissions.

Eddy Covariance (EC) has been proposed as a long-term monitoring solution for geological storage projects and is considered suitable for monitoring areas 1000–100 000 m^2 in size. Eddy Covariance is a key micrometeorological technique, which has traditionally been used for assessing ecosystem exchange of CO_2 in a variety of natural and agricultural settings. It measures the vertical transfer of scalar variables such as CO_2 *via* eddies from upwind of the instrumentation, and correlates the measured CO_2 flux to the upwind source area based on several key assumptions. These assumptions include that the upwind source area is homogeneous, flat and uniform, which in turn requires that horizontal gradients in CO_2 concentration are zero and that horizontal and vertical gradients in the covariance of CO_2 concentration and orthogonal wind directions are zero.

Work undertaken at the GA-CO2CRC Ginninderra controlled release facility, where CO_2 is released from the shallow subsurface (at 2 m depth), suggests that CO_2 leakage in the near subsurface will follow paths of least resistance up to the surface. Similar observations have been made at the ZERT facility in Montana and the CO_2 Field Lab in Norway. This leads to CO_2 leaks having localised, patchy surface expression, rather than a diffuse wide-scale leak which one typically expects (Lewicki *et al.* 2010). The implication of this is that the source area for a leak is highly inhomogeneous, meaning the magnitudes of CO_2 flux values measured using EC are grossly unreliable. These limitations were discussed in Leuning *et al.*'s (2008) review on CCS atmospheric monitoring technologies yet are not addressed in much of the recent EC leak quantification literature.

This presentation will present findings from the first subsurface release at the CO2CRC facility in Canberra (March–May 2012), where EC data was analysed for application in leak detection and quantification. The CO_2 release rate was 144 kg/d. Eddy Covariance was successfully used to detect the leak by comparing CO_2 fluxes in the direction of the leak to baseline wind sectors. Median CO_2 fluxes in the leak direction were 9.1 µmol/m^2/s, while the median background flux was 1.0 µmol/m^2/s. Separate measurements taken using a soil flux meter found that the daytime background soil flux had a median flux of 1.8 µmol/m^2/s but the peak soil flux over a leak was 1100 µmol/m^2/s.

Quantification and spatially locating the leak were attempted, but due to the problem of source area inhomogeneity, no substantive progress could be made. How an inhomogeneous source area contributes to 'lost' CO_2 from the system, through advection and diffusion, will be discussed, coupled with suggestions for how these parameters can be evaluated in future experimental design.

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02EGD-04. UNDERSTANDING OF THE GEOMECHANICAL STABILITY OF CO_2 CONTAINMENT AT THE SOUTH WEST HUB, WESTERN AUSTRALIA: A COUPLED GEOMECHANICAL–FLUID FLOW MODELLING APPROACH

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An area in the Southern Perth Basin has been selected as a potentially suitable site for CO_2 injection, due to its proximity to major CO_2 emission sources and the presence of potentially suitable geology. The project for the testing and proving up of the storage area is known as the South West Hub Project or SW Hub. New data acquisition in the area has included a 2D seismic survey in 2011 and the drilling of the Harvey-1 stratigraphic hole in 2012. This numerical modelling study attempts to assess the geomechanical stability of the reservoir seal couplet during CO_2 injection at the SW Hub. The stratigraphy and fault structure of the 3D model are based on the architecture of an E–W cross section using a 3D geological model by Langhi *et al.* (2013), which was based on available seismic reflection and geological data. A finite difference code (FLAC3D: Fast Lagrangian Analysis of Continua) was used for the current models, which is capable of simulating the interactions between rock deformation and fluid flow in porous media. The rocks and fault zones in the models are simulated as Mohr-Coulomb isotropic elastic-plastic materials. The involved constitutive parameters include shear modulus, bulk modulus, cohesion, tensile strength, friction angle, dilation angle, porosity and permeability. In the models, the geomechanical and hydrological properties for the reservoir and top seal stratigraphic units are based on experimental data from drill core samples from the Harvey-1 hole (Delle Piane *et al.* 2013). The data for other rock units in the stratigraphic sequences of the model were chosen based on rock types, information from the literature and new experimental data. A series of models were performed to investigate the effects of CO_2 injection on the geomechanical stability of the reservoir, with injection rates of 1, 2, 3, 4 and 5 million tons per year over a period of 20 years. The results show that the simulated CO_2 injection scenarios do not lead to the reactivation of faults or breach of the top seal in the area. Some small smooth uplifts have been observed as a result of CO_2 injection. In the models assuming weak faults, average surface uplifts are ~0.33, 0.56, 0.82, 1.05 and 1.29 cm for the injection rates of 1, 2, 3, 4 and 5 million tons per year, respectively, over an area of ~5 km diameter. Uplifts are marginally smaller when assuming strong faults. It should be pointed out that the present results are preliminary under certain assumptions of model properties and conditions, and future model refinement will be carried out.

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RESOURCES

02REA1 – MAGNETIC ANOMALIES AND GEOLOGICAL INTERPRETATION

02REA1-01. MAGNETIC MINERALS, PHASE INTERFACES AND MAGNETIC ANOMALIES

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Magnetic anomalies are deviations from a global internal magnetic field produced by interaction with planetary crusts. Anomalies are measured over many length scales and at elevations ranging from near surface to satellites. Crustal anomalies reflect the magnetic minerals, which to various degrees respond to the changing planetary magnetic field. Anomalies are influenced by the geometry of the geological bodies, and by the magnetic properties of the constitutive rocks.

Parts of the continental crust have preserved excellent magnetic memories for billions of years. Through time, continents travel over the world and some minerals remember where they originated. These magnetic mineral-memory systems survived harsh environments, preserving an earlier magnetic field, and also travelling the globe, while the external field changed in intensity and direction thousands of times. During all this geological action, some crustal rocks retained most "magnetic sectors" in their "hard disk", today create remanent magnetic anomalies reflecting the time and position of their initial acquisition of remanent magnetisation. The crust is strongly heterogeneous in rock types and oxidation states. Until recently magnetism of the continental crust has been described in terms of bulk ferrimagnetism of crustal minerals, and much of it due to induced magnetisation. During the course of studying remanent anomalies and the minerals responsible for them, a new interface-based remanence type, "lamellar magnetism" (LM), was discovered in rocks containing finely exsolved (microns to nm) members of the rhombohedral hematite–ilmenite series. Rocks containing LM commonly have a strong, or dominant remanent component to the anomaly.

Nature is not a clean system, and many magnetic oxides are not single phases. How do intergrowths affect the basic magnetic properties related to magnetic anomalies, such as NRM and susceptibility? In the last decade significant advances has been made on studies on oxide intergrowths in natural and synthetic samples and their effect on magnetic properties. When intergrowths, or exsolution lamellae, are present in the oxides, the effect on NRM values is significant, and hence the shape and intensity of the magnetic anomaly is significantly different than if the oxide were only a single phase. Here we explore the contribution of remanence and susceptibility from rocks dominated by oxides with exsolution, many with LM, including oxidation–exsolution, or reduction–exsolution, and explore the effects these intergrowths have on magnetic properties.

As we image deeper into the crust at higher resolutions, and study rocks, which have been deeper, we need to understand what magnetic minerals are present at higher pressure, and what happens with increasing temperature to oxides, and their exsolution lamellae. Many modellers have assumed that in deep-seated rocks few, if any, minerals are magnetic. Should we expect a magnetic signature from very deep in the crust? Here we present data on oxides from rocks, which have been subducted to depths of >100 km, presently exposed in the Western Gneiss Region of Norway, and discuss the effects of this subduction on the oxides, phase interfaces, and magnetic properties.

02REA1-02. PECULIARITIES AND PROBLEMS IN THE REMANENT MAGNETISATION OF RHOMBOHEDRAL Fe–Ti OXIDES

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Room-*T* remanent magnetism of rhombohedral Fe–Ti oxides depends on opposite sublattice magnetisations between alternate Fe-bearing layers parallel to the (001) basal plane. Pure Fe_2O_3 with equal moments would ideally be an antiferromagnet, but opposite sublattice magnetisations in (001) are a fraction of a degree from being 180^o apart, creating a weak “spin-canted” ferromagnetic moment, important in paleomagnetism, but too weak for significant remanent anomalies.

Strong remanent magnetisation commonly has two sources. In ordered metastable ferri-ilmenite solid solutions, Ti substitution in alternate layers causes unequal and opposite moments, and strong ferrimagnetism. Quenching and annealing from high-T toward order, brings the material through transitory states with antiphase domain microstructures causing magnetic self-reversal.

Fully ordered metastable ferrimagnets cannot survive slow cooling in deep-seated igneous and metamorphic environments, and will be replaced by ilmenite hosts with hematite exsolution lamellae (hemo-ilmenite) or hematite with ilmenite lamellae (ilmeno-hematite). Such mixtures of ilmenite, only antiferromagnetic below 57 K, and hematite, with canted antiferromagnetism, would not alone provide significant remanence. However, studies, beginning 2002, show there is a substantial remanent moment related to contacts between exsolution lamellae and hosts, produced by Fe-enriched single 'contact layers' parallel to (001), that reduce charge imbalance on phase interfaces. Such layers, with unusual Fe^{2+}–Fe^{3+} charge ordering, were first discovered in Montecarlo simulations, later supported by bond–valence arguments, DFT calculations, Mössbauer studies, and low-T exchange bias experiments.

Contact layers on both sides of a hematite lamella, or at both sides of an ilmenite lamella within a magnetised hematite host, have identical magnetic moments in the same direction, producing an 'uncompensated spin' in one direction. Translating these concepts to lamellae in hemo-ilmenite and ilmeno-hematite, brings out important contrasts in behaviour.

In an Fe–Ti ordered ilmenite host, initiation of a hematite lamella concentrates Fe^{3+} in a single cation layer, positionally uninfluenced by the magnetising field, but with a moment influenced by it. To demagnetise, or change remanence direction, the field only influences individual lamellae, not the surrounding ilmenite.

In an Fe–Ti disordered titanohematite host, initiation of an ilmenite lamella concentrates Ti^{4+} in a single cation layer with adjacent contact layers in a chemical position strongly influenced by the magnetising field, and its orientation with respect (001) of the magnetised host. With (001) oriented parallel to the magnetising field during exsolution, contact layers seek host positions compatible with the field direction, creating a strong lamellar remanence. With (001) normal to the magnetising field, chemical positions are not field-influenced, and remanence will be weak. The field influence on remanence intensity ('external force effect') will be strongly involved in an assemblage of titanohematite host grains with strong lattice-preferred orientation. To demagnetise, or change remanence direction, change in magnetic orientation of contact layers also involves magnetic reorientation of the surrounding host, therefore resulting in a very high coercivity.

Phase interfaces parallel to (111) of cubic oxides and (001) of rhombohedral oxides can also influence magnetic remanence, though is less well understood, i.e., oxidation–exsolution of ilmenite in magnetite, reduction–exsolution of magnetite in ilmenite, maghemite/magnetite in hematite.

02REB1 – MAGNETIC ANOMALIES AND GEOLOGICAL INTERPRETATION

02REB1-01. THE FIRST NATIONAL-SCALE MAPPING OF MAGNETISATION DIRECTION

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Much of Australia is covered with aeromagnetic data measured on flight lines at 400 m spacing or less, and from this data Geoscience Australia has compiled a national total magnetic intensity (TMI) map at 80 m cell size. We have applied to this grid a novel analysis, which adaptively clips the grid into rectangular samples, containing isolated field variations ('anomalies'). These samples are then analysed to recover an empirical estimate of their source magnetisation direction by using cross-correlations of invariants of the pseudo-gravity gradient tensor, the magnetic gradient tensor, and the original TMI image, using many test magnetisation directions. This analysis has the considerable advantage that it is not dependant on the spatial distribution of magnetisation (although the analysis is more accurate for compact magnetisations), and that the cross-correlation metrics are insensitive to uncorrelated noise. The analysis has already been proven successful on application to synthetic grids forward computed for specified magnetisations.

Application to the (8.3 GB) Australian national grid clearly poses much greater challenges. There are inevitably problems with inappropriate windowing of anomalies, which contain either multiple magnetisations, or only a part of an anomaly. In many cases such problems lead to a low value for the maximum cross-correlation score, which we use as a quality control or 'confidence' factor on a returned result. The national grid itself is sliced and projected into the seven UTM zones 50–56 (with a small overlap between each zone), and each is analysed separately requiring a few days of calculation on a multi-core personal computer. Each result returns a TMI image for the analysed anomaly, along with the relevant information such as the recovered magnetisation direction, local field, confidence etc. Each result is then viewable in Google Earth as a KML file. We are currently testing a selection of the some 50 000 anomalies analysed from the national grid against the initial 256 entries in the Australian Remanent Anomalies Database and from paleomagnetic studies.

This is the first national scale mapping of magnetisation direction that we are aware of. We expect to improve the quality of the solutions as we test and develop the method further. We are also developing new methods to analyse the results. In particular, we wish to map the extent of individual magnetisation events, but this is complicated by the fact that across any one area, rocks of quite different age and magnetisation direction may be found in close proximity, so that simplistic analyses such as local averaging are of limited validity. Nevertheless, we are confident that this first national map of magnetisation direction will lead towards new insights into the distribution of thermal events and structural rotations of the (substantially covered) basement rocks across Australia.

02REB1-02. GILES, COMPLEX, MAGNETISM

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Rocks from the Musgrave Block are mainly comprised of granulite facies quartzo-feldspathic metasedimentary and meta-igneous rocks, but also include a suite of layered mafic to ultramafic intrusions, known as the Giles Complex. The Giles Complex comprises peridotites, pyroxenites and gabbronorites, which collectively form one of the largest suites of this type on Earth. The geophysical characteristics of the Giles Complex are poorly known, but have received renewed interest since discovery of the Nebo-Babel Ni–Cu–PGE deposit.

Magnetic field data are a major mapping tool over this vast area of poor exposure. However, there are a multitude of challenges in understanding the magnetic expression of magmatic nickel sulfide systems. Variability in concentration and grainsize of pyrrhotite and magnetite determine the proportions of induced and remanent magnetisations in particular layers of layered igneous intrusions. Furthermore, remanence can be highly stable, lasting millennia, through to highly unstable, acquired at low temperatures in the present field, or during drilling. Some lithologies, e.g., Kalka Intrusion cumulates have >50% magnetite, associated with very high magnetic susceptibilities (e.g., >1 SI). However, remanence is very soft and held in multidomain magnetite. Others, e.g., Mount Harcus, have high intensity (up to 200 A/m) and very stable remanence in single domain magnetite. This stability is due to lamellar crystal structure caused when titanomagnetite exsolves into fine-grained intergrowths of magnetite and ilmenite at subsolidus temperatues and becomes ferromagnetic when the rock cools through 580°C. Pyrrhotite may also be the primary remanence holder in some circumstances, e.g., graphitic zones of the Pallatu Intrusion. Remanence in pyrrhotite is easily detected because ~95% remanent magnetisation is removed after heating to >320°C, the Curie point of pyrrhotite. Remanence in pyrrhotite is variably stable and can be associated with very high Koenigsberger ratios (up to 300). However, it can be easily remagnetised during moderate metamorphism, due to its low Curie point.

Many layered intrusions have complex architecture, and their magnetic anomalies commonly sit within complex background fields. Although the magnetic anomalies of layered ultramafics reflect bulk properties of the bodies, sharp contrasts in rock properties, and limitations of sampling, make calculating bulk magnetisations difficult. Some of these issues may be circumvented by using only the magnetic anomaly to determine magnetisation direction. An automated method was used to identify and cut out individual anomalies, based on a transformation of the magnetic field into a magnetisation map (an invariant of pseudo-gravity gradient tensor). Trial magnetisation directions were applied iteratively, to determine the optimal fit to each anomaly and the recovered total magnetisation direction (remanent plus induced) plus a jpg of the anomaly were then exported directly into GoogleEarth™.

The knowledge gained from rock magnetic studies can elucidate characteristic remanent magnetisation vectors for specific rock suites, which are integrated with automated techniques, to map mafic suites. The remote identification of specific mafic suites, based on their characteristic magnetisation directions can be used to refine areas that are prospective for magmatic Nickel PGE mineralisation.

02REC1 – RECONSTRUCTING PRECAMBRIAN GEOLOGICAL PROCESSES, PALEOGEOGRAPHIC AND GEODYNAMIC SETTINGS, AND ORE DEPOSITS

02REC1-01. FORMATION OF A 2.7 GA LARGE IGNEOUS PROVINCE BY PROGRESSIVE CRUSTAL CONTAMINATION OF TWO PULSES OF KOMATIITIC MAGMATISM: A LITHOLOGICAL AND GEOCHEMICAL STUDY OF THE AGNEW GREENSTONE BELT, KALGOORLIE TERRANE, YILGARN CRATON

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The *ca* 2.7 Ga Agnew Greenstone Belt (AGB), hosting significant gold and nickel deposits, is a ~3 km thick package of mafic to ultramafic rocks formed by two pulses of plume derived magmas, both of which were progressively contaminated by felsic crust. Our model is constrained using field, drillcore, element geochemical and geochronological data. Lithological and textural constraints indicate the paleoenvironment was a deep marine setting far from any landmass, where a number of subaqueous extrusive basaltic sheet and pillow flows, and komatiitic spinifex flows, as well as sub-volcanic sills, erupted onto or near to the ocean floor. Most mafic to ultramafic units are separated by thin (<0.5 m) mudstone and chert intervals. Compositional and lithological constraints indicate the belt consists of nine conformable mafic to ultramafic units that can be divided into an upper and lower sequence, with each sequence consisting of komatiite that is overlain by komatiitic and tholeiitic basalts. Based on new TIMS data, half of the stratigraphy was emplaced over *ca* 10 Ma and magmatism ended at 2690.7 ± 1.2 Ma. Assimilation and fractional crystallisation modelling demonstrate that compositions are consistent with derivation from one magmatic source (N-MORB-like) and that melts record overall increasing amounts of crustal contamination and crystal fractionation. The felsic contaminant is poorly constrained (modelled compositions include local sources and average Archean values from the literature) and crystal fractionation is consistent with a crystallisation sequence of Ol→Opx→Cpx→Pl. Taken together, the data are best explained by plume-derived komatiitic volcanism followed by stalling of komatiitic melts in the crust where assimilation, fractionation and homogenisation occur, generally at shallow crustal levels (<50 km) where plagioclase fractionation is possible. Episodic eruption from a few magma chambers leads to the emplacement of progressively contaminated and fractionated derivative melts. The AGB is an excellent stratigraphic and geochemical match with Ora Banda 260 km to the south. This research has important implications for the evolution of the Kalgoorlie Terrane and the origin of basaltic rocks associated with komatiites.

02REC1-02. A NEW PALEOMAGNETIC STUDY OF THE WARAKURNA LARGE IGNEOUS PROVENCE: THE GILES COMPLEX, MUSGRAVE RANGES, CENTRAL AUSTRALIA, AND EURO AREA, YILGARN CRATON, WESTERN AUSTRALIA

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A paleomagnetic investigation of the Mt Harcus intrusion, Giles Complex, Central Australia, has determined a mean paleomagnetic direction from 19 drill core intervals (3 to 6 core samples each) of Declination = 309.1°, Inclination = 56.5°, α_{95} = 5.0°, yielding a paleomagnetic pole of Latitude = 9.9°N, Longitude = 91.3°, A_{95} = 6.6° for the North Australian Craton (NAC). A similar, although smaller, investigation of the Earoo intrusion, Yilgarn Craton, Western Australia, has determined a mean paleomagnetic direction from 2 drill core intervals (2 core samples each) of Declination = 349.1°, Inclination = 49.9°, α_{95} = 8.1°, yielding a paleomagnetic pole of Latitude = 28.2°N, Longitude = 107.9°, A_{95} = 10.4° for the West Australian Craton (WAC). All directions are of reverse polarity (positive inclination). Both the Mt Harcus and Earoo intrusions are thought to belong to the *ca* 1.07 Ga Warakurna Large Igneous Province (WLIP) and the ~40° difference in declinations is analogous to the declination difference, that has been remarked on previously by several groups of workers, between the Alcurra Dolerite from the Musgrave Block (NAC) and the Bangemall Basin Sills (WAC).

Similarly, paleomagnetic results from the Kimberley (NAC) and Earaheedy groups (WAC), which are broadly coeval at 1.79–1.76 Ga, yield declinations that differ by ~40°. A third pair of poles from the WAC and the NAC displaying 40°

difference in declinations comprises those from the 755 Ma Mundine Well dykes (WAC) and the Walsh Tillite cap carbonate (NAC). Although the exact age of the latter is unknown, it is generally correlated with other *ca* 600 Ma Neoproterozoic postglacial cap carbonates but may be as old as 755 Ma. Further new evidence from other workers for the 770 Ma Johnnys Creek Member of the Bitter Spring Formation, central Australia (NAC), also provides support for the ~40° rotation, which more closely aligns the new pole with the 755 Ma Mundine Dyke Swarm pole (WAC). Therefore, three and maybe four pairs of studies provide evidence for a Neoproterozoic rotation between the Western Australian Craton (WAC) and the Northern Australian Craton (NAC). PepinNini and AusQuest provided the drill core for this study.

02RED1 – RECONSTRUCTING PRECAMBRIAN GEOLOGICAL PROCESSES, PALEOGEOGRAPHIC AND GEODYNAMIC SETTINGS, AND ORE DEPOSITS

02RED1-01. GENESIS OF THE CENTRAL ZONE OF THE NOLANS BORE RARE EARTH ELEMENT DEPOSIT, NORTHERN TERRITORY

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The Nolans Bore rare-earth-element (REE) deposit is located 135 km northwest of Alice Springs and has an identified mineral resource of 1.2 Mt rare-earth-oxide. The deposit is segmented into three sections; northern, central and southeast zones. The northern and southeast zones consist of northeast-trending, steeply dipping fluorapatite veins hosted in Paleoproterozoic orthogneiss. The central zone was defined in 2011 and is markedly different from the remainder of the deposit. It is a highly brecciated zone with a high content of allanite, which is enveloped by a broad, epidote dominated alteration zone.

The central zone mineralisation is hosted in schistose metasediments that lie below the gneiss that hosts the northern zone. The breccias were categorised into four types; type BX1 is similar to the fluorapatite veins found in the northern zone, while the BX2, BX3 and BX4 types are almost exclusive to the central zone, and are distinguished by brecciation and some amount of allanite infill. Apatite clasts in the BX2, BX3 and BX4 type breccias commonly include large (up to 2 mm) inclusions of allanite and occasionally monazite. REE-carbonate is also found as a late infill phase in BX3 and BX4 breccias.

Geochemical analysis reveals that much of the REE inventory in BX1 is hosted in fluorapatite. Brecciation and fluid alteration in the central zone caused recrystallisation of BX1 type apatite breccia to form (REE-rich) allanite and REE-poor apatite. BX1 type apatite has no Eu anomaly, whereas apatite and allanite in the BX2 and BX3 type ores, have significant negative Eu anomalies. This is due to formation of the surrounding epidote alteration zones that feature a large positive Eu anomaly. Where allanite and apatite are both present, the apatite is relatively depleted in light REEs while allanite is relatively light REE enriched, suggesting co-crystallisation. Furthermore, the phosphorus to REE ratio does not change between breccia types, suggesting that the REEs and phosphorus are locally recycled and distributed into the newly forming minerals.

U–Pb isotopic dating of thorianite (ThO_2) in the BX1 type apatite yields an estimated formation age of *ca* 1450 Ma. By contrast, Sm–Nd isotopic dating of the minerals within the central zone (allanite, apatite, thorite) yields an alteration age of 402 ± 13 Ma. This age is supported by *in-situ* U–Pb ages on BX4 monazite, and titanite from the epidote alteration zone, that also returned ages around *ca* 400 Ma. This data supports the hypothesis of alteration and recrystallisation of the central zone at a much later time than the deposition of the original fluorapatite veins. Furthermore, these dates correlate with shear activation events of the Redbank Shear Zone (1500–1400 Ma) and the Alice Springs Orogeny (450–300 Ma), indicating the Nolans Bore deposit served as an excellent recorder of regional deformation events.

Geochemical analysis of the alteration minerals suggests that the alteration fluid was highly acidic and reducing, with formation temperature between 450–800^{o}C, which is consistent with temperatures of the Alice Springs Orogeny of ~500^{o}C.

02RED1-02. GEOCHRONOLOGY AND LITHOSTRATIGRAPHY OF A MAJOR BIRIMIAN SEDIMENTARY BASIN: INSIGHT INTO THE TECTONOSTRATIGRAPHIC EVOLUTION AND GOLD MINERALISATION CONTROLS OF THE SIGUIRI BASIN, GUINEA (WEST AFRICA)

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In many gold district, it becomes apparent that the understanding of gold mineralisation occurrences strongly relies on our ability to integrate the tectonostratigraphic evolution underlying the early basin architecture of a given belt. The Siguiri Basin, in northeastern Guinea, is one of the biggest Birimian basins of West Africa and hosts one of the first gold producers from this region: the Siguiri district. Mapped as fine undifferenciated sediments of upper Birimian age, the Siguiri sediments actually display multiple mappable lithofacies visible on the field and in geophysical datasets. Three main sedimentary formations, predominantly striking N–S were identified in the Siguiri district and sampled for dating. The Kintinian is a >400 m thick formation that consists of a basal dark-brown shales with local intercalation of microcrystalline undifferentiated rock, overlain by a clast supported conglomerate. The basal conglomerate is in average about 100 m thick and shows polymictic clasts including limestone, shale, banded iron formation fragments, felsic volcanites and possible mafic clasts. The clasts are angular and poorly sorted suggesting a proximal origin. Unconformably overlying the Kintinian formation, the Fatoya formation consists of metric beds of medium to coarse-grained greywackes. Based on logged sections it is suggested that the Fatoya formation presents a minimum thickness of ~400 m. The contact between the Fatoya and the overlying Balato formation was not observed in drill-core. The Balato formation is dominated by centimetric alternations of shale–siltstone and fine greywacke. U–Pb dating was undertaken by SHRIMP II on detrital zircons from all three formations. Geochronology results show a large temporal gap in between the maximum ages of deposition between the stratigraphic top of the Kintinian formation, to the west, and the Fatoya and Balato formations, to the east. Collectively, the stratigraphic reconstruction and geochronological study of the Siguiri district, are indicative of a major N–S unconformity in the Siguiri Basin. Representing a fundamental flaw in the basin and crustal architecture, this N–S unconformity is regarded as acting a primary control on ore fluid migration leading to the formation of a world-class gold district.

02REE1 – MULTISCALE CHARACTERISATION OF ORE FORMING PROCESSES

02REE1-01. METAL RELEASE FROM BIOTITE DURING PROGRADE METAMORPHISM AS A SOURCE FOR Pb–Zn ORE DEPOSITS

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The majority of the world's largest Pb–Zn resources are in Mississippi Valley-Type or Sedimentary Exhalative deposits, where mineralisation is largely hosted by carbonate and siliciclastic sedimentary rocks. In most cases, the primary source of the metals and the importance of metal contents in the host lithology/protoliths remain poorly constrained. The mobility of Zn and Pb during metamorphism has been a point of debate in the literature (e.g., Ague 2011), but to date there is little consensus on the mechanisms or efficiency of element mobility during fluid flow.

Here, we present the first systematic study of Zn and Pb behaviour during prograde metamorphism on a mineral-, bulk rock-, and regional-scale. We examine psammitic to pelitic rocks from the high temperature/low pressure (0.3–0.5 GPa) regional metamorphic belt of the eastern Mt Lofty Ranges, South Australia. Our sample suite covers a range of metamorphic grades from greenschist facies (~350°C) up to migmatite grade (650–700°C), and so allows us to evaluate element loss during prograde metamorphism. There is no significant change in the concentration of most major and trace elements (e.g., Th, REE, HSFE, LILE) with metamorphic grade, but we do observe a significant decrease in Pb and Zn content with increasing metamorphic temperature, even when protolith variations are accounted for. Mineral composition analysis reveals that biotite host >80 % of the Zn in staurolite-absent metasedimentary rocks, and muscovite and biotite host considerable amounts of the rock inventory of Pb. Up-temperature flow of Cl-bearing fluid led to a continuous depletion of Zn (up to 75%) and Pb (up to 50%) on a mineral and bulk-rock scale during prograde metamorphism. A shift to heavy Zn isotope compositions with increasing metamorphic grade is also consistent with Zn dissolution by Cl-rich fluids.

Our results show that large Pb–Zn deposits can source their metal endowment from saline metamorphic fluids emanating from continental crustal sequences. In this case pre-metamorphic Pb and Zn enrichment would not be required for genesis of large sediment hosted Pb–Zn ore deposits.

Reference

Ague J J 2011. Extreme channelization of fluid and the problem of element mobility during Barrovian metamorphism. *American Mineralogist* **96**, 333–352.

02REE1-02. REGIONAL SCALE METASOMATISM IN THE HAMERSLEY BASIN: A 100 000 KM^2 FOOTPRINT?

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Mafic to intermediate lavas of the Fortescue Group form the lowermost stratigraphic unit of the 100 000 km^2 Hamersley Basin on the southern margin of the Archean Pilbara Craton, Western Australia. Superimposed on the regional burial metamorphic gradient, which extends from prehnite–pumpellyite facies in the north to greenschist facies in the south, are widespread zones of intense metasomatism. Hydrothermal alteration is focussed along lava flow tops, interpreted to represent zones of enhanced primary permeability. Metasomatism progressively produces a suite of pumpellyite–quartz/epidote–quartz-dominated assemblages. Whole rock geochemical data indicate that metasomatism is associated with significant depletions in the alkalis, Mg, and heavier first transition series metals (Mn–Zn, including Fe). Such mineralogical and geochemical trends have been documented in mafic rocks around the world where they are associated with the circulation of highly saline fluids derived from sea water. A similar fluid source is therefore inferred for the Fortescue group. Thermodynamic modelling of metamorphic and metasomatic mineral assemblages can reproduce a regional metamorphic gradient (210°C, 2 kbar in the north, 335°C, 3.2 kbar in the south). However, modelling for the metasomatised rocks indicate equilibration at the same pressure–temperature conditions across the basin (260–280°C, 2.5–3 kbar), equivalent to all samples being from approximately the same structural level. This implies that metasomatism occurred coeval with, or post-dating the majority of structural deformation in the Hamersley Basin, itself associated with the Ophthalmian orogeny. Ophthalmian folding provides an appropriate driving force behind regional-scale fluid flow across the Hamersley Basin. Previous studies have suggested a link between Ophthalmian folding, flow of a saline, surface-derived fluid and upgrading of the world-class iron ore deposits in the Hamersley Group, which overlies the Fortescue Group. We propose an extension of this fluid flow to the Fortescue Group, metasomatism of which includes widespread Fe loss and may have contributed a source of Fe to the iron ore deposits.

02REF1 – MULTISCALE CHARACTERISATION OF ORE FORMING PROCESSES

02REF1-01. MULTISCALE CONTROLS ON GOLD MINERALISATION AT PLUTONIC GOLD MINE, MARYMIA INLIER, WESTERN AUSTRALIA

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Plutonic Gold Mine (Plutonic) has a total endowment of ~10.5 Moz Au and is the largest gold deposit in the Plutonic Well Greenstone Belt of Western Australia. Hosted in amphibolite-facies Archean rocks (P_{max} = ~8 kbar; T_{max} = ~600°C), Plutonic is an example of a world class Au deposit with a long and complex mineralisation history. The mine sequence comprises predominantly metabasaltic rocks with thin, intercalated metasediments including cherts, shales and graphitic shales (locally termed the Mine Mafic Package). Gold is concentrated along boundaries between different mafic units and is often spatially associated with the metasediments.

Understanding the controls on Au mineralisation at Plutonic Gold Mine requires a multi-scale approach. Plutonic is located on the southern margin of the greenstone belt in a zone of complexity where large, regional-scale, structures intersect the over-thrust granite. At a more local scale, the hosting of the deposit within the Mine Mafic Package, overlain and underlain by ultramafic rocks, provided an ideal rheology contrast between the more ductile ultramafic rocks and the more brittle mafic rocks to focus Au-bearing fluids through this unit. Within the Mine Mafic Package, portable XRF data demonstrate that the primary mafic stratigraphy focussed these Au-bearing fluids along mafic unit boundaries and both through and adjacent to the intercalated metasediments.

A large number of high-grade lode samples from across Plutonic were analysed by a variety of techniques, including PIXE (Proton-Induced X-Ray emission microprobe), microprobe, X-ray fluorescence mapping, and scanning electron microscopy (SEM-EDS) analyses. Micro-scale characterisation of high-grade samples reveals calc-silicate (epidote–clinozoisite) alteration that is not present in lower-grade samples, and that sulfides are less abundant close to the

Au. The replacement of biotite by chlorite is also a key alteration associated with the high-grade Au-mineralising fluid. Gold is coarsest where Au particles are located on the margins of sulfide and quartz grains, as well as inclusions within quartz, suggesting the importance of a rheological contrast at the microscale. Deposition of Au is interpreted to be related to an overpressured hydrothermal fluid circulation event late in the geological history of Plutonic as at all scales visible Au cross cuts and often brecciates other minerals and textures.

Understanding how a deposit such as Plutonic formed requires key evidence at a variety of scales from disparate datasets, and the integration of these data to form a genetic model that is robust at all scales.

02REF1-02. QUARTZ GEOCHEMISTRY IN ORE GENESIS; MERLIN (MO–RE), CLONCURRY

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Quartz is a common gangue mineral in hydrothermal ore deposits. It occurs commonly throughout the paragenetic sequence, allowing insight into the temporal and geochemical changes of ore genesis. The Merlin (Mo + Re) deposit examined in this study lies within the Proterozoic Eastern Fold Belt (EFB) of the Mount Isa Inlier, Australia. The ore body is a geochemically unique, fault breccia-hosted high-grade deposit on the fringe of the Mt Dore IOCG characterised by potassic, silicic, and propylitic alteration zones. The variation in hydrothermal quartz of Merlin was studied using Scanning Electron Microscope (SEM), SEM – Cathodoluminescence (SEM-CL), and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) techniques to give insight into the geochemical components and formational conditions and constraints. Three distinct quartz generations were identified. Phase one quartz was chemically rounded, classified by a moderate SEM-CL response, high Ti (7.2ppm μ, σ 1.8), distinct and clustered Ge (0.53 μ, σ 0.06) but low Al + Li. Phase two quartz post-dated and rimmed phase 2 quartz, displaying a high SEM-CL response with a distinctly high Al + Li but low Ti LA-ICP-MS response. Charge balance calculations suggest this quartz phase was formed by a highly acidic fluid. The third generation of quartz overprinted both phases with a distinctly low SEM-CL response that deported to low to below detection Al + Li + Ge, and moderate Ti (3.2ppm μ, σ 2.0). The Ti in quartz geothermometer indicated that phase 1 quartz formed at 415 ± 16°C and phase 3 quartz 383 ± 21°C at 0.5 kbar. Fluid inclusion studies of the generations of quartz distinguished a high temperature >500°C multi-solid saline fluid in quartz 1. Laser-Raman spectroscopy identified that the multi-solid inclusions contained ferropyrosmelite, a mineral commonly found in other Cloncurry IOCG-related fluid inclusions, indicating a similar origin for phase 1 quartz cores. Phase 3 quartz fluid inclusions were low salinity (4.3 ± 0.3 NaCl wt% equiv.) with a temperature of 385 ± 3.8°C. These fluid inclusions were undergoing a phase transition quartz deposition, based on the presence of intermixed vapour-rich and fluid-rich inclusions. Micro-molybdenite inclusions and a spatial relationship of phase 3 quartz to large molybdenite grains indicate this is representative of the ore formational Merlin hydrothermal fluid. Overall the quartz geochemistry describes an early IOCG-like >500°C fluid that evolved to a highly acidic state to partially dissolve quartz, and then further evolved to a lower temperature hydrothermal fluid with a variable physicochemical state. Fluid inclusion evidence suggests this fluid underwent a phase transition and condensation to a moderate temperature, ~385°C, low salinity, low trace element formation fluid that was directly related to ore formation. This captured hydrothermal evolution of the Merlin deposit is revealed in the variation in quartz geochemistry, allowing an exceptional understanding of the paragenetic and geochemical conditions of the unique deposit.

02REF1-03. TECTONO-STRATIGRAPHIC EVOLUTION OF THE SADIOLA GOLD CAMP, MALI, WEST AFRICA: DEFINING THE FRAMEWORK OF A WORLD-CLASS GOLD PROVINCE

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The Sadiola Hill gold deposit (~8.5 Moz) and ancillary pits are located in the emerging world-class Kédougou-Kénieba Inlier, a window of deformed Paleoproterozoic volcano-sedimentary rocks along the Mali-Senegal border. Gold deposits within the camp exhibit two distinct styles of mineralisation on the basis of different ore parageneses, nature and chemistry of wall-rock alteration. Au–As–Sb mineralisation at Sadiola Hill has characteristics typical of mesozonal orogenic gold deposits. In contrast, the Fe–B–REE–P-rich Alamoutala deposit shows field relations and mineralogical features atypical for Birimian gold mineralisation, which could indicate a strong hydrothermal influence from surrounding granodiorite stocks. Using a combination of field mapping together with geochronology

and litho-geochemistry, we show that the geological evolution and associated mineralisation in the Sadiola camp is controlled by the regional-scale Senegal-Mali Shear Zone and subsidiary structures. The terrane-bounding structure juxtaposes two domains different in nature. The western domain partially outcrops within the Senegal-Mali Shear Zone and consists in intermediate porphyritic metavolcanics and lava flows of andesitic to dacitic composition. The eastern domain consists in a sequence of shelf carbonates, distal turbidites and metapelites interpreted to represent a fore-arc environment deposited between *ca* 2150 and 2125 Ma. Following the deposition of the sedimentary succession, the polycyclic deformation history documented in this study is characterised by early thrusting tectonics and terrane accretion followed by strike-slip sinistral shearing under progressive NW–SE compression. Gold endowment in the Sadiola district is associated with that strike-slip dominated system during the late Eburnean tectono-magmatic history. Sinistral kinematics locally coeval with intrusion of *ca* 2090 to 2060 Ma granitoid plutons can be use to explain the diverse nature of gold mineralisation over the camp.

02REF1-04. THE TIMING AND CONTROLS ON THE FORMATION OF THE YANDERA DEPOSIT

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The timing of hydrothermal alteration and associated porphyry mineralisation at Yandera was investigated using $^{40}Ar/^{39}Ar$ geochronology. The furnace step heating method was employed to allow multiple argon populations to be identified and analysed. Samples containing the various alteration assemblages associated with mineralisation at Yandera were collected from drill core. The results showed that partial resetting of the argon population had been caused by the movement of hydrothermal fluids. Therefore maximum ages rather than definitive ages could only be obtained due to the presence of older argon populations. The maximum ages interpreted to represent the different alteration assemblages were all within error of each other, suggesting that the porphyry mineralisation at Yandera formed as a result of one hydrothermal system or several hydrothermal systems operating simultaneously over a short time period, not several temporally distinct events.

The ages obtained for the hydrothermal system at Yandera are about 3–4 Ma younger than all of the U–Pb ages obtained from zircons by Dr Malcolm Roberts from magmatic rocks in the deposit area. This shows that the magmatic bodies observed at the surface or in drill core are not the source of the fluids responsible for mineralisation. The short time period of mineralisation and the volume of fluid involved suggests that a burst of fluid from a magma source located at depth, younger than the magmatic bodies observed, was responsible for the formation of the deposit. Magmatic activity outside the deposit area, ductile deformation and metamorphism within regional structures were all also found to be older than the age of mineralisation. Hence, it was concluded that the surface geology, except younger brittle structures, which were not dated by argon, was largely irrelevant to the formation of the deposit. The source and movement of fluids appears to be key.

02REA2 – OPTICAL SENSING FOR ADVANCED MINERAL CHARACTERISATION FOR EXPLORATION AND MINING

02REA2-01. APPLICATIONS OF VISIBLE AND NEAR INFRARED SPECTROSCOPY IN STUDIES OF METAMORPHIC AND HYDROTHERMAL SYSTEMS

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The last twenty-five years have witnessed revolutionary advances in field, lab, and remote sensing applications of visible and near infrared (Vis/NIR) methods in support of mineral exploration. In contrast, only a few studies have focused on regional and contact metamorphic environments. Rather than distinct processes, metamorphic and hydrothermal systems should be viewed as part of a continuum. Conceptually, the metamorphic end member represents a rock-dominated system with close approach to thermodynamic equilibrium; mineralogical variation is a function of P, T, and bulk composition (X), and the spatial scale of variation approaches 10^3–10^4 meters. Conversely, the hydrothermal end member represents a fluid-dominated system with only localised approach to equilibrium; mineralogical variation is a function of the temperature, composition, and time-integrated flux of external fluid as well as the buffering capacity of local wall rocks, and the spatial scale of variation is on the order of 10^{-3}–10^3 meters.

Two mineralogical systems that are important in both hydrothermal and metamorphic environments and which are conducive to Vis/NIR mapping methods will be discussed: (1) compositional variation in potassic white micas, and (2) mineral distribution in metamorphosed impure carbonate rocks which include skarn deposits.

In potassic white micas (muscovite, illite, sericite, phengite) the dominant absorption feature near 2200 nm shifts as a function of octahedral cation substitutions as approximated by the alumino-celadonite exchange, $^{IV}Si + ^{VI}(Mg,Fe^{2+}) = ^{IV}Al + ^{VI}Al$. Studies of white mica in medium *P/T* metamorphic systems (<10 kbar) are consistent with largely *T* dependence. Wavelength decreases (Al increases) from 2225 nm (lower greenschist, ≤300°C) to 2195 nm (upper amphibolite, ≥650°C). However in high *P/T* metamorphic settings (15–25 kbar), blueschist and eclogite samples have wavelengths of 2225–2235 nm consistent with low-Al, phengite-rich micas. Compositional dependence (bulk composition and mineral assemblage) remains uncertain in both the medium *P/T* and high *P/T* series.

In contrast to regional metamorphic systems, spatial variation in white mica wavelength and composition in hydrothermal environments is complex; almost the entire wavelength range of medium *P/T* metamorphic systems may be found at the scale of a single deposit (e.g. 2192–2222 nm). Most systems that have been investigated are low *P* (<2 kbar) and relatively low *T* (<350°C). Consequently, variations in mica wavelength and composition are probably not dominated by *P* or *T* variation, but are more closely linked to the evolution of fluid composition in response to fluid–rock reactions with variable host lithology.

Vis/NIR applications in metamorphosed impure carbonates include studies of contact aureoles and skarn deposits. Spectrally identifiable minerals include calcite and dolomite along with phlogopite, talc, tremolite, humites, serpentine (retrogressed forsterite), and brucite (retrogressed periclase), and skarn minerals such as Ca-garnets, epidote, prehnite, scapolites, and vesuvianite. Vis/NIR spectra provide a potential indicator of the degree of hydration of the rocks that may delineate infiltration fronts or pathways of fluid flow; these boundaries may also be recognised by subtle reflectance increase (bleaching fronts) where infiltrating fluid has oxidised reduced organic carbon in carbonates.

02REA2-02. TOWARDS QUANTIFYING LATERITIC NICKEL COMPOSITION: APPLICATION OF REFLECTANCE SPECTROSCOPY

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Quantification of the composition of lateritic Ni deposits using traditional techniques, such as X-ray diffraction (XRD) analysis, is difficult because of their varied mineralogy and compositionally complex nature, which can see the distribution of economic (e.g., Ni) and gangue elements (e.g., Mg and Si), associated with a number of phases, such as Fe/Mn-oxides and hydrous Mg-silicates. Reflectance spectroscopy is now an established technique for mineral exploration and ore characterisation. The mineralogy of most lateritic nickel deposits show strong and distinctive absorption features in the 400–2500 nm visible-near infrared (VNIR) and shortwave infrared (SWIR) wavelength ranges. Hence, the main objective of this work was to demonstrate the suitability of reflectance spectroscopy for lateritic nickel characterisation, and in particular, establish a link to the factors causing elevated Ni and Co values in iron oxides (mainly goethite) of the "yellow laterite' horizon from the Vivaneau-Thiébaghi deposit, New Caledonia.

Powdered material of 87 composite samples of "yellow laterite" from selected diamond drill core were measured using CSIRO's HyLogging™ system and analysed using partial least squares (PLS) analysis for quantitative prediction of the mineralogy and composition of the "yellow laterite" Ni ore. This statistical process provides a means of assessing the relationship between a set of spectra and an assayed value, such as Ni %. The most important wavelengths regions include the large 1900 nm feature that is related to adsorbed water (on goethite). The depth of the 1900 nm feature decreased with sample depth, that is, deeper samples showed the smallest 1900 nm water feature. A PLS model using 12 factors was generated to predict the wt% Ni content in the yellow laterite with an r^2 of 0.702, which was statistically significant for the 87 samples examined. The weight percent Al_2O_3 content could also be predicted with 9 factors with an r^2 of 0.827, based on the depth of Al–OH absorption feature at about 2200 nm. Estimates of the weight percent Fe_2O_3, Cr_2O_3, SiO_2 and Co were also statistically well predicted.

A combination of reflectance spectroscopy, chemical composition and PLS was demonstrated as being a valuable approach to predict the chemistry and also to identify wavelength ranges and, therefore, the mineralogy associated with these predictions. This method, applied to Vivaneau-Thiébaghi powdered drill chips, could be extended to other lateritic nickel deposits with the goal of routinely predicting chemistry from the spectra of powders or drill chips. The method could also assist geologists to recognise specific rock types by matching reflectance spectra of unknown samples to reflectance spectra of samples with well-characterised mineralogy.

02REB2 – OPTICAL SENSING FOR ADVANCED MINERAL CHARACTERISATION FOR EXPLORATION AND MINING

02REB2-01. VIBRATIONAL SPECTROSCOPY OF CALC-SILICATE MINERALS AND ITS POTENTIAL IN MAPPING LOW-GRADE REGIONAL METABASITES

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The calc-silicate minerals epidote, prehnite and pumpellyite constitute major component of low-grade, regionally metamorphosed mafic rocks. They also commonly form through hydrothermal alteration of mafic rocks, including in the formation of ore deposits where their presence and/or composition can be a useful exploration indicator. Here, we examine epidote, prehnite and pumpellyite in a range of pure and mixed mineral samples, with X-ray diffraction (XRD), electronprobe microanalyses (EPMA) and Fourier transform infrared spectroscopy (FTIR). Hydroxyl group stretching fundamentals, ν(OH), were investigated in the mid infrared (MIR) range in conjunction with their first overtones, 2 ν (OH), in the short wavelength (SWIR) region.

Epidote exhibits a strong correlation between EPMA composition, crystal lattice parameters, as determined by XRD, and the wavelength positions of single ν (OH) and 2 ν (OH) features at around 2970 nm (3367 cm^{-1}) and 1550 nm (6452 cm^{-1}) respectively. These features shift towards shorter wavelengths with increasing Fe content, in agreement with previous studies. Pumpellyite displays four distinct ν (OH) and 2 ν (OH) features in the ranges 2750–3450 nm (3000–3635 cm^{-1}) and 1415–1512 nm (6615–7065 cm^{-1}) respectively. Four of these eight features display a weak correlation with EPMA composition, particularly Mg content: 'C'–ν(OH) at around 3160 nm (3165 cm^{-1}), 'D'– ν (OH) at around 3330 nm (3003 cm^{-1}), and 'd'–2 ν (OH) at around 1512 nm (6614 cm^{-1}) all shift towards shorter wavelengths with increasing Mg content. 'b'–2ν(OH) at around 1430 nm (6993 cm^{-1}) shifts in the opposite direction. Prehnites exhibit strong ν (OH) and 2 ν (OH) features at 2860 nm (3497 cm^{-1}) and 1477 nm (6770 cm^{-1}) that show no resolvable change in position over the available compositional range.

The identification of calc-silicate minerals by infrared spectroscopy enables mapping of metamorphic grade and zones of hydrothermal alteration over a large area. Mixed mineral samples in this study are from the Fortescue Group volcanics, Hamersley Basin, Western Australia. Regional metamorphic grade increases across the Hamersley Basin from prehnite–pumpellyite facies in the north to greenschist facies in the south. Across the basin, pumpellyite typically occurs in lower grade metamorphic zones than epidote, which becomes more dominant and progressively more Fe-poor in composition as grade increases. Prehnite and pumpellyite also occur in distinct zones of widespread metasomatism. Infrared spectral analysis of geographically distributed samples, using the ν (OH) and 2 ν (OH) features described above, successfully reproduced the observed mineralogical and compositional variations across the basin. The identification of diagnostic spectral features for epidote, pumpellyite and prehnite has important implications for mapping the distribution of these minerals in other low-grade mafic terranes. This is particularly useful in regard to defining zones of hydrothermal alteration, which may in turn be related to hydrothermal ore deposits.

02REB2-02. HOW HYPERSPECTRAL SENSING IS IMPROVING PRODUCTIVITY IN BHP BILLITON IRON ORE EXPLORATION

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Drill-hole logging in BHP Billiton Iron Ore Exploration is still a very manual process, completed by geologists in the field using their eyes and some basic tools. This delivers inconsistent and subjective results of which the quality is dependent on the geologists' experience. In 2009, the exploration team started trials with the collection of visible-near to shortwave infrared spectroscopic data (IRS data) for diamond core and rock chip drilling samples, with the primary aim of understanding how IRS data can assist with drill hole logging and prediction of metallurgical parameters. Five years on and the collection of IRS data has become standard practise across its Iron Ore Exploration Business.

IRS data are collected by a commercial laboratory and processed into pre-defined spectral parameters. These include depths, widths and minimum wavelengths of absorption features. This process compresses the data volume, improving handle-ability of the single drill hole and/or deposit scale datasets. A set of algorithms is pre-loaded to the primary database, which combines these spectral parameters with each other and/or with other available datasets (e.g. geochemistry) into mineralogy. Mineralogy is made available to every geologist in BHP Billiton iron ore as part of their standard log views in 1D, 2D and 3D. Some of the strengths of hyperspectral mineralogy include reliable quantification of hematite, goethite and goethite subtypes, as well as differentiation of clays (kaolinite–white mica–smectite). These products are proving valuable for geology modelling, including delineation of the base of hardcap, identification of the detrital-bedrock boundary and development of a high quality, lithology based model of detritals.

The lithology based detrital model is especially significant for mine slope design through detrital units. Up to now, geotechnical engineers had to rely on stratigraphy based detrital models to extrapolate local rock strength measurements to the entire detrital package. A large portion of the variability of detrital units is captured by variations in the mineralogy obtained from IRS data, allowing for more accurate and consistent detrital models that provide objective information to improve mine slope design.

At present, BHP Billiton Iron Ore Exploration is investigating the collection of IRS data on all of its sample pulps. Early indications are that IRS data collected on pulps deliver more accurate and repeatable mineralogy results, as well as improving the prediction of metallurgy parameters.

The envisaged future end state for hyperspectral sensing in BHP Billiton iron ore would encompass collection of IRS data, not only during exploration, but also during mining. Data collected during mining could include blast hole logging (ideally down-hole), mine face scanning and/or airborne hyperspectral scanning. The mineralogy based model that is created as a product from exploration, would be automatically updated as the data from mining come in, allowing real-time optimisation of the mine plan, the blast pattern and the processing plant, based on the mineralogical/metallurgical characteristics of the ore that is being excavated.

02REB2-01. SOUTH AUSTRALIA'S HEAVY MINERAL RESOURCES: MODELS, GEOLOGY AND EXPLORATION OF DEPOSITS

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Heavy mineral deposits are the principal source of several industrial minerals, including the main source of titanium feedstock for the titanium dioxide pigments industry, the principal source of zircon, and other heavy minerals produced as byproducts such as garnet, sillimanite/kyanite, staurolite, and monazite. Source rocks that contain heavy minerals are weathered and eroded, from which the detritus composed of sand, silt, clay and heavy minerals is contributed to fluvial systems. Streams and rivers transport the detritus to the coast, where it is deposited in a variety of coastal environments. The sediments are reworked by the actions of waves, tides, longshore currents, and wind, which are effective mechanisms for sorting the mineral grains based on differences in their size and density, resulting in forming laminated or lens-shaped packages of sediments several and even up to tens of metres thick that are rich in heavy minerals.

Most SA’s economic heavy mineral deposits, including numerous Paleogene and Neogene deposits, are distributed in the western (Eucla Basin) and eastern (Murray Basin) regions. The size of heavy-mineral deposits can be voluminous. Individual bodies of heavy mineral-rich sands are typically about 1 km wide and more than 5 km long. Many heavy mineral sands districts extend for more than ten kilometres, encompassing several individual deposits spreads along ancient (e.g., eastern Eucla and Murray margins) strandlines. On-going research seeks to predict more places where placer and other deposits might be located.

Knowledge of the Mesozoic and Cenozoic basin architectures and any sources of heavy minerals accumulated in the paleoshorelines and paleovalleys is important in the exploration for heavy mineral resources and is also of interest as guides to the location of potential deposits in the greenfield exploration areas. Evidence from sedimentology is combined with that of other geological and geophysical characteristics to arrive at a general reconstruction of basinal and paleovalley architectures and depositional environments.

Regional exploration for heavy mineral deposits can utilise: (1) sediment sampling (analysing for Ti, Hf, rare earth elements, Th, and U); and (2) remote sensing and geophysical surveys. Geophysical anomalies may be small, and surveys are generally more successful when conducted close to sources of interest. The major refinements in remote sensing and geophysical techniques, data processing, sedimentology and computer-aided interpretations are today providing an effective, economic and efficient model for exploring these highly prospective province and terrains. The most successful procedure for defining the paleoshorlines is to combine imagery and geological and geophysical methods to yield architectural and evolutional models of shoreline development. Geoscientific datasets have been integrated in an investigation of these Mesozoic and Cenozoic basins and peripheral paleovalleys that once drained the Gawler Craton, Musgrave and Curnamona Provinces as well as the Officer Basin and that have significance to heavy minerals exploration by incorporating the whole mineral system from, source, and transport pathways, to trap sites, upgrading and preservation.

02REB2-02. MAPPING ALTERATION MINERALS AND STRUCTURAL FEATURES ASSOCIATED WITH IOCG MINERALISATIN FROM ASTER DATA: A CASE STUDY IN THE SAVEH AREA, CENTRAL IRAN

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The Saveh area, located in the main volcanic arc of central Iran, is an important green field district for iron oxide copper–gold (IOCG) mineralisation. The vein-type IOCG mineralisation is mainly controlled by WNW-trending structures, silicification, brecciation and specular hematite occurring at the contact of Oligocene–Miocene felsic intrusion and Eocene basaltic andesite. In this study, Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) data of some 1500 km^2 in the Saveh area were evaluated to detect elements directly or with proximity associated with IOCG mineralisation. The laboratory spectra of the field alteration samples, from the known IOCG prospects, were combined with the mineral spectra of the USGS library and used for spectral analysis. Spectral angle mapper (SAM), least square fit (Ls-Fit) and band ratio methods were employed for mapping the key alteration minerals. Kaolinite, illite, chlorite and epidote were mapped by the SAM and Ls-Fit methods, using the short wave infrared (SWIR) bands of the ASTER multi-spectral data. Hematite and silica alteration were mapped by applying certain band ratios to the visible near infrared (VNIR) bands and the thermal infrared (TIR) bands, respectively. The linear and circular structures were also mapped from the high-resolution true colour composite image of the VNIR bands. The mapped fault lineaments, displacing Eocene to Quaternary rock units, were mostly trending in WNW and NE directions. The WNW-trending faults were interpreted as reverse dextral strike-slip faults and the NE-trending faults as reverse sinistral strike-slip faults. These faults have been active, resulting in triggering a couple of historical and instrumental earthquakes in this area. The mapped kaolinite and illite minerals mostly followed the circular structures along the contact the felsic intrusions, while the silica alteration and hematite mostly located along the WNW-trending strike-slip faults occurring at the contact of felsic intrusions and basaltic andesites. Due to the low spatial resolution of the TIR bands, the quartz veins, hosting known IOCG mineralisation, were not mapped. Whereas, the high spatial resolution of VNIR bands were helpful to map the hematite, directly associated with the known IOCG mineralisation. The mapped hematite in the known mineralised areas were mostly surrounded by kaolinite, illite and chlorite. On the basis of the recognition criteria of the known IOCG mineralisation, the identified favourable alteration minerals and structural features were combined by host lithologies and used to locate and rank several unknown copper–gold targets for follow-up exploration.

02REC2 – THE 3RD NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM

02REC2-01. There and Back Again: A Mineral Habit's Tale

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Infrared drill core imaging introduces large data volumes to the assessment of geological projects. The data provides high spatial detail, at millimetre scale, of mineral contents, textures and associations. However, high spatial resolution data needs to be utilised across various scales in a project. The challenge presented is thus to maintain

the integrity of information generated at the millimetre scale when considering the data across projects at metres to hundreds of metres, and even kilometre scales.

Other than mineralogical data, additional information can be extracted from image data of the drill core. The image data provides information on the quality/condition of the drill core for evaluation in a project. In addition to this, the consistency of depth measurements can be reviewed to understand the depth scale accuracy prior to the integration of additional data sets. With further processing, mineralogical indices can be extracted for the different minerals identified.

When compared over intervals, these data volumes promote a statistical approach to the analysis, review and presentation of the data. Statistical measures can be used to plot changes in mineralogical composition or crystallinity. Foliation and fabric information can be integrated with the mineralogy derived from the spectral data, and all of these types of information can be combined with mineralogical signatures and parameters to better identify or classify rock types. Similarly, lithology bands can be reviewed and extracted using the combined textural and mineralogical patterns. Statistical comparison of data can again be considered across different lithological units or bands. In the same fashion, the statistical comparison of vein types, assemblages, and compositions is also possible using spectral imaging data. Applying these techniques requires a shift from reviewing data across an interval level to considering the data, on a smaller scale, as objects in the core imagery.

When using hyperspectral data on drill core, the challenge remains working with extensive volumes of data. However, rather than being an issue of data management, the challenges are being encountered in data extraction, utilisation and presentation of the information. Now that datasets for various projects are available, where information and knowledge extraction are possible, the interpretation of the data is allowing us to reverse the typical core imaging process (data to information to knowledge). We are able to better understand the type of knowledge that is required from the data, which in turn drives requirements on how and what information extraction is required. This ultimately leads back to the data generation, where we can start to define the instrument and acquisition parameters necessary to achieve the desired knowledge. Slowly we are starting to see the requirements for core imaging being driven by the result requirements rather than the technology development.

02REC2-02. MAXIMISING THE VALUE OF NVCL HYLOGGER DATA: UNDERSTANDING AUTOMATED MINERALOGICAL INTERPRETATION

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Since the inception of the AuScope NVCL initiative in 2007, more geoscientists are accessing and assimilating HyLogger™-generated data into their projects. For the first time, high-resolution spectral datasets and drillcore imagery from diverse environments are readily available to geoscientists from widely varying backgrounds, ranging from researchers to explorers. Most geoscientists will access the automated HyLogger outputs using The Spectral Geologist (TSG™) software, which includes tools to model the spectral response to a mineral (or mineral mix) using an inbuilt library of pure mineral spectra. This returns a mineral mix result for each 8 mm section of drillcore, for the whole drillhole.

The HyLogger typically measures tens of thousands of spectra in each drillhole, across 872 channels in the Visible and Near Infrared, Shortwave Infrared and Thermal Infrared wavelength ranges. This generates voluminous datasets that are usually interpreted using an unmixing algorithm in TSG, called The Spectral Assistant (TSA™), which offers a mineralogical interpretation. The value lies in the high spatial resolution and the speed with which data are acquired, integrated and interrogated using the TSG software. TSA is a good tool to gain a quick overview of the bulk mineralogy within a drillhole and to map mineralogy and lithological changes in conjunction with high-resolution imagery. Other analytical techniques (such as XRD and petrography) usually only give detailed mineralogical information from specific sample sites (unless composited), whereas the HyLogger gives continuous semi-quantitative mineralogical information from the mid-section of the entire drillhole.

How well do geoscientists understand these HyLogger datasets and TSG products, particularly the different confidence levels that can be attributed to 'system' generated mineral products (automated spectral interpretation) compared with 'user' processed datasets? As with all data outputs (such as XRD results) a lack of understanding of the accuracy or precision associated with the mineral output may limit the geoscientist's faith in the value of the data in the TSG dataset.

Factors influencing the confidence level of a mineral match in a TSG dataset include:

- The quality of the input spectra as influenced by the quality of the core.
- Whether the TSG dataset has had any processing done (ie editing TSA to exclude infeasible/unlikely minerals from the modelling).
- Whether scalars (ways of targeting specific spectral parameters such as abundance or composition) are incorporated in the mineral interpretation process to validate the TSA interpretation.
- Whether the processing included spatially subsetting the spectra into mineralogically distinct domains to allow greater control in excluding geologically infeasible minerals.
- Whether the TSG results have been validated using an external analytical technique, such as XRD.
- Whether the user understands the methods and processes that led to the mineral output.
- Whether the processing steps are well documented.

Our aim is to increase a wider understanding of the methods and processes behind the mineral outputs from TSG and to assist geoscientists to use HyLogger datasets with confidence.

02REC2-03. SKARN STYLE ALTERATION & INVERSION MODELLING AT RED LAKE, SOUTH AUSTRALIA

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Spectral reflectance characteristics of skarn style alteration have been recognised in historic drill core from Red Lake on the Stuart Shelf, South Australia. The aim of the study was to identify a vector towards a possible igneous heat source for the skarn alteration, a region in the system that will potentially contain mineralisation. Modelling of geophysical data sets was used to complement the investigation into the spatial trends in mineralogy determined by spectroscopy. The area covered within this paper is situated within the southwestern quadrant of a regional scale gravity and magnetic inversion.

A series of open file drill cores were scanned using the HyLogger™ 3-3 instrument, and published through SARIG web site. The instrumentation rapidly measures drill core using infrared reflectance spectroscopy, and high-resolution linescan digital imagery. The spectral range includes 380–2500 nm (visible and short wave infrared, VSWIR), and also 6000–14500 nm (thermal infrared, TIR). Reflectance spectroscopy can identify a range of different minerals, from iron oxides in the visible wavelengths, through to clay mineral and carbonate species in the SWIR and tecto-silicates in the TIR. These minerals are important for identifying the alteration haloes surrounding skarn style mineralisation.

Skarn style alteration identified using HyLogger™ 3-3, included VSWIR minerals – goethite, hematite, chlorite, epidote, talc, amphibole and carbonates. The TIR identified prograde skarn assemblage of pyroxene and garnet along with a retrograde assemblage of epidote, amphibole, talc and K-feldspar in drill holes SAR 8 and SAR 9.

The cell size used for this geographically constrained gravity and magnetic inversion was 125 X 125 X 120 m. The inversion was completed using observed data from the DMITRE open file gravity database, and open file TMI airborne magnetic data. This data was upward continued to one vertical cell size (120 m).

The model of physical property distributions (magnetic susceptibility and density), was unconstrained from geological information.

A 3D plot of regions consisting of both high density and high susceptibility was produced. The depth extent of these regions ranged from approximately 500 m down to the base of the inversion model at 5240 m. Geologically, these regions are located within the Gawler Range Volcanics, Wallaroo Group and Donnington Suite.

The two drillholes SAR 8 and SAR 9 both penetrated the high susceptibility region and extended into the high-density region at depth. This correlates with the distribution of skarn minerals observed in the HyLogger data. Drillhole SAR 7 appears to have been terminated, approximately 140 m above the high susceptibility region.

Using recently, collected and updated petrophysical data over this region, has enabled the mapping of a third region possessing petrophysical statistics commensurate to the statistics of the Hiltaba Suite. This region is situated to the south of SAR 7 with a top of approximately 1000 m below surface.

02RED2 – THE 3RD NATIONAL VIRTUAL CORE LIBRARY SYMPOSIUM

02RED2-01. TARGETING IRON ORE IN BANDED IRON FORMATION USING THE HYLOGGING™ SYSTEM

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A central aim of this collaborative project between The University of Western Australia and the Geological Survey of Western Australia (GSWA) is to test the efficacy of hyperspectral logging techniques (i.e. 'HyLogging™ system') for the accurate mapping of hypogene and supergene alteration minerals related to high-grade iron ore (>55 wt% Fe) in Banded Iron Formation (BIF). For this purpose, six diamond drill holes were chosen from four BIF-hosted iron ore occurrences located throughout the Yilgarn Craton. Three holes were selected from Mt Richardson, whereas single holes were obtained from the Koolyanobbing, Windarling, and Beebyn deposits. All holes were drilled from surface and terminate at down-hole depths of between 172 and 430 m. The diamond drill core was scanned with the HyLogging™ system at GSWA's Core Library, Perth. All holes were additionally logged by conventional means, which involved recording relationships between rock types, textures, structures, and hypogene and supergene alteration mineral assemblages. Polished thin sections were prepared from representative samples of rock types and alteration styles to validate the interpretation of hyperspectral data. This abstract reports the results from a pilot study on one of the scanned drill holes from the Mt Richardson prospect, located in the Southern Cross Domain of the Yilgarn Craton.

The 193.8 m-long diamond drill hole from Mt Richardson intersects fresh and weathered BIF, several zones of high-grade iron ore in BIF, as well as gabbroic countryrocks. The BIF and gabbro were metamorphosed to amphibolite facies conditions and experienced retrograde greenschist facies metamorphism prior to hypogene and supergene fluid enrichment in iron. Gabbroic rocks display peak metamorphic amphibole locally replaced by retrograde metamorphic epidote and chlorite. Minor quartz–carbonate veins and alteration zones cut metamorphosed gabbro and BIF. The BIF records three main stages of hydrothermal alteration related to iron mineralisation, including: (1) early hypogene magnetite–quartz alteration, (2) later hypogene specularite–martite alteration, and (3) late supergene goethite–martite alteration. Each subsequent alteration stage at least partly replaces existing primary, metamorphic and earlier hypogene alteration mineral assemblages. Gabbro is altered to hypogene chlorite within 30 m of deformed contacts with BIF-hosted hypogene iron ore zones. Intense supergene goethite and hematite replaces primary, metamorphic and hypogene minerals in gabbro within 25 m of the present surface and along lithological contacts with BIF.

Collected hyperspectral data and interpreted mineral abundances correlate with the results of conventional logging, with improved accuracy and resolution for the identification of boundaries between different rock types and alteration zones. Existing computer-based scripts developed by CSIRO's Mineral and Environmental Sensing Group, including ferric oxide abundance, hematite–goethite ratio, and the ochreous goethite–vitreous goethite ratio, are useful for identifying and characterising iron ore zones. A newly developed, specularite script identifies hypogene specularite ore zones with improved accuracy compared to the ferric oxide abundance script. Proximal hypogene alteration zones in gabbro display an increased abundance of chlorite and the dominance of Mg-rich chlorite over more iron-rich mineral compositions. This pilot study demonstrates that the HyLogging™ system is an accurate tool for the mapping of hypogene alteration minerals associated with high-grade iron ore in BIF.

02RED2-02. HYLOGGING WET CORE FROM BROKEN HILL MANAGED AQUIFER RECHARGE PROECT

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Characterisation of aquifer properties is critical to the accurate prediction of groundwater resources and the management of managed aquifer recharge schemes. Properties are sensitive to variations in mineralogy, especially clays, but detailed mapping of aquifer mineralogy and linking to hydraulic properties is rare. Selected intervals of 12 sonic bores into the Calivil aquifer near Menindee on the Darling River, NSW were scanned using HyLogger™ technology.

In this paper two cores are compared demonstrating the effective extraction of mineral information from the thermal infrared (TIR) spectrum of two of the cores in order to evaluate mineralogy influencing the hydraulic conductivity of the Calivil aquifer in the East Bootoingee-Jimargil borefield. Recent developments in analytical software enable the selection of a restricted mineral set from the inbuilt spectral library. The reason for filtering the library in this instance is to reduce the contribution of the dominant mineral, quartz, from the mathematical modelling. The minerals selected for analysis were kaolinite and montmorillonite because they both share an absorption feature at 9 µm. Other minerals that share this feature such as pyrophyllite, microcline, plagioclase, cordierite, amphiboles, were excluded from the refined library because the sediments being examined are considered to be very mature and these phases would have been unlikely to survive or at least be in low abundance due to the associated weathering, transporting and depositional processes.

The relative proportions of the two phases, kaolinite and montmorillonite, derived from their spectral response were plotted as histograms. The correlation of colour boundaries with the changing proportions of kaolinite to smectite is evident. These boundaries also correlate with geophysical logs and other physical parameters of the core. Nuclear magnetic resonance (NMR) down hole logging showed that the hydrodraulic conductivity of Calivil aquifer was composed to two discrete classes that could not be differentiated on conventional methods. Hyperspectral data from the Hylogger is able to show that the better quality aquifer intervals, those that can store and release large volumes of water on demand, were shown to be high in kaolinite and low in smectite.

This has shown that much information can be gained from examining the TIR signal collected by the Hylogger instrument. Nearly all minerals that display diagnositic absorption features in the SWIR will have an equivalent spectrum in the TIR and through using restricted mineral libraries and constrained least squares fitting of spectral curves the information of interest can be extracted from TIR. This allows data to be collected even when the intervals retain original free water as was the case for some of the intervals in this study. This expands the range of potential HyLogger applications, especially to the characterising of aquifers marine and other subaqueous cores.

02RED2-03. EXPLORING FOR RARE EARTH ELEMENTS USING REFLECTANCE SPECTROSCOPY

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Rare earth elements (REE) are in high demand, and the minerals industry would benefit from new tools for discovering REE mineralisation. REE show specific absorption features in the visible near-infrared (VNIR) spectral range that appear to arise from poorly understood energy transitions by *4f*-orbital electrons within REE atoms themselves, regardless of mineralogical context. This suggests that reflectance spectroscopy might be developed as tool to explore for REE deposits irrespective of style or mineralogy. Our work sought to determine whether there are diagnostic absorption features or signatures that can be used to distinguish individual REE, or at least differentiate light REE-dominant from heavy REE-dominant mineralisation.

We used the Geological Survey of Western Australia's HyLogger™ to collect hyperspectral data in the VNIR, shortwave-infrared (SWIR) and thermal infrared (TIR) spectral ranges, for two independent suites of fifteen >99.99% pure REE oxide powder standards. These spectra exhibited repeatable, consistent, strong, sharp absorption features in the VNIR and SWIR ranges, and no detectable features in TIR. Each REE oxide returned a unique spectral signature, although visual inspection of spectra suggests that some absorption features are common to more than one element.

We assume that natural REE deposits are typically mixes dominated by either light or heavy REE, and that REE features in the VNIR spectral range are due to intra-atomic energy changes largely free from interference from common rock-forming minerals. We therefore derived "collective" VNIR spectra for "light" REE and "heavy" REE, using the down-sampling method employed by The Spectral Geologist (TSG)™ software, then selected the three most prominent features from each combined spectrum to create diagnostic algorithms or "scalars" that can be used to identify REE in any VNIR spectrum. These features occur at 745, 800 and 840 nm for "light" REE, and at 656, 812 and 915 nm for "heavy" REE.

We tested these "scalars" against HyLogger™ and TerraSpec™ reflectance spectra from several specimens of common REE-bearing minerals, drill core from the carbonatite-hosted, light REE-dominant Mount Weld and Cummins Range deposits, and outcrop samples from the hydrothermal vein-hosted, heavy REE-dominant Wolverine deposit, for all of which the REE chemistry was independently validated. The expected diagnostic, "light" or "heavy" REE signatures were consistently detected in all cases.

Reflectance spectroscopy therefore shows promise as an exploration tool for rapid, non-destructive detection and broad characterisation of REE mineralisation in powders, rock chips, drill core, or outcrop. However, our diagnostic "light" and "heavy" REE signatures should be tested against a greater variety of REE-bearing minerals and deposits. We also recognise that diagnostic signatures are strongly influenced by absorption features of REE that have very low concentrations in the principal REE minerals (Nd and Pr in light REE deposits; Ho, Er and Tm in heavy REE deposits), but do not yet know the threshold below which they are not manifested. Furthermore, preliminary analyses of selected REE phosphates, carbonates and chlorides have yielded VNIR absorption patterns different to that for corresponding oxides, suggesting that molecular bond type may influence VNIR spectral signatures, but this remains to be confirmed and quantified.

02RED2-04. CHLORITE COMPOSITIONAL CHANGES IN RESPONSE TO MINERALISATION: EXAMPLES FROM THE NYMAGEE MINE AND GREAT COBAR DEPOSIT, NSW

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Changes in chlorite composition in response to mineralisation were investigated using CSIRO's HyLogging™ systems based at the NSW Trade & Investment core library and National Virtual Core Library (NVCL) node at Londonderry, NSW. HyLogger™ data from four drillholes from the Nymagee Mine (YTC Resources Ltd) and three drillholes from the Great Cobar Deposit (Peak Gold Mines, New Gold Inc.) were analysed using CSIRO's TSG-Core software. The NVCL is a collaborative infrastructure project with AuScope. In summary, chlorite compositions, identified in the shortwave infrared (SWIR) band showed systematic changes in intensity of alteration with distance from ore.

Spectroscopically determined variations in chlorite and white mica chemistry have been reported before. However in this study the high-density sampling afforded by the HyLogging™ method plus geochemical correlations and a strong spatial association to more than one mineralising style provide further evidence of a robust, practical exploration application.

It was found that chlorite within mudstones in drillcore from the Nymagee Mine became progressively depleted in iron over a 25 m interval adjacent to the main pyrrhotite–chalcopyrite mineralised zone. This overprinted an earlier, more pervasive mineralisation stage comprising magnetite, Fe-chlorite and quartz veining.

The change in composition from Fe-chlorite to Mg-chlorite is attributed to mineralising fluid/wall rock reactions. These compositional changes are evident in the HyLogged™ spectroscopic data. In particular, changes in the wavelength of the Fe–OH absorption feature when plotted against drill-hole depth show a wavelength shift from 2263 nm corresponding to Fe-bearing chlorites to 2250 nm corresponding to Mg-bearing chlorites.

Similar trends are evident in data from the Great Cobar Deposit where two chlorite alteration types — Fe-chlorite (associated with copper mineralisation) and Mg-chlorite (associated with lead–zinc mineralisation) — are distinguished geochemically and hyperspectrally within the low-grade metamorphosed siltstones.

In addition, localised sericite alteration exists in both deposits, where it is defined geochemically by the relative abundance of aluminium. This is reflected in the type of white mica present and the wavelength of the Al–OH absorption feature in the hyperspectral data. For example, within the lead–zinc mineralised zones, phengite appears to predominate, whilst at the margins of these zones muscovite is more abundant. Hyperspectrally, this is evident in a shift towards shorter wavelengths for more aluminium-rich muscovites or to longer wavelengths for increasingly iron/magnesium contents in phengitic samples.

Due to the reasonable distance of 25 m over which the chlorite composition changes, vectors towards mineralisation may be used for locating nearby extensions to mineralised zones and perhaps assist with finding undiscovered mineral occurrences associated with the same mineralising events.

DYNAMIC PLANET

02DPA – COMPOSITION AND EVOLUTION OF THE EARTH

02DPA-01. INNOVATION IN AUSTRALIAN GEOCHRONOLOGY AND THERMOCHRONOLOGY

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The emergence of the *National Collaborative Research Infrastructure Strategy* (NCRIS) in 2006 represented a major departure from previous, mostly *ad hoc*, approaches to investment in research infrastructure in Australia. One of the 13 priority research capability areas funded under the initial NCRIS Infrastructure Roadmap was the "*Structure and Evolution of the Australian Continent*". *AuScope Ltd* was set up in 2007 to implement and manage a coordinated system of geoscience and geospatial infrastructure in this area. Importantly this new system involved not just hardware, but was rather an integrated program of technology, data and knowledge infrastructure. Additional funding from the *Education Investment Fund* starting in 2011 added new capabilities and enhanced existing research infrastructure in these areas.

Geochronology and thermochronology have been at the centre of one of the six functional components within AuScope in the geochemistry-based program in *Earth Composition and Evolution*. Developments in this area have built on a long history of Australian innovation in geochronology, thermochronology and isotope geochemistry over the last 60 years. Pioneering advances have been made, and continue to be made, by researchers in Australia both in developing new methods and technologies, as well as innovative applications to important geological problems and opening up the vastness of geological time to precise calibration.

From pioneering origins at UWA in the 1950s, geochronology emerged as a major field of study in the Research School of Earth Sciences at ANU in the 1960s, leading to one of the most important developments for geochronology and isotope geochemistry in the world, the development of the Sensitive High-Resolution Ion Microprobes (SHRIMP) instruments in the 1980s, amongst many other notable achievements. Over this period geochronology, thermochronology and isotope geochemistry also became established at a range of other centres so that today there are concentrations of expertise and advanced technical capabilities in all states. Three examples from Curtin, Melbourne, and Macquarie Universities have been involved in the AuScope Program in (U–Th)/He Thermochronology, Automated Fission Track Analysis and Laser-ablation ICP-MS based methods, respectively. Like many of the other developments in this field these examples involve world-leading technical developments as well as applications of novel systems to unconventional problems in dating and crustal evolution.

These examples are evidence of a continuing strong tradition of innovation by researchers in Australia in geochronology, thermochronology and isotope geochemistry and are also strong contributors to our international standing in the Earth sciences. The importance of access to advanced infrastructure, taken in its broadest sense, to these developments cannot be overstated. Few, if any, of these innovations would have been possible without the most advanced equipment, access to workshops of the highest quality, and high-level, ongoing technical support. It is vital that future infrastructure programs take account of these fundamental requirements of our science, and also that the geoscience research community takes a coordinated role in determining the most appropriate models to provide access to increasingly expensive and shared facilities.

02DPA-02. ZIRCON PRODUCTION, U–PB GEOCHRONOLOGY AND HF–O ISOTOPE CHARACTERISTICS OF THE MIDDLEDALE GABBROIC DIORITE: IMPLICATIONS FOR THE TEMORA ZIRCON REFERENCE MATERIAL

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All studies employing zircon U–Pb age information, Hf-isotope analyses, or oxygen isotope data, require instrumental calibration using well-characterised zircon reference materials that are ideally homogeneous on submicron and larger scales and in abundant supply. The Middledale Gabbroic Diorite (MGD) in NSW hosts one suite of such reference materials, the internationally distributed zircon standard TEMORA 2 and its prototype standard, TEMORA 1. Previous work has shown that the MGD is petrographically and geochemically heterogeneous. It has also been observed that although TEMORA 1 and TEMORA 2 have the same U–Pb ages (416.8 Ma), they are variable in oxygen isotope composition ($\delta^{18}O$ = 7.9–8.2‰); furthermore, as no Hf isotope study of the TEMORA 1 zircons has been reported, the outcrop- to pluton-scale Hf-isotopic variability is unknown. Curiously, the original characterisation revealed that the more altered TEMORA 2 host rock has an order of magnitude more zircon than the TEMORA 1 host rock, despite similar bulk-rock Zr concentrations. Petrographic observations in concert with bulk-rock and mineral geochemistry and zircon U–Pb geochronology have been applied to investigate these observations. A combination of variable grainsize, textures, mineralogy and extent of alteration (particularly of clinopyroxene and hornblende) has led to the identification of different lithologies within the pluton. Additionally, this study has revealed coherent magmatic geochemical trends. Laser ablation-ICPMS trace element data (in combination with electron microprobe data) of minerals in thin section are used to investigate the link between increased alteration and higher zircon abundance. Mineral trace element maps show that the products of late-stage alteration (particularly actinolite after hornblende) are depleted in Zr, and many other trace elements, relative to the unaltered mafic, magmatic phases. It is posited that the conversion of hornblende to actinolite liberated Zr, providing additional Zr for the late-stage crystallisation of zircon. New U–Pb SHRIMP ages (414.8, 416.1, 414.8 and 414.1 Ma) confirm the uniformity of the zircon in this respect across the pluton and reaffirm the value of TEMORA 2 as a robust U–Pb geochronological reference material. Using SHRIMP II, *in-situ* zircon oxygen isotope data have been acquired for the four dated samples (samples A, B, J and N), the mean $\delta^{18}O$ values of which (7.48, 8.16, 8.42 and 8.19‰, respectively) encompass the accepted values for TEMORA 1 ($\delta^{18}O$ = 7.9‰) and 2 ($\delta^{18}O$ = 8.2‰). Likewise, the Hf-isotopic composition of the zircon populations ($^{176}Hf/^{177}Hf$ = 0.28284, 0.28272, 0.28268 and 0.28267, respectively) are similar to the accepted TEMORA 2 composition ($^{176}Hf/^{177}Hf$ = 0.282686 ± 8). Together with petrographic observations, these data reveal the TEMORA 2 zircon and host to be broadly reflective of the relatively coarse-grained portions of the MGD, and that the isotopically less evolved compositions (i.e. the lower $\delta^{18}O$ of TEMORA 1 and low $\delta^{18}O$, high $^{176}Hf/^{177}Hf$ of sample A) are associated with a relatively fine-grained, marginal lithology. Given $\delta^{18}O$ values greater than the typical mantle-derived zircon value of 5.3‰ and the broad co-variation between O- and Hf-isotopic compositions, the data imply the pluton evolved by crustal contamination of a primitive magma.

02DPB – COMPOSITION AND EVOLUTION OF THE EARTH

02DPB-01. BUILDING NATIONAL INFRASTRUCTURE USING TERRANECHRON® AND LITHOSPHERE MAPPING

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Through *AuScope Earth Composition and Evolution*, CCFS/GEMOC (Macquarie University) has provided access to the TerraneChron® methodology, resulting in a significant contribution to research in academic, Government and industry spheres. In the first NCRIS funding cycle usage was oversubscribed, exceeding allocated targets with 129 collaborative projects undertaken: 29 Australian University; 29 International; 33 State Governments; 2 International Government bodies; 36 Industry. 104 publications in international peer-reviewed journals resulted from the collaborative work and 92 TerraneChron® reports on funded collaborative projects were provided to companies and Government agencies.

TerraneChron® is GEMOC's unique methodology to study crustal evolution and evaluate the metallogenic potential of terranes, especially in difficult or poorly exposed areas. The approach integrates *in-situ* analysis of U–Pb [1] and Hf isotope [2], and trace-element [3] compositions of single zircon grains by laser ablation (LA) mass spectrometry. The methodology is applied to zircons from drainage samples collected within defined catchments sampling areas of the crust formed in different tectonic settings, and can be complemented by zircons separated from exposed lithologies for groundtruthing.

The LA-ICPMS technique provides a rapid, cost-effective method to determine the age distribution of a crustal terrane. Hf isotopes tell whether magmatic protoliths involved a juvenile source (young mantle-derived magmas), reworking of pre-existing crust, or a combination of these processes. This information reveals the nature of crustal evolution by tracking the nature and timing for reworking episodes and new mantle input. The unique global TerraneChron® database enabled re-evaluation of the rate at which the continental crust has grown at different stages of Earth's history [4, 5].

TerraneChron® also provides a framework to identify terrane-scale events ('Event signatures'; [6, 7]) and to compare the histories of different terranes. This can be used to assess whether specific tectonic terranes were once part of the same orogenic domain or if they have always been discrete. TerraneChron® forms an integral component of Global Lithospheric Architecture Mapping [8,9] that has generated maps of the composition and architecture of the lithosphere by integrating geophysical, geological and geochemical data. Several recent studies identify strong spatial correlation between lithospheric boundaries and the location of large concentrations of several styles of mineral deposit [10, 11]. The use of TerraneChron® to fingerprint tectonic signatures, associated with different styles of mineralisation through time, provides a framework for the construction of multi-isotope maps to enhance exploration strategies and prioritise targets. The development of appropriate data protocols and models to construct multi-isotope maps and as a proxy for paleogeophysics is a strategic direction for future NCRIS AuScope initiatives.

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02DPB-02. THE ENIGMA OF CRUSTAL ZIRCONS IN UPPER MANTLE ROCKS: INSIGHTS FROM U–PB AGES, HF–O-ISOTOPES AND TRACE-ELEMENT SIGNATURES (TUMUT REGION, SE AUSTRALIA)

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Reports of "crustal" zircons in the ultramafic rocks of ophiolites are becoming common – but what do these zircons record? This study focuses on the ophiolitic rocks of the Tumut region, in the Lachlan Fold Belt of SE Australia, where two subvertical linear belts crop out discontinuously over a NNW–SSE strike length of 140 km. The more deformed and metamorphosed rocks are in the western Wambidgee serpentinite belt, part of which has undergone upper amphibolite-facies metamorphism. In contrast, the eastern Coolac serpentinite belt contains a high proportion of massive (unfoliated) rocks and has only undergone greenschist-facies metamorphism. On its eastern contact, it is either faulted against, or intruded by, the S-type Young granodiorite [1].

New U–Pb, Hf- and O-isotope and trace element data were obtained for zircons from a range of rocks from both serpentinite belts of the Tumut region. These rocks include two (high-Al and high-Cr) massive chromitites, leucogabbro, plagiogranite and rodingite in the Coolac belt, and a plagiogranite from the western Wambidgee belt. Detrital zircon grains have been recovered from gullies draining outcrops consisting of mainly weakly serpentinised massive porphyroclastic harzburgite of the Coolac belt. Zircons from the Young granodiorite collected at the contact with the Coolac serpentinite belt were studied to take the "fingerprints" of crustal grains and to refine the tectonic relationships and timing of the granitic magmatism.

U–Pb dating of zircons from the plagiogranite of the western Wambidgee belt defined a single age population with a concordia age of 483.5 ± 2.3 Ma. These zircons show a narrow range of strongly positive εHf (from +11 to +14), consistent with their crystallisation from mantle-derived melts. In contrast, the origin of zircons from the Coolac belt is complicated by the range of U–Pb ages (main population at *ca* 430 Ma and inheritance from about 442 Ma to over 2300 Ma) and the large proportion of zircons with negative εHf and heavy (>6) $\delta^{18}O$, indicative of a crustal origin. Furthermore, the similarity between the Coolac ophiolite-derived zircons and the magmatic and inherited suites from the Young granodiorite may indicate that the zircons were introduced into the Coolac peridotites during the voluminous granitic magmatism that occurred in the region *ca* 430 Ma ago. In this case, the zircons carry no information on the origin of the Tumut ophiolite and only suggest that emplacement of the Coolac rocks had most likely preceded granitic magmatism of the Lachlan Fold Belt.

During this study several small, up to 10–20 µm, laurite (RuS_2) grains were found in massive (high-Cr) chromitites from the Quilter's open cut in the Coolac serpentinite belt. A range of 'unradiogenic' $^{187}Os/^{188}Os$ values (0.1146–0.1220) collected on the laurites gives Re-depletion model ages varying between 0.84 and 1.89 Ga, with a maximum at around 1.18 Ga and a shoulder at *ca* 1.64 Ga. These data imply that the mantle beneath southeastern Australia is at least Mesoproterozoic in age.

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02DPB-03. PERFORMANCE OF THE HELIX-MC MULTI-COLLECTOR NOBLE GAS MASS SPECTROMETER – RESOLUTION OF ARGON ISOBARIC INTERFERENCES

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Analyses of noble gas isotopes by multi-collector mass spectrometry substantially improve measurement precision and accuracy, with the potential to revolutionise applications to cosmo-geo-sciences. The Helix-MC noble gas mass spectrometer manufactured by Thermo-Fisher is a 350 mm, 120 degree extended geometry, high resolution, multi-collector mass spectrometer for the simultaneous analysis of noble gas isotopes. The detector array includes a fixed axial (Ax) detector, 2 adjustable high mass (H1 and H2) detectors and 2 adjustable low mass (L1 and L2) detectors. Each detector is equipped with a Faraday/ion counting multiplier CFM (Combined Faraday and CDD Multiplier) detector. Mass resolution and mass resolving power on the H2, Ax and L2 detectors of the Helix-MC operated at 9.9 kV accelerating voltage, installed at the Australian National University (ANU) are approximately 1800 and 8000, respectively. The noble gas handling system on-line to the Helix-MC consists of: (1) a resistively-heated, double-vacuum, tantalum furnace system, (2) air actuated vacuum crusher, (3) Photon-Machines diode laser heating system, (4) Janis He cryogenic trap assembly, (5) gas purification system and (6) standard gas pipette tanks, which are fully automated and controlled by the Qtegra software platform developed by Thermo-Fisher.

Eleven repeat measurements of atmospheric Ar using the H2 Faraday (1E11 ohm resistor) and L2 CDD collectors on the Helix-MC, yield a mean $^{40}Ar/^{36}Ar$ ratio of 322.09 ± 0.28 (0.089%) with a 4700 fA ^{40}Ar beam current. This result compares favourably with the precision achieved by the ArgusVI at the University of Melbourne (318.12 ± 0.17; 0.052%; n = 10) with a similar beam size of 4,200 fA. The high mass resolution of the L2 collector, permits complete separation of the ^{36}Ar and interfering, 3 x 12C (required mass resolution (MR) of 1100) and partial separation of H35Cl (MR = 3900). This capability enables evaluation of the significance of Ar isotopic interferences related to the correction of atmospheric Ar from the total Ar measured in geological samples.

From a MD-2 biotite standard (collected from the GA1550 Mt Dromedary site), we observed beam intensities for ^{40}Ar, ^{36}Ar, $H^{35}Cl$ and $^{12}C_3$ of 4826, 0.775, 0.027 and 0.024 fA, respectively. Corresponding $^{40}Ar/^{36}Ar$ and $^{40}Ar/(^{36}Ar + H^{35}Cl$ and $^{12}C_3)$ ratios are 6452 and 6054, respectively. It is noted that a significant fraction of $H^{35}Cl$ released from MD-2 could not be completely removed by purification procedures, and this interference cannot be corrected by blank subtraction. It is stressed, however, that the very high proportion of radiogenic ^{40}Ar to total ^{40}Ar released from MD2 biotite means that the correction of atmospheric Ar using either ^{36}Ar or the combined $^{36}Ar + H^{35}Cl$ and $^{12}C_3$ peak, influences the estimation of radiogenic ^{40}Ar by <0.3%. On the other hand, when $^{40}Ar/^{36}Ar$ ratios in samples, such as young basalts, are close to the atmospheric value, corrections for atmospheric ^{40}Ar using interference-corrected ^{36}Ar could become more significant.

02DPB-04. NEW DEVELOPMENTS IN $^{40}Ar/^{39}Ar$ GEOCHRONOLOGY FROM MULTI-COLLECTOR MASS SPECTROMETRY

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Recent years have seen the development of a new generation of multi-collector mass spectrometers for noble gas geochronology and geochemistry (ARGUSVI, HELIX, Noblesse). The first multi-collector ARGUSVI instrument for $^{40}Ar/^{39}Ar$ geochronology was installed in the School of Earth Sciences at the University of Melbourne in 2011. The mass spectrometer is connected to a Photon-machines Fusions 10.6 CO_2 laser for sample step-heating and fusion. The first results from this system were published in 2013 and demonstrate the significantly enhanced analytical capabilities of these new instruments, compared with older generation systems.

In this presentation, we will document results from selected $^{40}Ar/^{39}Ar$ dating standards and samples, using the ARGUSVI system. Standards considered include Fish Canyon Tuff sanidine (FTCs) [1], Alder Creek Rhyolite sanidine (ACRs) [1], A1 Tephra sanidine and Mt Dromedary biotite (MD-2; = GA1550). Samples studied include young basalt samples, <300 kyr old [2]. $^{40}Ar/^{39}Ar$ analyses conducted using the ARGUSVI system show significantly enhanced precision levels (>10x), compared to previous mass spectrometer systems. This capability has enabled resolution of age gradients in the step-heating spectra of the sanidine standards in routine runs for $^{40}Ar/^{39}Ar$ geochronology. However, other standards (MD-2 biotite) and samples (basalts, anorthoclase feldspar) show flat age spectra. These new results complicate the assignment of accurate ages to sanidine standards and associated unknowns.

Uncertainties in standard ages are less significant for $^{40}Ar/^{39}Ar$ dating of young basalt samples. In this regard, the ARGUSVI system is particularly well suited for high precision $^{40}Ar/^{39}Ar$ geochronology of young basalt samples (<100 kyr). As an example, samples from the Tyrendarra basalt flow within the Newer Volcanic Province of SE Australia yield an age of 37.6 ± 0.3 ka (0.8%, 2σ).

In conclusion, the unprecedented enhancement in analytical precision of the ARGUSVI mass spectrometer presents new challenges, but also new opportunities for the $^{40}Ar/^{39}Ar$ dating technique.

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02DPC-01. AN EVALUATION OF APATITE FISSION TRACK DATING BY LA-ICP-MS

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Analysis of trace element compositions by laser ablation ICP-MS has become a widely used tool in *in-situ* geochronology. Although primarily used for U–Pb dating, LA-ICP-MS has been successfully adapted to other techniques such as apatite fission track or (U–Th)/He, making it an ideal tool for multi-system thermochronological studies. For fission track dating, LA-ICP-MS has several important advantages over the conventional external detector method (EDM), particularly in terms of sample turn-around time and the fact that neutron irradiations (and the handling of radioactive materials) are no longer necessary, while providing a similar level of *in-situ* information. Another key benefit of LA-ICP-MS fission track dating is that it could potentially be used as an absolute dating technique, instead of the indirect “Zeta” approach that relies on calibration against independently dated age standards. However, beyond the pioneering studies of Hasebe *et al.* (2004, 2009), little work has been done to validate this new approach and address some of the calibration and standardisation issues associated with fission track dating by LA-ICP-MS.

We present an extensive dataset of fission track results that were analysed using both the LA-ICP-MS and EDM techniques. Both methods were applied on identical grains, thereby eliminating uncertainties associated with natural variability in the fission decay. The samples were selected to represent a variety of fission track ages, ^{238}U concentrations and length distributions. The latter vary significantly depending on the thermal history experienced by a sample and are important because they relate the (2D) fission track density – counted microscopically on an internal mineral surface – to the (3D) distribution of ^{238}U spontaneous fission events, which are then compared to the ^{238}U concentration measured by LA-ICP-MS to calculate the fission track age. The results show that for samples with long mean track lengths (>13 µm), fission track ages from LA-ICP-MS and EDM are concordant within analytical uncertainties and define a well-behaved 1:1 relationship, independent of sample age or ^{238}U concentration. Although the relative difference in single grain ages varies significantly in either direction, there are no systematic variations between the two methods, suggesting that this variation is simply due to random sampling effects. However, for samples with lower mean track lengths (<12–13 µm), fission track ages determined by LA-ICP-MS are consistently older (up to 25%) than those obtained by the EDM method, by a degree that seems to reflect the amount of track annealing (shortening) experienced by a sample. These results show that while fission track dating using LA-ICP-MS works very well for samples with relatively simple and fast cooling histories (moderate to long mean track lengths), systematic differences can occur between the EDM and LA-ICP-MS methods for samples that underwent slow, protracted or complex cooling histories (short mean track lengths).

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02DPC-02. CHANGES IN GLOBAL MAGMATISM AND THE LIMITATIONS OF HF–O ISOTOPE DATA IN ZIRCON

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Analytical developments allowing for the rapid analysis of U–Pb age and Hf and O isotopes in single zircons have enabled collection of large datasets that provide insight into igneous rock generation. These datasets have variously been used to investigate the formation of individual plutons through to commenting on global magmatism and continental growth.

Application of Hf isotopes to regional or global scale studies is used to establish the addition of new material to the crust (e.g. mantle magmatism) *vs* reworking of older crustal material. Recently O isotopes have been proposed as a tool to filter out mixed, "non-meaningful" Hf model ages from those model ages that can be considered to be truly representative of crustal generation events. We use a new compilation of Hf and O isotope data from magmatic rocks to demonstrate that O isotopes are not a reliable filter for "non-meaningful" Hf model ages. Based upon the published petrogenetic interpretations of the studied rocks at most only ~16% of Hf model ages are suggested to be non-mixed. This proportion may be further reduced if we consider the possibility for modified mantle compositions or contributions from multiple mantle-derived lithologies of differing ages in the source region.

Global O isotope compilations may be able to provide insight into the changing styles of magmatism throughout Earth history. The O isotope compilation of Valley *et al.*[1] demonstrates a restricted clustering of zircon O isotope values in the Archean that expands in range from the Paleoproterozoic onwards. This was suggested to indicate the increased role of supracrustal material (sedimentary rocks) in the generation of post-Archean magmatic rocks. We present a new compilation of 6203 zircon O isotope data from sedimentary and igneous rocks. This new dataset shows a similar pattern to the Valley *et al.* dataset but with 3.8% of the data falling above the maximum envelope defined by Valley *et al.* Data that plot above the maximum envelope largely do so at times associated with supercontinent amalgamation (e.g. *ca* 2700–2500 Ma, *ca* 2000–1800 Ma, *ca* 1000 Ma and *ca* 600–500 Ma). This is perhaps consistent with increased incorporation of recycled sedimentary rocks into magmatism during higher rates of collision and crustal thickening associated with supercontinent amalgamation as opposed to an alternate setting such as an island arc. To assess whether there has been a significant change in the proportion of mantle and crustal melts into global magmatism over time we use a reduced O isotope dataset of 4227 data. This is done so as to avoid biasing the interpretation towards studies, which collect multiple datapoints from a single magmatic rock (i.e. 1911 analyses from 120 igneous rocks). Stochastic modelling of this dataset is used to demonstrate that there does not need to be significant changes in the proportion of mantle-derived melts into igneous rocks throughout Earth history. Variation in parameters such as the proportion of 'mantle-like' zircons can largely be achieved simply through the changing composition of crustal reservoirs over time.

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02DPC-03. DATING MOVEMENT THROUGH MICROSTRUCTURE

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Dating movement in shear zones is of particular interest to structural geology and tectonics, but timing something as intangible as movement can be difficult unless there are specific phenomena that can be attributed to the associated deformation. Processes such as recrystallisation and/or the growth of new fabric forming minerals are candidate processes, for if there is new mineral growth, $^{40}Ar/^{39}Ar$ geochronology can be used to constrain its timing. However, the new grown minerals need to be sufficiently retentive of radiogenic argon to allow those ages to escape significant modification during subsequent events. The technique can also work if deformation causes significant reduction in grain size, for example when micro-shear zones shred white mica until diffusion distances are small enough to allow rapid argon loss under the conditions that apply during shear zone operation. Again the modified material needs to remain sufficiently retentive of radiogenic argon to allow ages to escape significant modification during subsequent events. The question then arises as to what other processes might allow movement in shear zones to be dated using $^{40}Ar/^{39}Ar$ geochronology?

K-feldspar can be crushed and cataclased (± recrystallised) in ductile shear zones associated with mylonites. Can K-feldspar be used to date the timing of movement? Forster & Lister (2009) tested this in the South Cyclades Shear Zone, on Ios, Cyclades, Greece. The data obtained seem reliable, for the same age was determined from newly recrystallised white mica, and from Rb–Sr measurements in adjacent calc-mylonites. Forster *et al.* (2014) document the methodology utilised and repeated the experiment on shear zones in the Wyangala Batholith. The work shows a systematic reduction in the estimated activation energy as deformation proceeds. Overall the range in closure temperature is from ~280°C in the smallest domains of the groundmass, to ~530°C in the most retentive domains of the porphyroclastic grains. The intermediate domains (~60% of the volume) have closure temperatures that range from 440–480°C. It is shown that $^{40}Ar/^{39}Ar$ geochronology should be able to date the timing of movement if ‘closure temperatures’ for the range of diffusion domains in the cataclased K-feldspar bracket the time–temperature conditions of mylonitisation.

Arrhenius data sometimes show the existence of highly retentive K-feldspar cores, and these retain older ages. In the past these older ages have been interpreted as the result of “excess argon”. It now appears that they record the timing of events at earlier stages in the rock history. Because these cores are so retentive, these ages survive as relicts. Mylonitisation under biotite-grade greenschist facies appears to modify and decreases both diffusion dimensions and activation energy during grain comminution and cataclasis, so that eventually the argon clock resets during shear zone movement.

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02DPC-04. THE AUSCOPE AGOS GEOHISTORY FACILITY: A NOVEL INSTRUMENT SUITE FOR LASER MICROANALYTICAL *IN-SITU* U–TH–SM–PB–HE GEOCHRONOLOGY AND THERMOCHRONOLOGY

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The RESOchron is a new instrument designed to conduct rapid, automated *in-situ* U–Th–Sm–Pb–He (and trace element) analysis of multiple mineral grains. This novel capability permits a detailed interrogation of the time–temperature history of rock types containing apatite, zircon, rutile, titanite and other accessory phases. In addition to providing a conventional U–Pb geochronology capability, the system provides thermochronometry data *via* (U–

Th–Sm)–He dating. The benefits of *in-situ* analysis to helium thermochronology research relative to conventional standard single crystal analysis methods include:

- increased research productivity (10–20 fold),
- eliminate the need to use hazardous HF for zircon and other resistate minerals,
- eliminate the need for F_t corrections,
- avoid mineral/gas inclusions and other sources of contaminants, and
- a new capability to conduct He mapping and depth profiling.

The analytical system integrates four commercially available components:

- a 193 nm excimer laser based on the Resonetics RESOlution™ M-50-LR design,
- a helium mass spectrometry module based on the Australian Scientific Instruments Alphachron™ design,
- an ICP-MS module, and
- two swappable analytical chambers built by Laurin Technic P/L:
    - M50 flow-through cell for trace element, and
    - an ultra-high vacuum (UHV) cell for helium analysis.

Using the excimer laser ablation system, polished zircon grains are helium extracted in the UHV cell (typically using a 30 s ablation, 33 µm beam, 3 Hz, 12% attenuation and 80 mJ). Pit volumes are then measured and U, Th and Sm are subsequently analysed in a laser pit ablated overtop of the original helium pit (<8 µm deep) using traditional ELA-ICP-MS methods. (U–Th)/He ages calculated using radiometric decay equations.

Initial technique development using fragments of Mud Tank and Sri Lankan (B188) zircon allow the determination of system sensitivity for helium dating. Despite its Neoproterozoic age, Mud Tank zircon has a homogeneously low He content (1.08×10^7 ncc/g) due to the low abundance of U and Th (10 ppm and 6 ppm, respectively). These characteristics do not make Mud Tank zircon a good choice for an analytical standard, however they do provide a test of the sensitivity of the RESOChron instrument because ^{4}He can be reliably measured in pits as small as 10 µm diameter and 10 µm deep, and with a precision ± 1.2% on larger volumes. The ^{4}He extraction process has no discernable impact on the U and Th content of the residual sample material indicating an apparent preservation of parent–daughter relationships.

Sri Lanka zircon B188 with U and Th contents of 518 ± 12 ppm and 57 ± 2 ppm, respectively, is a more prospective *in-situ* double dating standard with RESOChron *in-situ* ages falling within 10% of known U–Pb (558 ± 8 Ma) and (U–Th–Sm)/He (435 ± 10 Ma) ages.

Future development work will focus on improving the accuracy of pit volume measurements, optimising laser settings for helium extraction, improving standardisation for U–Th–Sm measurement (eg. matrix matching) and characterising more prospective zircon standards for *in-situ* methods.

02DPD – COMPOSITION AND EVOLUTION OF THE EARTH

02DPD-01. HIGH PRECISION 40AR/39AR DATING OF <100 KA BASALTS FROM SOUTHEASTERN AUSTRALIA USING AN ARGUSVI MULTI-COLLECTOR MASS SPECTROMETER

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Acquiring high precision ^{40}Ar/^{39}Ar geochronological data for young mafic volcanic rocks, particularly low potassium examples younger than 0.5 Ma, has historically been a challenging task. This is due to low ^{40}Ar radiogenic argon yields, high atmospheric argon levels, difficulty in precise measurement of ^{36}Ar and, sometimes, extraneous argon contamination. The introduction of new generation, highly sensitive, multi-collector mass spectrometers, (e.g. ARGUSVI, HELIX) marks a major advance in overcoming these obstacles. The Thermo Fisher Instruments ARGUSVI mass spectrometer installed in the Noble Gas Laboratory at the University of Melbourne, which is connected to an extraction line equipped with a Photon Machines Fusions 10.6 CO_2 laser, was the first of its kind to be commissioned and has been producing data since late-2011. We have already demonstrated the ultra-high analytical precision level (<0.1%) achievable with this instrument using ^{40}Ar/^{39}Ar dating standards (Phillips & Matchan 2013). More recently, we have illustrated how this system enables an order of magnitude improvement in analytical precision (<1%, compared to 10%) and simultaneously improves our ability to detect minor isotopic disturbances in *ca* 285 ka alkali basalt, compared to 'conventional' single-collector mass spectrometry (Matchan & Phillips 2014). Having now established sample preparation and analytical procedures, we are focussing our attentions on extending the application of the technique to groundmass samples younger than 100 ka, including those of Holocene age.

The Pliocene–Holocene Newer Volcanic Province of southeastern Australia provides a rich source of well-preserved, suitably aged flows. Previous age constraints for eruptions occurring within the last 100 ka are relative only, having been provided by cosmogenic exposure dating, regolith studies, or ^{14}C dating of basal swamp deposits or crater-lake sediments. We present new $^{40}Ar/^{39}Ar$ step-heating data for basalt groundmass samples from Mount Porndon, Mount Eccles and Mount Schanck. These preliminary results are highly encouraging. For example, a high precision $^{40}Ar/^{39}Ar$ age of 37.6 ± 0.3 ka (0.8%, 95% CI) calculated for the Tyrendarra flow (Mount Eccles), provides an independent control for the cosmogenic neon exposure dating study of Gillen *et al.* (2010) undertaken on this lava flow.

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02DPD-02. Fe ISOTOPES AND THE CONTRASTING PETROGENESIS OF A-, I- AND S-TYPE GRANITE

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Granite magma results from numerous processes (partial melting, fractional crystallisation, crustal assimilation, magma mixing, melt-residue segregation) acting on a range of source materials (mafic mantle melts, meta-igneous and meta-sedimentary crustal sources) in different tectonic settings. The complexity of this source–process–setting matrix has led to the generation of a diverse range of granite classification and nomenclature schemes. The radiogenic isotopes of elements such as Nd, Sr or Pb provide indispensible insights into the *sources* of granite magmas, but are not indicative of processes of petrogenesis. Iron isotopes are a powerful tool for tracking magmatic processes, particularly shedding light on redox equilibria in high temperature systems. Because the site preferences of the stable isotopes of Fe are dependant on valence state, Fe isotope fraction is larger at magmatic temperatures than some other high mass stable isotopes.

We show with a combined set of published, and our own new Fe isotope data from S-, I- and A-type (ferroan) granites that this isotope system provides great insight into the *processes* of granite formation, in particular whether or not the system is oxygen-buffered (ie 'Open' or 'Closed'). Magmatic processes result in complex Fe-isotopic differentiation trends that lead some granites to evolve to isotopically heavy iron with $\delta^{57}Fe$ >0.35‰. These variations are similar to those previously reported (Poitrasson & Freydier 2005; Heimann *et al.* 2008; Telus *et al.* 2012). Heavy values are not necessarily the product of late-stage hydrothermal fluid loss, though this process can be important.

A-type (ferroan) granites reach very heavy $\delta^{57}Fe$ values (0.4–0.5‰) whereas I-types are systematically lighter ($\delta^{57}Fe$ = ~0.2‰). S-type granites, which are clearly more reduced than I-types, show a range of intermediate values, but also tend to be heavy ($\delta^{57}Fe$ ≈ 0.2–0.4‰). Modelling using the Rhyolite-MELTS suggests that these contrasts are controlled by the oxidation conditions of the magma systems, in particular whether the system is relatively oxidised or reduced and whether or not it is externally oxygen-buffered. Most extreme enrichments in the heavy isotopes of Fe only occur when total iron concentration in melts is low corresponding to the latest stages of fractional crystallisation or early stages of continental crustal anatexis. We conclude that ferroan A-types result from protracted, closed magma chamber fractionation of moderately reduced mafic magmas, mostly in the mid to upper crust, where fractionation leads to delayed magnetite saturation and where the ferric iron budget is finite. I-type systems are associated with the supply of relatively oxidised subduction-related magmas from the mantle wedge to the upper plate, where open system AFC processes evolve in lower crustal hot-zones. S-type magmas are crustal melts extracted from the margins of the I-type AFC hot zones, and are externally buffered at reduced conditions imposed by sulfidic or graphitic sedimentary crustal protoliths. This results in the domination of low $\delta^{57}Fe$ ferrous iron–magnesian silicates in the residues of S-type granite melt formation and the complementarily heavy isotopic composition of the produced melts.

02DPE – MANTLE, DEEP AND SHALLOW

02DPE-01. MULTI-ANVIL HIGH-PRESSURE TECHNOLOGY AND MINERALOGY OF THE DEEP MANTLE

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Ted Ringwood opened new research field of high-pressure mineralogy and petrology. A number of high-pressure minerals were firstly synthesised at his laboratory in 1960s–80s, many of which were later discovered in nature and named after Australian scientists, such as wadsleyite, ringwoodite, majorite, lingunite, etc. I joined Ted's group in mid 1980s, and made some collaborative work with him on the phase transitions in complex chemical compositions relevant to the mantle and subducted slab lithologies, using a multianvil high-pressure apparatus.

Since the middle 1990s, after Ted passed away, I have been working in developing experimental techniques in multi-anvil apparatus by using synchrotron *in-situ* X-ray observations and sintered-diamond anvils, in order to accurately measure the phase transition pressures and some key physical properties of high-pressure minerals under the pressure and temperature conditions of the lower mantle. It has been demonstrated that the upper mantle and mantle transition region are of a pyrolite composition as predicted by Ted, except for the bottom part of the latter region, where a layer of harzburgitic composition is suggested to exist to account for the observed seismic velocities. Efforts have also been made to constrain the chemical composition of the lower mantle in the light of mineral physics tests based on laboratory measurements and seismological observations, but we have not yet reached a decisive conclusion on this issue.

On the other hand, I first reported the synthesis of sintered bodies of pure nano-polycrstalline diamond (NPD) in early 2000s, which was inspired by Ted's effort and success to produce ultrahard material by sintering powders of natural diamond, named as Advanced Diamond Composite (ADC). The NPD was found to have extremely high hardness, even harder than single-crystal diamonds, and has been successfully used for anvils for diamond anvil cell (DAC), as well as for some industrial applications. Efforts have been directed to produce the NPD samples with higher quality and larger dimensions, and now we can synthesise highly transparent and flawless NPD rods with 1 cm in both diameter and length, using a large multianvil apparatus operated in a 6000 ton press. Thus synthesised NPD rods are processed with pulsed-laser to form anvils for multi-anvil apparatus, which have been tested for applications to the mineralogy of the deeper regions of the Earth's interior, yielding some promising initial results.

39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

02SBA - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

02SBA-01. SMALL FAULT IDENTIFICATION THROUGH SEISMIC DIFFRACTION IMAGING

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Faults are one of the most important geological structures that need to be delineated before any underground coal mining operation can commence. Even an unexpected small fault with a throw of a few metres can create safety issues and lead to costly delays in production. While seismic surveys are quite successful at locating faults with throws greater than 5–10 m, reliable techniques for resolving more subtle faults, shears and other minor features are yet to be developed.

There are two types of seismic energies that can be used for subsurface imaging: specular reflections and diffractions. Specular reflections are created by smooth surfaces between layers of differing impedance contrast such as at coal-rock interfaces. Specular reflections are used in conventional seismic reflection surveys. Diffractions can occur at local discontinuities between layers caused by faults, pinch-outs and fractures. Diffractions can therefore be used for fault identification but they are often ignored or suppressed by modern high fold reflection surveying and by data processing procedures such as stacking and migration. In the past, diffraction patterns on low fold reflection sections were sought by seismic interpreters as an indication of small faults where the discontinuities of the seismic reflections are less evident. In recent years, the interest in diffraction imaging has rekindled and imaging techniques have been developed for petroleum seismic data processing, which makes small fault detection possible through diffraction imaging as well as by conventional seismic reflection mapping.

In this paper, we demonstrate that diffractions can be separated from reflection seismic data through f–k or moving average filtering of the NMO-corrected common-offset and shot gathers. The extracted diffractions can be used to identify small faults that are difficult to detect using conventional seismic reflection processing. Numerical examples illustrate that the extracted diffractions can be used to identify faults with a throw of 1m, even in a moderately noisy environment, and when the migration velocities are not accurate. In addition, there is an opportunity to extract the diffraction signals from existing final stacked seismic sections without the need for extensive reprocessing. The feasibility to extract diffractions from post-stacked seismic sections is tested by both numerical and real data examples.

02SBA-02. INTEGRATED ANALYSIS AND MODELLING OF GEOPHYSICAL LOGS FROM COAL MEASURE STRATA

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Introduction

In coal mining, there are well established qualitative applications of geophysical logs such as picking tops and bottoms of coal seams from density logs, estimating UCS from sonic logs and identifying marker bands from natural gamma logs. However, there is less use of quantitative methods aimed at estimating rock properties, be it for geological purposes such as mapping sandstone and siltstone interburdens or for geotechnical applications aimed at determining rock quality via the Geophysical Strata Rating (GSR).

Successful quantitative analysis requires an understanding of the physical basis of the log measurements, their precision and the sources of noise that might be present. If measurements from different logs are to be combined, the resolution provided by each of the logs should be matched using appropriate filtering, resampling and choice of end points. Different processing parameters may be required when logs are being assessed for holes from separate drilling programs and where different logging tools with different calibration factors have been employed.

One of the great attractions for quantitative geophysical log analysis is that it allows interpolation of results between holes and the creation of 3D models of the subsurface. Done properly, powerful insights into the subsurface geology are provided. Core and chip logging are unlikely to deliver equivalent results.

Sample rate issues

While it is now common practice to acquire geophysical logs at 1 cm depth intervals, this does not provide measurements, which are uniquely representative of each point in the borehole and free from the influence from points nearby. In the case of sonic logging, the velocities are measured between receivers typically separated either by 20 cm or 1 foot, depending on the tool. The velocity that is obtained represents the velocity of the sonic wave (a seismic P-wave) over the interval between these receivers.

In the case of the radiometric logs (density, neutron and natural gamma), the measurements are reliant upon radiation caused by rock mass interactions with radiation from an artificial source, or from the decay of naturally occurring radioactive materials. In both cases, the nuclear processes that are occurring do not provide constant radiometric flux and there is a certain amount of randomness in the measurements. In the case of the density and neutron measurement, the distance between the source and the detectors might limit the vertical resolution to about 20 cm. For natural gamma measurements, natural gamma radiation might be received at the detector from a volume of material within a radius of about 30 cm. Because the total amount of radiation that is received also tends to be much lower than for the density and neutron measurements, natural gamma readings show more variability (are inherently more noisy).

So while the use of 1 cm spaced logging data may be useful for detecting coal seam margins, quantitative log analysis which is mainly directed towards determining properties of the clastic rocks beyond the coal does not require such densely sampled data. Pre-processing of logs by resampling them to 5 cm intervals will provide 4 measurements over a typical minimum detectable geological unit. Resampling also provides the opportunity for smoothing or filtering to be applied to improve data quality. The size of the geophysical data files that need to be manipulated is also reduced.

Porosity and clay content

Logging contractors often provide with the final borehole logging files, an interpretation of the porosity of the borehole strata. This involves a calculation, which is based on a simple rock model whereby the rock grains are assumed to be quartz with a density of 2.65 t/m^3, and any departures from the measured density are assumed to be due to fluid-filled pore spaces. A problem with this is that rocks containing grains that are lithic or are dominantly comprised of clay minerals, might have rock 'matrix' densities that are slightly greater than quartz (about 2.7 t/m^3). A better approach for porosity determination is to determine the matrix density from inspection of the density logs and to ensure that the calculated porosities are geologically plausible. This approach also allows variations in the calibration of different density tools to be accommodated.

For determination of the clay content, the usual calculation involves scaling natural gamma logs so that the maximum readings correspond to clay-rich materials and the minimum readings correspond to materials, which are deficient in clay (i.e. quartz rich). The main issue with this approach is that not all clay rich materials are emitters of natural gamma radiation. The main sources of natural gamma radiation are an isotope of potassium (^{40}K) and any uranium and thorium that might be present. Potassium is present in many clay minerals but kaolinite is a clay mineral that contains no potassium and is not detected by a natural gamma log. Similarly, sandstones that contain heavy minerals (rutile etc.) may include thorium and may be associated with anomalously high natural gamma readings.

Neutron logs provide an alternative approach to determining clay content. This is because neutron logs respond to the hydrogen that is present in the rocks. In clastic rocks, hydrogen is present in pore waters and in water bound within the clay minerals. If allowance is made for the water present in the pores via the porosity determinations from density logs, the amount of clay that is present can be inferred from neutron logs. It is often helpful to be able to calculate the clay content from both natural gamma and neutron logs.

Knowledge of the porosity and the clay content allows objective geological characterisation. For example, porous sandstone units can be identified as units with low clay contents and high porosities. In the case of claystones and siltstone, these both have high clay contents but the claystones have lower porosities. Gradational rock units can also be characterised. Correlation of units between holes is made easier.

Geophysical Strata Rating

Estimation of Uniaxial Compressive Strength (UCS) from sonic logs is practiced throughout Australia's coalfields. More recently, the GSR has been introduced as an empirical measure, which takes the sonic velocity, porosity and clay contents determined from the geophysical logs and provides a measure of rock quality on a scale of 10 to 100. The advantage of the GSR over sonic-based UCS estimations is that with the GSR, consideration is made of the geotechnical effects of variations in porosity and clay content, and the velocity measurements are corrected for the increase in velocity that occurs with depth.

The GSR, porosity and clay content are all objective measures of rock properties. Because they are obtained along the full length of a borehole, it is possible to interpolate them between boreholes to construct 2D and 3D models of the subsurface.

Modelling

Figure 1 shows an example of a section from a model of clay content based on the interpretation of natural gamma logs. This section is cut from a 3D model which has been flattened so that the top of the working coal seam is at 0 m elevation. To construct this model, the elevations of major coal seams and other key horizons were determined and then interpolated between boreholes. These interpolated horizons were then used to constrain the interpolation of the geophysical parameters between horizons. Through this process, variations in layer thickness could be accommodated. Figure 1 clearly shows how the data obtained from quantitative analyses of geophysical logs allows detailed stratigraphic information on the geological conditions at mine sites to be obtained.

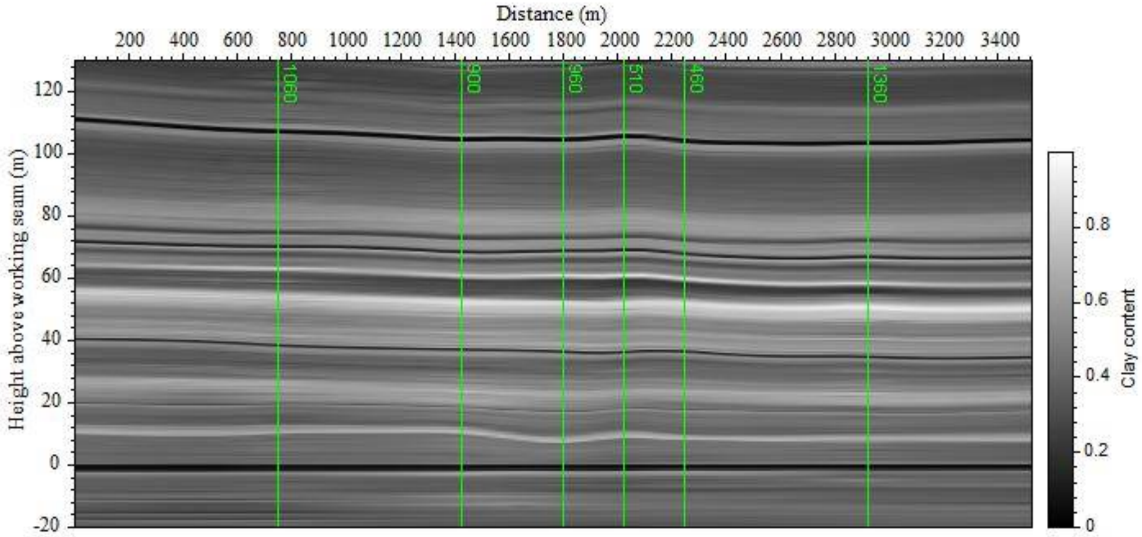

Figure 1. Vertical cross section through a 3D model based on the interpolation of clay content determined from natural gamma logs. Clay-rich bands have lighter colours and sandstones are grey. Coal seams are black.

Conclusion

This extended abstract briefly touches on how quantitative interpretation of geophysical logs can provide powerful understanding of geological conditions. Logs are routinely obtained in exploration boreholes but the geological and geotechnical benefits that the logs can provide are lost if their use is restricted solely to the determination of depths to coal seam margins. In undertaking quantitative log analysis, the physical basis of the logging measurements needs to be recognised. The logs should be resampled and filtered so that any noise in the data is reduced and the logs provide data at depth increments that match the reality of the measurements.

02SBA-03. MOVING WINDOW POWER SPECTRUM ANALYSIS OF POTENTIAL FIELD DATA : NEW TOOLS FOR IMAGING BASEMENT TOPOLOGY AND STRATIGRAPHY IN THE SYDNEY BASIN

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Spector & Grant (1974) published a novel, if not revolutionary, methodology to extract geological contacts (surfaces) from potential field (magnetics and gravity) images, utilising the radial power spectrum.

It has long been recognised that longer wavelength anomalies arise from deeper targets. By reducing the focus to tops of a continuum of equisized vertical prisms with unlimited depth extent, the method minimises many of the ambiguities inherent in potential field interpretation including target magnetisation/density contrast, location, strike and size. The target becomes an interface that is well suited to subhorizontal stratigraphic mapping in sedimentary basins.

Original applications in minerals exploration suffered sampling noise and computational shortcomings. The method has since been refined by others (Kivior & Boyd) to overcome noise limitations through window subsets, window size optimisation, and a moving window concept resulting in the more refined Moving Window Power Spectrum Analysis (MWPSA). Modern computing power readily available to geophysicists is also now up to the task.

The MWPSA method has been patented overseas by a major oil company. The company has embraced the method for mapping basin basement and suitable stratigraphy.

The concept is being developed by others including Geoscience Australia.

Preliminary work indicates up to 6 surfaces can be mapped in the Bowen Basin with the deepest surface at 1200 m depth.

This method could be applied throughout the Sydney Basin to existing magnetic and gravity datasets (airborne and ground) for both academic and commercial purposes. For example:

1) Using aeromagnetic data to map magnetic basement and strata with marked magnetic contrast (e.g. sills, tuffs).
2) Mapping the base of basalt flows
3) Using gravity data to map basement, faults and image coal seams.

Note that MWPSA processing is both computationally and labour intensive, and currently may cost more than the initial survey. That said, the results are still significantly lower cost compared to seismic and drilling.

There is potentially a niche application for gravity interpreted with MWPSA in environmentally sensitive and/or noisy areas such as exploring beneath urban areas where seismic, electrical and magnetic data cannot be readily acquired.

02SBB - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

02SBB-01. A GEOLOGICAL REVIEW OF THE COBBORA AREA, NSW

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The Cobbora exploration area is located on the western fringe of the Sydney-Gunnedah Basin in central NSW. Smaller reconnaissance style coal exploration programs were carried out in the 1970 to 1990's, but in the past 10 years two substantial exploration programs have defined the local geology and have resulted in some areas undergoing mine design.

The Cobbora area is defined as the southernmost part of the Gunnedah Basin. However, the local geology has been described using a mix of local and well-established descriptors from the nearby Western Coalfield, which is considered to be the northernmost area of the Sydney Basin.

A review has been carried out of the newly available exploration data to either reconfirm that the Cobbora area is part of the Gunnedah Basin or explore the possibility that it may instead be part of the Sydney Basin, or even a new sub-basin. The review aims to identify correlations and common naming conventions used within the Cobbora area against exploration areas in the southern Gunnedah Basin and the northern Sydney Basin. Key stratigraphic sequences have been identified and geophysical data are used to establish correlations.

02SBB-02. SEDIMENTARY AND COAL SEAM STRATIGRAPHY IN THE MAULES CREEK SUB-BASIN – AN UPDATE

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Early Permian geology of the Maules Creek Sub-basin comprises an early mafic (Werrie Basalt) and felsic (Boggabri Volcanics) volcanic episode with dominantly marine clastic sediments (Goonbri Formation). The early formations are overlain with a westerly grading para-dis-non conformable contact by late early Permian terrestrial sediments and coal seams (Maules Creek Formation).

The Goonbri Formation is now recognised to be a marine formation equivalent to the upper Dalwood Group in the Hunter Coalfield with thickness up to 50 metres in the east of the sub-basin. A 1 m thick pelletoidal claystone marks the boundary between the Goonbri Formation and the Greta Coal Measures in the Vickery area in the type bore VKY001C. The Goonbri Formation becomes coaly towards the northeast of the sub-basin.

The pelletoidal claystone of the Leard Formation is diachronous and is sourced from deeply weathered Boggabri Volcanics shed from paleotopographic highs to the west during periods of basin erosion (lowstands).

Recent exploration and mining in the Maules Creek Sub-Basin has allowed the five previous formal and informal coal seam naming conventions to be consolidated into the one stratigraphy. The new coal stratigraphy of the Maules Creek Sub-basin in decending order is: Herndale (2 splits), Onavale (3 splits), Teston (3 splits), Thornfield, Braymont (5 splits), Bollol Creek (New), Jeralong (3 splits), Merriown (3 splits), Velyama, Nagero, Northam (3 splits), Therebri (2 splits), Flixton, Tarrawonga (3 splits), Templemore (4 Splits), and Cranliegh (5 splits).

The Maules Creek and Leard formation names remain, as the predominant westerly source of sediment for these formations is not consistent with the northeasterly source for the Rowan and Skeletar formations of the Hunter Coalfield.

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02SBB-03. OVERVIEW OF GROUNDWATER RESPONSES TO LONGWALL COAL MINING IN THE SYDNEY BASIN, AUSTRALIA

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Longwall coal mining operations often depend on the hydraulic and geomechanical properties of the strata above the mined seam to limit environmental effects. The overburden strata in the constrained zone above longwalls plays an important role in controlling fracturing, depressurisation, change in hydraulic properties and therefore groundwater flow. A review of the current state of knowledge of these processes above longwall mines will be presented in this paper.

A number of detailed geotechnical studies have been undertaken to understand subsidence induced fracturing and its propagation above the seam. However, very few studies have addressed the change in hydraulic parameters that influence groundwater flow through the disturbed and undisturbed zone. Some studies have attempted to define the extent of the zone of fracturing, based on the responses at a number of operations worldwide and linking it to maximum surface tensile strains. These are mainly based on geotechnical understanding and changes in bulk hydraulic conductivity as this drives the increase in groundwater inflow into the underground workings. These studies mostly assume that the changes that occur are finite, however it has been shown that this is not the case, as the preferential pathways may change, the reduction in groundwater saturation can result in decrease in permeability and clays with swelling properties may result in reduction in fracture size or may completely close fractures. The observed pressure head reduction in the strata above the fractured zone may not necessarily be associated with water movement but rather with redistribution of stresses following the passage of the longwall.

Current groundwater modelling studies within the Sydney Basin generally assume at least one aquitard layer, which generally coincides with the geotechnical estimate of the height of the zone of fracturing. This layer serves to provide the limit to the vertical extent of longwall mining impact on groundwater. However, this layer may not hydraulically represent an aquitard, as its properties may be similar to the underlying and overlying strata. There are limited studies that characterise mineralogy and behaviour of these aquitard units and tracer techniques are rarely applied to study the degree of hydraulic disconnection or connection.

The groundwater response to longwall mining therefore requires a multidisciplinary approach including: geomechanics, hydrogeology and geochemistry. Although, generalisations can be made based on theory, or worldwide experience, this may not always be applicable to a specific site. This paper aims to present the current understanding of the depressurisation and the impact from underground mining on groundwater within the Sydney Basin by using examples from several underground operations and a wide monitoring network of multilevel piezometers. The paper also identifies the areas where knowledge gaps exist to better focus research directions.

02SBB-04. AN EVENT HORIZON IN THE SYDNEY BASIN: PASSAGE OF A FOREBULGE?

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The Sydney Basin is well exposed along the coastline of Sydney's eastern suburbs, where the Hawkesbury Sandstone comprises predominantly medium- to coarse-grained fluvial sandstones deposited as a set of stacked channels. However, a number of localities along the coast, from La Perouse to Manly (25 km), display an unusual succession of rocks over a 2–3 m interval, indicative of a change from the normal depositional regime of the Hawkesbury Sandstone. This succession includes: polymict pebble to boulder conglomerate with weathered, ferruginous shale clasts; beds with overturned cross bedding; metre-thick shale horizons that are commonly deformed into slump deposits with isoclinal folds and fluidised textures of sandy matrix; and thick overlying channel fill deposits of cross laminated medium- to coarse-grained sandstone with basal, rounded quartz pebble lags. The orientation of cross bedding commonly dramatically changes direction across this interval.

These features denote a change from a higher energy regime below (sandstone deposition in a developing basin), to a lower energy and even non-depositional regime (shale deposition, exhumation and peneplanation), and back to a higher energy regime (thick bedded, coarse-grained sandstone deposition) marked by a change in paleocurrent direction.

The changes across this compressed interval suggest a period when the basin was temporarily inverted and exposed to weathering and erosion (polymict pebble to boulder conglomerate on a peneplained surface), followed by renewed, rapid basin deepening (slump deposits, overturned cross bedding, thick overlying sandstone beds), with a change in the direction of paleocurrent flow. We interpret this succession to reflect the passage of a forebulge on the outer edge of the developing foreland basin (Sydney Basin) that developed in response to collision between the New England Orogen (NEO) and the Lachlan Orogen. Slumps and beds with overturned cross bedding are attributed to seismogenesis accompanying the passage of the forebulge, stemming, ultimately, from a period of increased orogenesis in the NEO.

02SBC - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

02SBC-01. CHANGES TO THE AUSTRALIAN COAL REPORTING GUIDELINES

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The 2003 edition of the Australian Guidelines for Reporting of Inventory Coal, Coal Resources and Coal Reserves (the Guidelines) originated in 1971 as the “Code for Calculating and Reporting Coal Reserves”. Successive editions saw it advance to the point where in 1989 the JORC Committee recommended the adoption of the 1986 edition, called the “Code for Reporting of Identified Coal Resources and Reserves”, as an appendix to the 1989 edition of the “Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves”.

Over time, revisions to each document have been published, with the 2012 edition of the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code), suggesting that “for guidance on the estimation of Resources and Reserves in relation to coal deposits and for statutory reporting not primarily intended for the purposes of the investing public reference be made to the Guidelines or its successor documents”.

The 2003 edition of the Guidelines continued to use suggested maximum distances around Points of Observation, within which Coal Resources could be classified as Measured, Indicated or Inferred. In recent years a groundswell of professional geologists began to question the application of these arbitrary limits, with no regard for other criteria.

Failing to recognise the geological complexity in a coal deposit results in inadequate representation of the risks in the Resource classification. This could potentially harm the operational viability of a mine and lead to poor investment decisions. During the last minerals boom investor risk was in some cases not properly addressed by Coal Resource reports issued under the direction of the Guidelines, with consequential damage to the reputation of the mining industry as an investment choice.

A reassessment of the application of the Guidelines was seen by many as needed when estimating and classifying Coal Resources. Only through greater confidence in the preparation of higher quality technical estimates and reports could confidence in the minerals industry at large be restored.

In 2012, the Coalfields Geology Council of NSW and the Queensland Resource Council, combined with a group of dedicated industry professionals, commenced a review of the 2003 edition of the Guidelines with the mandate to provide a better supporting document to the JORC Code. The review culminated in the publication of an exposure draft of the “Australian Guidelines for the Estimation and Classification of Coal Resources” in March of 2014.

Consideration of developing a best practice manual was assessed against a more generalist guideline when undertaking the review. Confidence in an estimation to then assist in the classification of Resources is now prescribed through assessment by a number of methods such as evaluation of the local geological conditions, data analysis through verification, statistical and geostatistical methods, geological modelling and identifying critical data.

This paper details the changes to the Guidelines and the challenges faced by the review committee in undertaking the review. The new guidelines provide an opportunity for technical professionals working with coal deposits to provide more assurance and confidence to the investing public through undertaking more appropriate studies that provide a more rigorous assessment and classification of Coal Resource risk.

02SBC-02. RESOURCE CLASSIFICATION IN COAL: IT'S TIME TO STOP GOING AROUND IN CIRCLES

Monica Davis

MD Geology, Newcastle, NSW

Since 1961 the Australian Coal Guidelines (under a variety of titles) has recommended the use of distances between boreholes for resource classification in coal. In each edition of the Guidelines, the maximum recommended distance between boreholes has been specified for each level of confidence in resource classification.

In this presentation, four geostatistics based methods of resource classification were applied to a dataset in the Sydney Basin, and the results compared to the recommendations of the Guidelines. When significant differences between the methods were discovered, the question of 'what were the recommendations of the Guidelines based upon?' was raised.

The source of the wisdom of resource classification in the coal Industry is unravelled, using interviews with present and past members of the committee across the past six decades, records of the Standing Committee for Coalfield Geology (now the Coalfield Geology Council of NSW (ed)), and letters between the SCCG and the Joint Ore Reserves Committee (JORC). The growing divide between the Australian Coal Guidelines and the JORC code through the late 1970's is illuminated, and begins to explain how the two reference documents became so disparate.

As the audience and purpose of resource reporting and evaluating project risk has changed over the past six decades, the technology that we use to assess confidence in coal estimation has not. This paper not only challenges the distances between boreholes that the Guidelines have recommended to date, it also challenges the concept of using distances in resource classification at all.

02SBC-03. CAN NEW STANDARDS IMPROVE COAL RESOURCE ESTIMATION AND REPORTING PRACTICE?

Tom Bradbury[1] & Sue Border2

[1]BSc (Hons), MAusIMM, Project Manager, Geos Mining Minerals Consultants. [2]BSc Hons, Gr Dip, FAIG, FAusIMM, Principal Geologist, Geos Mining Minerals Consultants

Recent implementation of JORC 2012 has tightened some definitions and added new checks for resource estimators to consider. CoalLog standards were designed to improve and upgrade the collection and coding of geological and geotechnical data, which ultimately can lead to improving efficiency and accuracy in resource estimation. The draft revision of the Australian guidelines for coal estimation and reporting also aims to improve standards.

Are the changes needed and will they work? We consider some examples of past poor practice and inconsistent resource classifications, both from the Sydney Basin and elsewhere.

Although compliance with JORC 2012 would eliminate some of the most extreme differences between resources defined by different competent persons, as resource classification relies on the judgement of a single competent person, some inconsistency in classification is likely to remain. It will not remove the option for some promoters to seek the competent person who will give the most generous figures.

Adherence to the maximum distances between points of observation in the old Australian coal resource guidelines may have improved consistency in classifications, but sometimes this was at the expense of geological common sense. Use of the maximum distances in unfavourable geological environments or with an insufficient distribution of core quality data, has led to some exaggeration of resources. We therefore applaud the removal of the standard distance buffers from the current draft coal resource guidelines. However the draft guidelines will leave a lot more discretion in classification to the competent person, therefore perhaps decreasing consistency in classification.

We conclude with some suggestions for consideration to improve efficiency and consistency in resource estimation and classification. We also recommend a system of peer review of resources, either to be recognised as best practice or as mandatory in future updates of standards.

02SBC-04. COAL EXPLORATION DATA INTEGRITY AND MANAGEMENT

Brett Larkin

GeoCheck Pty Ltd

The principal asset of nearly every coal mining company is the coal it has in the ground. However, the true size of this asset will only be known once it has been mined and maybe not even then. In the meantime investment decisions are based on a resource estimate derived from the company's exploration database. From one point of view then, the real asset that the company has is its data. Considering this, it is astounding how often the data's collection and management is left to the most inexperienced members or even non-members of the company.

Data integrity starts at the drill site. Issues here include:

- Coring the appropriate intervals
- Achieving the required core recoveries
- Good reconciliation of geologist and driller's depths
- Appropriate sampling
- Consistent geological logging using a thoroughly reviewed system such as CoalLog
- Recording only source data such as defect position rather than summary data such as RQD
- Quality core photography
- Timely geophysical logging
- Consistent geological and geophysical zero depths
- Well-calibrated geophysical tools

Data integrity continues during initial processing. Issues here include:

- Data entry that checks for invalid items, such as, incorrect codes or numerical values outside range.
- Double keying of numerical data such as analytical results.
- Checking that compulsory data such as unit depths, unit lithotypes, Rock Mass Units types, and sample numbers on analytical results, are entered.
- Checking for invalid combinations of items, such as depths out of order, percentages not adding up to 100%, appropriate qualifiers on lithologies, and seams out of stratigraphic order.
- Appropriate filtering and manipulation of the geophysical data.
- Appropriate adjustment of depths of non-geophysical data to the geophysical data.

Following data entry, integrity checks need to be made of the entire database by the project data manager. These include identification and rectification of:

- Data in inconsistent formats, for example, data that was collected using a slightly different dictionary to the one used in the database or data collected before the adoption of the CoalLog standard format.
- Missing data, for example, hole coordinates from the surveyors, lithological and sampling information from the data collection geologist, analytical results from the lab, geophysical data from the logging company, missing geophysically adjusted data, and seam interpretations from the analysing geologist.
- Incorrect data, for example, hole coordinates and seam naming. This is best performed using graphical output such as hole location plans and cross sections.

Finally, good data management is required on a continuing basis. Issues here include:

- Recognising that there is observational and interpretational data which can further be split into raw, working and finalised observational data and working and finalised interpretational data, each requiring different data management procedures.
- Preservation of raw data, including original hand-written coding sheets, data as initially collected on field tablets, unprocessed and unfiltered geophysical data.
- Regular backups.
- Ensuring that the data can be easily exported in a format for import into any system that requires it.

Poor data integrity checks and data management put at risk a company's most valuable asset, their exploration database.

02SBC-05. THE COAL QUALITY DATA EXCHANGE (CQDX) PROJECT – IMPLICATIONS FOR DATA UNDERPINNING RESOURCE REPORTING

Jared Armstrong

GSA member

A recent ACARP[1] project (C21014) examined the exchange of coal quality information between Geoscientific Information Management (GIM) Systems and Laboratory Information Management Systems (LIMS). This presentation examines the findings of the project, and its impact on data validation and data management that underpins resource reporting.

It was recognised that the process of exchanging coal quality data between laboratory and geological databases and modelling systems often required multiple data transformations and sometimes manual data transcription. Multiple data transformations and transcriptions increase the probability for the introduction of errors into the dataset. The ACARP project was commissioned to investigate ways the transformations and transcriptions could be minimised to increase efficiency and data quality.

The project achieved its primary objective by implementing a communication methodology (CQDX) through which both coal laboratory systems and mining companies could interact. The methodology produces more reliable data sets and clearer instructions between all parties involved which in turn reduces laboratory turnaround time. This was achieved by:

- Innovating and enhancing an existing technology to work with coal quality data
- Building a secure and sustainable methodology
- Proving its viability by demonstrating the technology works in a production environment
- Engaging the coal industry via a series of meetings, presentations and an information session during the project
- Researching and proposing a governance framework for effective management of this technology as a standard going into the future

The JORC Code has undergone a number of revisions since 1971, with emphasis on Materiality, Transparency and Competence at the core of each of revision. It is assumed future revisions will continue this focus. The theme of increased transparency is complemented by the CQDX ACARP project whereby a key deliverable was increased transparency of data delivery into geological databases and modelling systems.

To understand the relevance of CQDX to reporting a resource statement in accordance with the JORC Code, it is important to understand the various components that underpin a public statement. Like the tip of an iceberg, the public statement represents the results of the entire estimation and reporting process. The public statement is underpinned by geological models that are in turn supported by a range of detailed interpretations and evaluations based on available data as described in the recently circulated exposure draft of the Australian Guidelines for the Estimation and Classification of Coal Resources (March 2014). Thus, the quality of these data significantly influences the quality of the public statement.

Preparation of a public statement compliant with the JORC Code is no trivial task. Preparation of the model, interpretation of evaluations and preparation of original data sets takes significant time. The preparation of data sets using CQDX can significantly contribute to a reduction in this time and increase data reliability and validity. CQDX provides a degree of transparency, efficiency and compliance between laboratories and geological databases and modelling systems never before realised.

Reference

[1] Australian Coal Industry Research Program (ed)

02SBD - 39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

02SBD-01. COAL SEAM GAS IN NSW – 35 YEARS OF DISCOVERY IN A NUTSHELL

Malcolm Bocking

Bocking Associates CBM, Castle Hill, Australia

The first dedicated coal seam gas (CSG) boreholes in NSW and Queensland, at Appin and Blackwater, were drilled and hydraulically fractured by BHP's Hematite Petroleum, in 1980. Nine years earlier, similar trials had been undertaken in Alabama, USA, long considered the birthplace of the modern CSG industry. Those trials foresaw hydraulic fracturing of vertical boreholes as a way to remove gas ahead of mining. Simultaneously, based on experience at the Island Creek Mine in Virginia, USA, AGL stepped forward with Occidental to prospect in the Sydney Basin. They planned for the commercial production of methane utilising horizontal drilling in virgin coal long before its subsequent mining. The resulting 26 deep Moonshine and Bootleg holes were the first of more than 300 deep boreholes drilled by 30 Operators, to investigate CSG in NSW. To date, one commercial CSG field utilising both hydraulically fractured vertical boreholes and horizontally drilled boreholes, is producing at Camden, and a second is approved at Gloucester, both under the stewardship of AGL. Pilot production has also been undertaken by others elsewhere.

The CSG investigation holes that are drilled to evaluate the gas present, its distribution, producibility and origins, also reveal information on the enclosing stratigraphic sequence, the coal itself, its permeability, age, chemistry, origin, the enveloping stress field and any aquifers, as well as the presence of conventional gas and oil. They now illuminate these aspects, with a clarity not available from earlier drilling, across the Permo-Triassic Sydney Basin, its northward extension the Gunnedah Basin, the ancillary Gloucester Basin and their Triassic–Jurassic–Cretaceous counterparts the Clarence-Moreton and Surat Basins.

To date the information from 257 CSG exploration boreholes is available in the public domain. These, together with available information from three very deep-cored stratigraphic holes drilled for geothermal and sequestration studies, form the basis for this review. Largely cored and although generally less than 1200 m deep, the boreholes do provide continuously cored intervals of up to 1700 m, in holes up to 2220 m deep. Such material housed in the NSW Trade and Investment drill-core library, continues to support further studies such as the current IDTIMS chrono-stratigraphic program. (Some 55 000 coal exploration boreholes also exist in NSW, but, with some exceptions, are proprietary, shallower and clustered within the coal mining areas that cover only 10% of the coal basins of NSW.)

This data synthesis presents some lesser-known elements to the geology of the Sydney-Gunnedah basin as well as the state-wide patterns of CSG distribution, composition and origin and the extent of coal development. The results provide for a variable energy resource density of up to 25 PJ/km^2 for 'gas in place'.

Energy resource recovery and utilisation throughout the world follows various models and is provided with growth by emerging technologies. However, historic and recent environmental protection led changes to energy resources regulation, now limiting access to both coal and CSG in the energy rich basins of NSW. When these limitations are overlaid on the pattern of gas resource distribution, the available opportunities for development become apparent.

02SBD-02. OBSERVATIONS ON THE DISTRIBUTION OF COAL SEAM GAS IN THE SYDNEY BASIN AND THE DEVELOPMENT OF A PREDICTIVE MODEL

Scott Thomson[1], Duncan Thomson[1] & Peter Flood[2]

[1]Coalbed Energy Consultants, Lake Macquarie, Australia, [2]Top Education Institute, Sydney, Australia

Gas content and gas composition trends with depth have been investigated for the Sydney Basin.

Four distinct zones have been identified, which can be classified according to depth below ground surface. An upper low gas zone (Zone 1, 0–100 m), dominated by CO_2 and with very low gas contents (<0.7m^3/t), is underlain by a biogenic methane-rich zone (Zone 2, 100–~250 m), with a rapid rate of increase in gas content with depth, followed by a mixed gas zone (Zone 3, ~250–~600 m), comprising biogenic and thermogenic methane and magmatic CO_2, and having a lower rate of gas content increase with depth relative to Zone 2. Zone 4 (~600 m+) contains thermogenic methane and other 'wet gases'.

A model is proposed that provides a rationale for the origin and timing of emplacement of the various coal seam gases in the Sydney Basin.

02SBD-03. SYDNEY BASIN GAS LAYERING – THE HYDROCHEMICAL LINK

Agi Burra, Joan Esterle & Sue Golding

University of Queensland

The delineation of the extent of CO_2-rich gases and higher hydrocarbons in coal seam gas reservoirs in the Sydney Basin is important for reservoir production optimisation and also safety in under-ground coal mines.

Gas distribution in the Sydney Basin is complex and varied; however, some underlying patterns are discernable. Hydrocarbons of thermogenic origin at depth are overlain by shallower zones of biogenic methane. The depth of the interface between these two layers varies, but a zone of mixed gases is consistently present. Some areas also contain significant volumes of CO_2 gas in the mixed gas zone and it is commonly attributed to magmatic origins. CO_2 is not always present in intruded or heat-affected areas and it can occur in areas that were not subjected to igneous activity. An alternative hypothesis for the origin of the deep-seated CO_2 is from mineral dissolution and/or a by-product of methanogenesis through the acetate fermentation pathway. It is hypothesised that hydrodynamics and hydrochemistry of formation waters in the subsurface play an important role in defining the extent of coal seam gas layering: both by limiting meteoric influx (and thereby biogenic methane accumulations), as well as regulating the level of bicarbonate saturation and salinity in the groundwater (and thereby the presence of various gas types).

Meteoric influx penetrates along bedding and via vertical fractures. The shallow, hydrostatic (gravity-driven) flow is countered at depth by geopressured formation waters migrating towards lower pore pressures. A transitional zone where these two flow regimes meet is postulated to provide the conditions for the mixed gas zone region to develop. Overprinting the hydrodynamic framework is the hydrochemical facies development of groundwaters from fresh, bicarbonate-rich composition in highland (or inland) recharge areas towards more saline and sodium-rich makeup in coastal or low-lying discharge areas. Formation waters associated with methanogenesis exhibit sodium-rich and brackish characteristics. On the other hand, excess CO_2 from bicarbonate-rich waters are normally precipitated as carbonates along flow paths, and may also be liberated under marked chemical changes, for example, in salinity or alkalinity. In these instances, CO_2 may be liberated and trapped as a gas in the coal matrix.

In this manner, hydrodynamic and hydrochemical changes along the groundwater flow path result in the development of gas layering in the subsurface. A dataset consisting of over 2000 coal seam gas samples from ~100 boreholes was collated from publically available data (supplemented by a private dataset from the Hunter Coalfield), including approximately 88 gas carbon isotope results to assist with gas origin interpretation. Hydrochemical, porosity and permeability data were sourced from literature and used to identify the extent of groundwater flow under hydrostatic pressure, as well as assisting in the delineation of various hydrochemical regions in the basin.

Results show that gas contents increase with depth in the hydrostatic flow section of the strata, culminating in 'peak gas contents' at the top of the transitional flow zone. Below this horizon, the influence of biogenic and hydrostatic sources decrease, and the appearance of thermogenic ethane signals the upper extent of the geopressured waters. A mixed gas zone exists between these two flow layers that contains significant volumes of CO_2 gas in some (mainly, up-gradient and fresh water hosting) regions. The origin of this deep CO_2 gas is thought to be magmatic; however, due to the hydrochemical development of groundwater along flow path (including with depth) from bicarbonate-rich fresh water to more Na and Cl-rich brackish waters, the deep CO_2 gas in the mixed gas zone may alternately have originated from the excess bicarbonate contents in the groundwater where abrupt chemical changes in parameters such as salinity, temperature or pressure have occurred. As a result of the extent of groundwater facies in the basin, up-gradient fresh-water regions, particularly in the vicinity of geological features assisting the rapid and deep penetration of freshwaters into sediments (e.g. extensive fracture sets associated with large regional monoclines around the edges of the basin), appear to host large volumes of deep CO_2 whereas more saline and Na and Cl-rich waters down-gradient are almost completely devoid of deep CO_2 gas. The base of the hydrostatic flow regime marks the disappearance of biogenic methane and high concentrations of CO_2 from reservoirs, leaving thermogenic gases (including higher hydrocarbons) dominant in deep gas accumulations.

The significance of these findings is that gas zonation can be traced across the coal seam deposits of the Sydney Basin, and the various gas markers identified such as the 'peak gas' (or ethane) horizons can be mapped with more confidence across the region. Additionally, groundwater chemistry can provide further assistance in the tracking of likely coal seam gas accumulations in the subsurface, particularly in the context of delineating the undesirable, deep (and high volume) CO_2-accumulations, which are associated with outbursts in underground coal mines and considered an impurity in coal seam gas (CSG) produced for energy utilisation. This study introduces key gas zone horizons that can be identified and utilised for the optimisation of CSG exploration and production, and gas drainage activities.

A more detailed discussion of the data, phenomena and conclusions presented here is provided in Burra *et al.* (2014).

Burra A, Esterle J & Golding S 2014. Coal seam gas distribution and hydrodynamics of the Sydney Basin, NSW, Australia. *Australian Journal of Earth Sciences* **61**, 427–453.

02SBD-04. GAS PENETRATION INTO FINE PORES OF COALS: COMPARING SYDNEY BASIN AND NORTH AMERICAN COALS

Richard Sakurovs[1], Lilin He[2], Yuri Melnichenko[2], Tomasz Blach[3], Leslie Ruppert[4] & Tony MacPhee[5]

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The porous nature of coals allows them to store and release a large amount of gas, a property important in determining the rate and amount of fugitive emissions from coal seams. However, the nature of the pores and how gas is stored and released is still poorly understood.

Small-angle neutron scattering (SANS) and ultra small-angle neutron scattering (USANS) are increasingly used to characterise, non-destructively, the pore size distribution of materials over the size range 1 nm to 10 µm. SANS and USANS record the scattering from all pores, including pores that are inaccessible to fluids and therefore cannot be measured with techniques that involve gas sorption or fluid intrusion, such as mercury porosimetry. Recent developments have allowed SANS and USANS to be able to discriminate between pores accessible to gases and those inaccessible to these gases.

We determined the fraction of inaccessible pores as a function of pore size in eighteen bituminous Sydney Basin coals and six coals of similar rank from the US and Poland. For pores of greater than 50 nm radius, all pores in all coals were largely accessible to methane. In the case of pores of around 8 nm size, regional differences were apparent. In the Sydney Basin coals the fraction of 8 nm pores that were accessible to methane increased with increasing amounts of inertinite and the relationship was linear, suggesting that all of these pores in inertinite are accessible by methane. In contrast, pores of this size in inertinites from the eastern U.S. and Poland were not accessible to methane. Regional differences in inertinite behaviour have been suggested before but this was the first time that such differences have been observed (Sakurovs *et al.* 2012) .

The work reported here reports an extension of this study using SANS. Further vitrinite-rich and inertinite-rich US coals were examined, and they followed the trend established previously for US coals. Seven western Canadian coals were also examined. Although the western Canadian coals were found to be more similar to Australian coals in their relationship between maceral composition and closed porosity than they were to US coals, there were also systematic differences from Australian coals. These differences may explain previously suspected regional variations that are not observed by standard tests of coal properties but nevertheless affect their industrial utility. These results also suggest that relationships between coal permeability and other coal properties found for some coals may not be universally applicable.

Sakurovs R., He L., Melnichenko Y. B., Radlinski A. P., Blach T., Lemmel H. & Mildner D. F. R. 2012. Pore size distribution and accessible pore size distribution in bituminous coals. *International Journal of Coal Geology* **100**, 51–64.

MAWSON LECTURE

Early vertebrate evolution – some contributions from the rocks of East Gondwana (Australia–Antarctica)

Dr Gavin Young

Research School of Earth Sciences, The Australian National University

'Deep Time' (the great age of the Earth) was only widely accepted in western science less than 200 years ago. This gave time for species to evolve, and enabled Charles Darwin to formulate his evolutionary theory. As tangible evidence of past evolutionary change, fossils (biological inclusions in sedimentary rocks) received detailed discussion in Darwin's revolutionary book (1859).

At that time fossil vertebrates from Australian rocks were hardly known, although the giant extinct marsupial *Diprotodon* from Wellington caves was noted by Darwin (1859). However much older fossils had already been discovered. Reverend W. B. Clarke (before 1844) had identified Devonian fossil bones in coastal red mudstones near Eden, NSW (the first Southern Hemisphere record, recently revealing the giant Late Devonian lobe-finned fish Edenopteron). In the 1870's the Lower Devonian limestones of Burrinjuck (NSW) and Buchan (Victoria) yielded fossil bones, and in 1911 during Scott's Antarctic Expedition Debenham and Griffith Taylor (the Australian geologists) found fish fragments in glacial moraine at Mt Suess, the first vertebrate fossils from the Antarctic continent, and the first identifiable fossils from the 'Beacon Sandstone'. This thick sedimentary sequence in the Transantarctic Mountains yielded Permian *Glossopteris* leaves to Scott's Polar party several weeks later (found with their bodies in November 1912). The announcement in London (1914), that the fossil fish remains proved the existence of Devonian rocks in Antarctica, therefore caused some surprise, and raised important paleogeographic problems to explain how freshwater fish known from the Old Red Sandstone of Scotland could reach a latitude of 77^{o} south.

Ongoing research on these, and numerous subsequent fossil discoveries across our continent, has clarified issues of Devonian continental position and paleogeography, and documented a surprising diversity of vertebrates from East Gondwana during the time interval when the first forests and complex terrestrial ecosystems were evolving, and our ancestors moved from water onto land. Numerous examples demonstrate the middle Palaeozoic contiguity of Antarctica and Australia, to form the eastern part of the Gondwana supercontinent. In addition, much older vertebrate fossils from central Australia represent the oldest vertebrate hard tissues from the fossil record (late Cambrian of western Queensland), and the world's oldest diverse fish fauna (the *Arandaspis* assemblage of the Amadeus Basin). The latter demonstrates that a Gondwanan distribution pattern was already established by Ordovician time.

The exceptional preservation in our Devonian vertebrate fossils was recognised in the 1950s-60s, when the British Museum removed to London over 2000 specimens from two internationally significant sites: Burrinjuck (near Canberra), and Gogo (Kimberley, WA). High resolution computed tomography of these remarkable fossils at the ANU now provides new data on jaw evolution, brain morphology, and function of major sense organs in ancient vertebrates, at a level of detail Charles Darwin could never have imagined.

WEDNESDAY 9 JULY

PLENARY

PLEN3-01. GROUNDWATER AND THE GEOSCIENCES: MILES TO GO BEFORE WE SLEEP

C T Simmons

National Centre for Groundwater Research and Training, Australia, and School of the Environment, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia; E-mail: craig.simmons@flinders.edu.au

This talk describes important international challenges and opportunities for groundwater. A myriad of policy/management, research, technical practice, education/training and overarching governance/institutional matters are described. Possible solutions and strategies are considered. The new Australian *National Groundwater Strategic Plan* is outlined and provides a strategic vision for Australian groundwater science, management and policy for the next 10 years to ensure that we sustain our groundwater resources and enable on-going access to this increasingly valuable resource. The strategic planning process, outcomes and lessons learned may be of value to other regions of the world. This talk demonstrates that there has never been a greater opportunity for international groundwater research, education, management and policy reform to make a difference for the long-term management and sustainability of groundwater resources worldwide.

ENVIRONMENT

03EVA – COAL SEAM GAS AND GROUNDWATER

03EVA-01. HYDROGEOLOGICAL MANAGEMENT AND RESEARCH FOR A MAJOR CSG PROJECT

Andrew Moser

Origin Energy, Brisbane, QLD 4001, Australia

While many people are familiar with a limited range of potential or perceived impacts from coal seam gas production, few realise the breadth of hydrogeological activities required to address regulatory compliance and social license to operate issues.

Origin, as the upstream operator of the largest of the Queensland CSG to LNG operations, oversees a portfolio of management and research activities, which together would likely constitute the largest ever single groundwater project in Australia.

This presentation will briefly cover the major areas of hydrogeological operations for the Australia Pacific LNG project including:

- baseline surveys;
- monitoring bore network construction and operation;
- springs baselining and monitoring;
- aquifer and aquitard static and numerical model refinement and parameterisation;
- regional flow dynamics;
- subsurface and ground surface movement monitoring;
- interconnectivity studies;
- aquifer injection programs; and
- impact mitigation measures.

The role of research initiatives within these scopes will also be addressed. These programs have already yielded a step change in the extent of available groundwater data in the Surat Basin, and the potential for major revision of some long-standing concepts of Great Artesian Basin hydrogeology.

03EVA-02. The Law and Reality of the Coal Seam Gas Industry in New South Wales and Queensland

Adam Edwards

ANU College of Law, Australian National University, Canberra, Australia

The Coal Seam Gas (CSG) industry in Australia is relatively immature compared to that of mining and conventional oil & gas production. As such existing environmental legislation and administrative processes may not be suitably developed to adequately environmentally manage the rapid development of the industry. This paper critically reviews federal and state environmental legislation as it applies to the development of CSG and analyses the effectiveness of the Environmental Impact Assessment (EIA) process and public engagement in granting licences to develop CSG.

Federal legislation generally and until recently has had limited influence over the management of environmental impacts of CSG, however both NSW and Queensland legislation does not comprehensively cover all possible environmental and community concerns. NSW is principally caught by such legislation as the Petroleum (Onshore) Act (1991) and Environmental Planning and Assessment Act (1979), with similar legislation in Queensland, and Federally by the Environment Protection and Biodiversity Conservation Act (1999) amendment - Water trigger.

Current EIA is judged by many not to be adequate to address the developing CSG industry, and there seems to be little environmental reconciliation undertaken. The NSW Land & Environment Court has defined the legality of an Environmental Impact Statement, as one that is comprehensive in the treatment of the subject matter ("not bamboozling"), objective ("not biased by the consultants towards their employer"), and one that alerts decision makers and the public to the effects on the environment and the consequences to the community in carrying out the activity. And smart gas companies should also point out how they would manage any impacts on the environment.

But in the legal case of O'Connor and O'Connor v Arrow (Daandine) Pty Ltd (2009) (Qld) we see an illustration of the general confusion CSG activities are licenced under, where a lease was granted under the Petroleum and Gas (Production and Safety) Act 2004 (Qld), and environmental authority under Environmental Protection Act 1994 (Qld); a water pipeline to discharge and treat waste water associated with CSG 2.8km in length was judged to be "an authorised activity" under the licences, but that the proponent had not given notice of entry in relation to that activity. Such cases illustrate the lack of engagement with landholders and ineffective or incomplete environmental assessments prior to the development of projects.

03EVB – COAL SEAM GAS AND GROUNDWATER

03EVB-01. IMPACTS OF COAL SEAM GAS EXTRACTION ON WATER RESOURCES AND WATER-RELATED ASSETS IN EASTERN AUSTRALIA

David A Post

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Coal seam gas extraction may potentially impact the water resources of a region in a number of ways. These can include pressure head loss due to groundwater pumping, reductions in low flows in surface water systems, disposal of co-produced water, as well as changes in water quality. These changes in the water resources of a region may then impact on water-related assets within that region, including ecological, economic and socio-cultural assets. Not all of these impacts will be direct. Some will be indirect (where a change in one factor can lead to other changes, for example changes in groundwater level leading to changes in the low flow regime of a river). Some impacts will also be cumulative, where the impacts of coal seam gas extraction at multiple locations may lead to impacts which are greater than the additive impacts of each extraction considered in isolation.

To help determine these impacts, the Bioregional Assessment Programme has been developed (www.bioregionalassessments.gov.au). This programme is a collaboration between the Department of the Environment, the Bureau of Meteorology, CSIRO Water for a Healthy Country Flagship and Geoscience Australia. It aims to provide a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas (and coal mining) on the water resources of a region.

This presentation will provide an overview of the issues related to the impacts of coal seam gas extraction on surface and groundwater resources and water-related assets in six bioregions across eastern Australia. The methodology to determine these impacts will be described, and results to date will be presented.

03EVB-02. PROPAGATING UNCERTAINTY FROM GEOLOGICAL TO ECOLOGICAL MODELS

Luk Peeters[1], Dan Pagendam[2] & Brent Henderson[3]

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Bioregional assessments aim to estimate the cumulative impact of coal mining and coal seam gas development on water related assets in a selection of bioregions across Australia. A crucial part in assessing that risk is quantifying the uncertainty associated with a predicted change in a probabilistic manner.

The overarching philosophy of the Bioregional Assessment Programme requires all research to be transparent, reproducible and repeatable. The methodology also needs to be generic and flexible as predicting the impact of coal related activities will entail integrating different scientific disciplines, at different spatial and temporal scales. In addition to these conditions, the methodology needs to be robust even in data-sparse or data-poor regions.

A crucial starting point for the uncertainty methodology is that every aspect of the model needs to be open to scrutiny. Any numerical aspects of the models that can be changed in an automated fashion will therefore be included in the formal uncertainty analysis. There will always be a number of model choices and assumptions that cannot be changed automatically. In the documentation of these assumptions it is necessary to incorporate the motivation of the particular choice or assumption, the available alternatives and, essentially, the perceived effect on the prediction.

The latter is a key concept in the methodology; for each system or subsystem for which an uncertainty analysis needs to be carried out, a clear prediction needs to be identified. This is a single model output, well defined in space and time, for which the uncertainty needs to be quantified. Ultimately these metrics will culminate in the assessment of the effect of coal development on an asset.

After defining the prediction, a global sensitivity analysis will be carried out. In this sensitivity analysis all aspects of the model that potentially can contribute to uncertainty will be incorporated to identify the most influential aspects that dominate the uncertainty in the prediction. Only the most influential factors will be included in the following uncertainty analysis.

In the absence of observation data, the prior uncertainty in each factor, obtained from hard data or expert elicitation, will be propagated to the prediction using Monte Carlo simulation. When relevant observation data are available, i.e. data that are able to constrain the factors that influence the prediction, a Markov Chain Monte Carlo procedure will be implemented.

The environmental simulation models that will be used in the Bioregional Assessments, especially the groundwater models, are notorious for having long runtimes. To reduce the computational demand and to be able to run the 1000's of model runs needed for the uncertainty analysis, a model emulator will be created for each metric.

The uncertainty methodology is generic and flexible, firmly founded in probabilistic uncertainty propagation based on both hard data and expert elicitation, whilst still highly automatable and computationally tractable through the use of model emulation.

03EVB-03. GROUNDWATER MODELLING IN THE BIOREGIONAL ASSESSMENT PROJECTS

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The Bioregional Assessment Projects aim to investigate the cumulative impacts of large coal mines and coal seam gas upon water dependant ecological, cultural and economic assets. Currently under investigation are six Bioregions (Northern Inland Catchments, Lake Eyre Basin, Clarence-Moreton Basin, Northern Sydney Basin, Southern Sydney Basin and Gippsland) that comprise 15 sub-regions, which are the reporting unit. Each of the 15 sub-regions has a different level of proposed development, data availability and number of assets, which means that the modelling approach within each sub-region will be different.

The diversity in the numerical models being applied across the Bioregional Assessment Programme makes consistency in the model development impossible, but consistency in the application of the models will ensure that the results in each sub-region are comparable. Each model will be run using a single coal resource development pathway representing a likely future level of development rather than a series of scenarios representing a range of possible levels of development. A main focus of the modelling is in categorising the uncertainty in the prediction of the impact of the coal resource development pathway upon the assets; this will entail the uncertainty in the conceptual model, model parameters and future climate forcing (see Peeters et al presentation for more details).

The groundwater modelling undertaken in this phase of the Bioregional Assessment Programme aims to build a legacy for the future. Where possible, these models will be made available publicly to ensure the transparency of results by enabling anyone to reproduce the results that will be reported as well as being a starting point for future development of numerical groundwater models in these sub-regions.

03EVB-04. GEOLOGICAL AND HYDROGEOLOGICAL DATA ANALYSES TO SUPPORT BIOREGIONAL ASSESSMENTS IN THE CLARENCE-MORETON BASIN

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Various geological and groundwater data have been collated to support the bioregional assessments of the impacts of coal seam gas and large coal mining developments on water-dependent assets in the Clarence-Moreton bioregion (eastwards-draining part of the Clarence-Moreton Basin). These data sets underpin the conceptual models for bioregional assessments; however, they do impose constraints on the model's ability to predict potential impacts. As the data sets are sourced from different institutions located in two states, Queensland and New South Wales, they often have inconsistent formats with varying quality standards.

In order to maximise the usefulness of the data and facilitate its quality assessment process, a number of tools and workflows were developed to unify the data formats. A 3D geological model has been constructed to integrate the existing geological and geophysical data and knowledge. The pre-existing drill logs, core profiles, seismic cross sections, and other measured data form the skeleton of the model, and the model was then populated by spatial interpolation in GoCAD (Paradigm). Stratigraphic boundaries, lithology and major faults were also represented in the model. The temporal trends and spatial patterns of water levels and water quality were plotted using Kriging, and also investigated using nonparametric statistics: the Mann-Kendall trend test and the Theil-Sen estimator of the slope of the trend. Permeability measurements from drill stem testing were converted to hydraulic conductivities under consideration of the influence of temperature on water viscosity. Specific capacity and other pumping test data were used to evaluate transmissivity using the TGUESS method (Bradbury & Rothschild 1985). Variogram analyses were also conducted for hydraulic parameters along some down-hole profiles and throughout the basin. Where stratigraphic log data were missing or unreliable, well-screened intervals were assigned to an aquifer based on the stratigraphic boundaries (formation tops) from the 3D geological model. Water chemistry data were used to identify possible surface–groundwater interactions, as well as hydraulic conductivity between deep and shallow aquifers. Uncertainty analysis is a key component of this project, and different uncertainty quantification techniques have been proposed based on the data type, quality and density. The output of this analysis has an uncertainty description where the prediction uncertainty arising from the uncertainty of source data can be evaluated through deterministic uncertainty propagation or other stochastic methods.

The integrated methods and workflows developed during this project can be transferred to other sedimentary basins to assess the potential impacts of CSG activities or coal mining on water resources.

Reference

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03EVC – COAL SEAM GAS AND GROUNDWATER

03EVC-01. PERMIAN AND TRIASSIC HYDROGEOLOGY OF THE SOUTHERN SYDNEY BASIN: IMPLICATIONS FOR COAL SEAM GAS DEVELOPMENT

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The prospective Permian coal seam gas regions within NSW are significantly different from the younger Jurassic coal seam gas targets that are currently being exploited in the Surat Basin in south-eastern Queensland. The southern Sydney Basin is home to AGL's coal seam gas Camden Gas Project (CGP), which has been operating since 2001 and produces 5% of NSW's gas. The area is characterised geologically by laterally continuous stratigraphy including low permeability Permian coals and a lack of productive aquifers, formed following deep burial in compressive foreland basin conditions. Overlying the Permian sediments are several Triassic sandstone units (including the regional Hawkesbury Sandstone aquifer) separated by extensive claystone units that form tight aquitards. In contrast, the intracratonic Surat Basin is characterised by shallower burial, younger stratigraphy, and relatively less diagenesis, resulting in preservation of porosity and permeability and, therefore, productive aquifers surrounding the targeted coal measures.

The CGP consists of 144 gas wells (of which 97 are currently operational), low-pressure underground gas gathering pipes and a gas plant facility. In the year July 2012–June 2013, approximately 4.7 ML of deep groundwater and 5.5 PJ of natural gas (96% CH_4) were produced from the CGP wellfield. These produced water volumes are several orders of magnitude less than those associated with the Surat Basin gas wells. The conceptual hydrogeological model of the CGP, based on data collected from the CGP, indicates the negligible hydrogeological impact extraction of coal seam gas has had on the shallow beneficial aquifers and surface water within the region.

One of the key indicators of separation between the water bearing zones of the Permian coal seams and the shallower Triassic sandstone aquifers is the fact that many of the operating wells have been dewatered to the point where they now produce negligible amounts of water from the coal seams and are not deriving water from adjacent groundwater systems. Given the proximity to industry in the Sydney metropolitan area and low water volumes, management of produced water is relatively easy. There are no water gathering pipelines and the treated produced water is recycled for beneficial use without the need for industry operated water treatment plants, as distinct from many of the coal seam gas fields in other parts of Australia.

03EVC-02. BASELINE HYDROCHEMICAL AND ISOTOPIC STUDIES OF GROUNDWATER AND SURFACE WATER IN THE GLOUCESTER BASIN, NSW

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Groundwater level and quality monitoring programs provide the primary scientific data to assess potential impacts to groundwater and surface water resources from coal seam gas (CSG) extraction. Hydrochemical and isotope studies are important verification techniques in the development of conceptual models for connected groundwater and surface water systems, and define natural or pre-development baseline conditions.

The Gloucester Basin is a structurally complex geological basin comprising Permian sedimentary and volcanic rocks that have been folded into a synclinal structure. The groundwater system comprises four main hydrogeological units that overlie largely impermeable Carboniferous basement rocks: alluvial deposits along major creek lines, shallow (<150 m) fractured rock zones, and a thick succession of low permeability coal measures comprising interbedded coal seams and interburden units of very low permeability.

Currently there are 45 groundwater-monitoring bores and 9 surface water-monitoring sites installed within AGL's Stage 1 Gas Field Development Area (GFDA) in the northern part of the basin. Groundwater monitoring has been carried out since 2011. Nested monitoring bores were installed at several sites to assess the water quality characteristics of the different hydrogeological units. Two comprehensive water quality sampling events were undertaken in 2011 and 2013, with further sampling events and isotope studies carried out as part of gas flow testing programs and hydrogeological investigations of fault zones.

Groundwater quality is variable but typically poor, with salinity generally decreasing with depth. Groundwater in the alluvial deposits is fresh to brackish, shallow rock groundwater quality is brackish, and groundwater from the interburden and deep coal seams is brackish to slightly saline. Groundwater hydrochemical types vary between Na–Cl to Na–Cl–HCO_3 dominant. Dissolved metals are present at low concentrations. Naturally occurring hydrocarbons have been detected in all hydrogeological units and presumed to originate from the coal seams. Dissolved methane gas is also present in all hydrogeological units, being at lowest concentration in the alluvium (<0.05 mg/L) and generally increasing with depth, with interburden units and deep coal seams having moderate to high concentrations (up to ~30 mg/L).

Environmental isotopes show that all groundwater is derived from meteoric recharge and generally increases in apparent groundwater residence time with depth. Radiocarbon isotope analysis of groundwater samples shows that alluvial aquifers contain modern and sub-modern water (<1000 years before present (BP) on average). Groundwater in the shallow rock system was found to contain water that was on average 12 000 years BP. A combination of radiocarbon and chlorine-36 dating indicates that groundwater in the deeper interburden and coal seams (below 300 m) is much older (>300 000 years). Groundwater age was found to increase with depth at the nested monitoring bore sites.

This paper presents the results of the hydrochemical and isotope studies used to confirm the hydrogeological conceptual model and to assess potential hydraulic connection between the hydrogeological units.

03EVC-03. ASSESSMENT OF AQUIFER/AQUITARD CONNECTIVITY IN THE GALILEE AND EROMANGA BASINS USING GEOLOGY, HYDROCHEMISTRY AND $^{87}SR/^{86}SR$ ISOTOPES

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An integrated geological and hydrogeological study is currently being undertaken in the Galilee and Eromanga basins as part of an investigation that aims to assess the degree of connectivity between Permian coal seams of the Galilee Basin and the overlying aquifers of the Great Artesian Basin (GAB).

Previous studies of groundwater hydrology in the GAB have shown that there are two main aquifer sequences that can be identified based on the differences in their potentiometric surfaces and chemical character. The lower aquifers (Jurassic–Lower Cretaceous) are artesian, with water of 500–1500 mg/L and of Na–HCO_3 type. The upper Cretaceous aquifers are mostly sub-artesian, with salinities of 1000–3000 mg/L and Na–Cl type.

To better study the potential relation between these basins and their water-bearing formations we have also utilised multivariate analysis of hydrochemical data, including within the same aquifer group. Historical samples (365) sourced from the DNRM groundwater database were used for this purpose. In a first step, a hierarchical cluster analysis (HCA) of water chemistry data was carried out, leading to the identification of four distinct hydrochemical clusters. In the upper aquifer group of the GAB, samples of the Wallumbilla Formation are assigned mostly to the cluster 1 and 4, while the other formations of the upper group typically clusters as 2 and 3; this indicates that the Wallumbilla Formation is chemically different from the other formations. In the lower Jurassic aquifer group of the GAB, samples of the Hutton Sandstone are mostly within clusters 1 and 4, whereas samples from the other units are mostly assigned to cluster 2.

In order to determine whether the differences in hydrochemistry are related to recharge processes or water–aquifer interaction, 65 samples were analysed for $^{87}Sr/^{86}Sr$ (the Sr isotope ratio is controlled mostly by interaction with the aquifer material). The analysis shows that there is a high degree of variability of $^{87}Sr/^{86}Sr$ signatures in the groundwater, with values ranging from low radiogenic ratios to close to the Phanerozoic seawater ratio (0.704960 to 0.711989: 46 samples). However, there is also a group with highly radiogenic ratios that have not previously been identified in GAB aquifers (0.712314 to 0.724204: 19 samples). Most of the high radiogenic values were identified from the Triassic units of the Galilee Basin, but two are from the Hutton Sandstone and the Westbourne Formation, respectively. All the samples with highly radiogenic strontium isotope ratios can be linked to one of the hydrochemical clusters found in the HCA, suggesting that aquifer mineralogy is a major control on the groundwater composition.

03EVC-04. INTERPRETING GROUNDWATER CHEMISTRY TO FRAME WATER RISKS OF CSG DEVELOPMENT

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Water issues represent the greatest risk to the developing CSG industry. While a number of numerical models have predicted possible drawdown of water levels in some aquifers, these models have necessary simplifications and assumptions. Groundwater chemistry including stable and radiogenic isotopes can be used to aid interpretation of groundwater flow paths and reactions.

This work is using company and government water chemistry data to aid understanding of connectivity, groundwater flow paths and geochemical interactions. This is being done through a 3-D visualisation system that combines the latest 3-D geological model of the basin with water chemistry analyses. Geochemical and statistical analyses will also be combined with reactive transport modelling in a 3-D visualisation system. The database and 3-D Vis system will be presented and initial findings will be discussed.

03EVD – COAL SEAM GAS AND GROUNDWATER

03EVD-01. FAULT SEAL CHARACTERISATION FOR CSG–AQUIFER INTERACTION

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When forecasting the potential for interaction between Coal Seam Gas (CSG) development and adjacent aquifer systems at regional scale, an important consideration is to adequately characterise the seal potential of faults. A number of fault seal analysis techniques applied in conventional hydrocarbon exploration can be augmented with hydrodynamic data to make fault seal interpretation more robust. Across-fault seal potential is normally assessed first by juxtaposition analysis using Allan diagrams. Across fault membrane seal capacity has been shown to effectively be estimated using shale gouge ratio analysis that generates a permeability forecast given the observed fault throw distribution and the nature of shale volume fraction that has been in contact with the slip surface. Up-fault leakage potential can be estimated by examining the fault zone architecture in conjunction with the *in-situ* stress regime. All of these methods can be enhanced with standard hydrodynamic analysis of the pressure, salinity and temperature data. An approach to integrated fault seal analysis is presented that can be used to estimate fault seal properties relevant to dynamic simulation aquifer response to CSG development.

03EVD-02. HYDROGEOLOGICAL FIELD INVESTIGATION OF A FAULT ZONE IN THE GLOUCESTER BASIN, NSW: IMPLICATIONS FOR ASSESSING REGIONAL GROUNDWATER IMPACTS

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A critical stage in assessing impacts of coal seam gas (CSG) extraction on groundwater and surface water systems is developing a conceptual framework for how these systems are connected and, in particular in geologically complex areas, the role of faulting in groundwater flow and gas migration. However, often there are limited field measurements of hydraulic properties of faults in the study area, leading to large uncertainties in the conceptual model and numerical predictions. Field investigations within AGL's Gloucester Stage 1 CSG development area identified a strike-slip fault in the vicinity of gas test wells, providing an opportunity to investigate the hydraulic characteristics of the fault zone.

The Gloucester Basin is a structurally complex geological basin formed during the Permian. Seismic surveys show that the petroleum exploration licence (PEL) area is dominated by west-dipping strata intersected by a number of westerly-dipping thrust faults and near-vertical oblique strike-slip faults. The target fault for this study is an easterly-dipping strike-slip fault, which in the upper 200 m, appears to splinter into a number of related structures within a broad 300 m wide fault zone.

A comprehensive testing and monitoring bore network was installed within and adjacent to the fault structure. The hydraulic characteristics of the fault zone were investigated by inducing drawdown in both the fault zone (in a three-day pumping test) and the adjacent deeper coal seam water-bearing zones (29-day gas well flow test) and monitoring the effects on the shallow groundwater system. As well as drawdown data, water samples were collected and analysed for groundwater quality, dissolved methane content, isotopic composition and age.

Test pumping within the fault zone indicated that the fault zone did not cause strong preferred longitudinal flow, but rather comprises a heterogeneous, weakly transmissive zone in the near surface. By contrast, depressurisation of coal seams during the 29-day 'Stratford 4' flow test caused no drawdown in the shallow groundwater monitoring bores within the fault zone. Hydrochemical parameters did not change significantly in the shallow groundwater during or after the flow test, with the exception of dissolved methane, which declined within the fault zone. This paper presents the results of the fault investigation and implications for the role of faulting in groundwater flow related to CSG development.

03EVD-03. ASSESSING THE ROLE OF FAULTING ON GROUNDWATER IMPACTS FROM COAL SEAM GAS: LOCAL-SCALE NUMERICAL MODELLING IN THE GLOUCESTER BASIN, NSW

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One of the main sources of uncertainty in predicting potential impacts to water resources from coal seam gas (CSG) and coal mining operations is a lack of knowledge of the role of faulting in propagating groundwater depressurisation. Depending on the nature and orientation of a fault, the structure may act as a conduit or a barrier to groundwater (or gas) flow, or vary spatially between these conditions. It is impossible to identify and characterise all faults in a study area, which adds further uncertainty to conceptual models and model predictions.

The potential role of faults in groundwater flow and in influencing depressurisation associated with CSG extraction in the Gloucester Basin is explored in this groundwater modelling study. The Gloucester Basin is a structurally complex geological basin comprising Permian sedimentary and volcanic rocks that have been folded into a synclinal structure. 2D and 3D seismic surveys and field investigations show that the basin is dominated by west-dipping strata intersected by a number of westerly dipping thrust faults and near vertical oblique strike-slip faults.

Local-scale numerical models were developed using FEFLOW for two cross sections through AGL's Stage 1 Gas Field Development Area (GFDA) for which the geology and groundwater conditions are well known. The models were constructed and parameterised using data and estimates from recent groundwater investigations and in accord with the hydrogeological conceptual model and water balance developed for the Gloucester Basin. The potential role of faults was explored by running the models multiple times, and varying the permeability of the faults each time to simulate faults as conduits and barriers relative to the coal seams and interburden.

The results of the modelling study indicate that the influence of faults tends to be localised and highly dependent on the nature and orientation of the faults, particularly in relation to the CSG production wells and perforated intervals. The broader, far-field depressurisation extent appears to be insensitive to the orientation and hydraulic characteristics of the faults and more sensitive to the bulk hydraulic properties of the rock mass. It is concluded that minor intra-basin fault structures are unlikely to influence the extent of depressurisation on a regional scale, and it may be unnecessary to include those structures in a regional groundwater model. However, major faults with vertical displacements of greater than ~100 m should be included, to allow for the most accurate representation of the geological structure.

03EVD-04. AQUITARD HYDRAULIC PROPERTIES ESTIMATION FROM WIRELINE LOGS ANALYSIS: AN APPLICATION TO THE SURAT BASIN, QUEENSLAND

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Aquitards are key elements of the subsurface hydraulic framework acting as sealing and compartmentalisation units that affect many usages of the pore space. These include hydrocarbon or water production, as well as storage of contaminants, carbon dioxide or nuclear waste. Aquitards are also critical in the context of multiple resource exploitation where they can act as barriers between different zones of usage. However, as aquitards do not contribute directly to the resource recovery or storage, their hydraulic characterisation is often lacking, especially on the regional scale. Also, pump or production testing is difficult to perform in aquitards due to the low permeability and flow rates; hence inherent long time frames for acquiring reliable test results.

Alternatively, hydraulic properties such as porosity and permeability can be estimated from well-based measurements such as geophysical wireline logs and those acquired from core sample analyses. In this work, we applied a standard petrophysical workflow combining wireline log measurement analysis in conjunction with core sample data for aquitard characterisation. The process is tested on the Westbourne Formation of the Surat Basin, Queensland.

Data availability and reliability show that limited measurements are available for a regional assessment. To evaluate the robustness of the techniques and to determine the applicability of the technique to a wider set of data, a comparison of different estimation methods for porosity was conducted. Then, within a geographical area of interest, several wells were selected with different data availability. Porosity and permeability estimations were performed in combination with wireline log porosity estimates and core measurements.

Finally, the upscaling of the hydraulic properties from the wireline logs to the formation scale is discussed in light of data availability and possible lateral variations.

ENERGY

03EGA – TERRESTRIAL SEQUESTRATION OF CO2 – ADVANTAGES OF THE BIOSPHERE

03EGA-01. TERRESTRIAL SEQUESTRATION OF CO_2 – MOVING TOWARD SOLUTIONS

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With carbon dioxide content of the earth's atmosphere over 398 ppm, more than 20 ppm greater than 10 years ago, and almost 100 ppm higher than for typical ice age interglacials, surface warming is causing jet stream instability and increasing frequency of extreme weather events. There is a need for action stabilising atmospheric CO_2 and methane at level, which do not accelerate change to threaten vital ecosystems and large human populations. The argument for significant anthropogenic enhancement of CO_2 levels is supported by the observed drop in $\delta^{13}C$ brought about by combustion of organic carbon fuels. The advent of energy intensive fuel reclamation like that proceeding in the Athabasca Tar Sands of Alberta seems inappropriate in the circumstances, and the mining, processing and combustion of up to 400 million tonnes per year of low grade, low rank coal from the China First Waratah Coal operation in the Galilee Basin will produce as much CO_2 in one year as did the combustion of Australia's total coal production in 2012.

Geosequestration has been slow to respond to the requirement that we sequester CO_2 at a rate equal to or greater than that at which it is being added to the atmosphere. While numerous basins appear able to accommodate carbon dioxide, very few operations worldwide such as Sleipner and Rangely, have been shown capable of geosequestering over 1 Mt per year in depleted gas reservoirs. The gas sequestered is a tiny fraction of that produced by the natural gas recovery process at these sites, inadequate to make any impact upon the rate of CO_2 increase. Projects like Futuregen and Zerogen, planning underground storage of power plant CO_2, have failed to be realised in recent years, due to the combined barriers of lack of suitable geological storage horizons; low porosity/permeability and mineralisation within target horizons; high costs of capture, compression and transport of CO_2; insufficient understanding of the detailed process variables within each site by industry; and the local public, and political machinations.

Mineral carbonation, terrestrial sequestration in stable carbonate minerals, has made several advances in the meantime. The University of Newcastle and Orica are establishing a mineral carbonation pilot plant, using serpentinite from the Great Serpentine Belt of NSW as a magnesium source rock, to produce magnesium carbonate bricks for building and refractory uses. Advances have been made in overcoming the barrier currently stalling rapid conversion of magnesium silicate (forsterite) deposits to magnesium carbonate. Magnesium dissolution from the silicate requires pH ~1, while precipitation requires pH ~8. A novel method is being developed using a tertiary amine which holds its proton at low temperature to maintain high pH for carbonate precipitation, and releases it at high temperature to lower pH and creates conditions necessary for dissolution, with the amine acting as a regenerable buffer.

Serpentinites from the Great Serpentine Belt have been shown to be more suitable for heat activation for the mineral carbonation process than partly serpentinised ultramafic rocks, which are more typical of the Coolac Belt near Gundagai. Using an activation strategy of prograde heating to produce active material with recovery of 80% of sensible heat from the dehydroxylated mineral, and direct combustion of natural gas to minimise secondary CO_2 emissions, a CO_2 penalty of only 7% yields 0.93 net tonne of available active serpentinite per tonne of serpentinite feedstock. The cost of serpentinite heat activation is A$1.25 per tonne of activated serpentinite.

Alternative mineral carbonation methods are being realised. Advances have been made in microbially-driven precipitation of magnesite. The use of catalytic anhydrase, small bubbles of nitrogen and enhanced alkalisation of solutions enriched in inorganic carbon by microalgae, is shown to accelerate degassing of these solutions, and precipitation of hydrated magnesium carbonate, nesquehonite. Petrographic and chemical analysis of weathering-derived magnesite at Attunga, NSW shows heavy $\delta^{18}O$ values compatible with a supergene formation from meteoric waters while low $\delta^{13}C$ suggests C3-photosynthetic plants as the predominant source of carbon. Despite complete supergene overprinting by meteoric waters that acquired carbon from percolation through soil, weathering-derived, nodular magnesite deposits hosted in ultramafic rocks at Attunga have formed in a two-step process, with the first step involving the hypogene formation of a pre-cursor magnesite deposit, with amorphous silica precipitation as a by-product. This weathering process could be modelled on a much greater scale, with emphasis on using the additional silica to improve the quality of magnesite building products.

03EGA-02. MINERAL CARBONATION AS A RELIABLE, SAFE AND PERMANENT MEANS TO SEQUESTER CO_2: CARBONIC ACID DISSOLUTION OF SILICATES AND CO_2 DEGASSING AS MECHANISMS IN AN INTEGRATED MINERAL CARBONATION SCHEME

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Mineral carbonation is a process that reacts CO_2 with mineral ions such as calcium or magnesium forming stable carbonate minerals, which are suitable for long term storage. The process is analogous to the process of silicate rock weathering which involves the fixation of CO_2 in the form of thermodynamically stable solid carbonates. Vast deposits of low-grade minerals such as magnesium and calcium silicate rock, suitable as a feedstock for mineral carbonation, exist worldwide. As the overall process of mineral carbonation is exothermic, there is opportunity to achieve sequestration at a significantly reduced energy penalty and hence great potential for the process to be economically viable. Its viability can be enhanced by the production of value added by-products during the carbonation process. Most importantly the production of environmentally safe and stable material in the form of mineral carbonates insures a reliable, safe and permanent fixation of CO_2 emissions guaranteeing no legacy issues being passed on to future generations.

The University of Newcastle continues to be active in the research field of mineral carbonation. One promising area of research is indirect aqueous carbonation involving the preparation of aqueous solutions to extract mineral ions from magnesium and calcium silicates and the subsequent mineral carbonation of these solutions. More particularly our research has involved the preparation of mineral and carbon enriched solutions from the dissolution of magnesium silicate rock (serpentinite) using carbonic acid. Carbonic acid is ubiquitous in nature, prominent in its role in the weathering of silicates. We have also researched the production of magnesium carbonates through the mechanism of CO_2 degassing using leachate derived from the carbonic acid dissolution of magnesium silicates. Both the processes of carbonic acid dissolution of silicate rock and CO_2 degassing of mineral and carbon enriched solutions lend themselves to continuous process operation boosting their suitability for incorporation in coal fired power plants. We present background to this area of research and coverage of research results and possible application of these processes to larger scale mineral carbonation.

03EGB – TERRESTRIAL SEQUESTRATION OF CO_2 – ADVANTAGES OF THE BIOSPHERE

03EGB-01. MINERAL CARBONATION EMPLOYING ULTRAMAFIC MINE WASTE

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Carbonate minerals are one of the primary carbon sinks being investigated as a strategy to sequester carbon dioxide (CO_2) produced by human activity. A natural hydromagnesite playa (Atlin, British Columbia, Canada) that has previously demonstrated the ability of phototrophic microorganisms to accelerate magnesium carbonate mineralisation from Mg-rich groundwater (Power *et al.* 2007) was used as our experimental model. Hydromagnesite precipitation conditions were refined using a 10 m long flow-through bioreactor inoculated with microbial mats collected from the playa–wetland. Chrysotile, from the Clinton Creek Asbestos Mine (Yukon, Canada), was used as a target substrate for sulfuric acid leaching, releasing as much as 94% of the magnesium into solution *via* chemical weathering. This magnesium-rich solution was used as a 'feedstock' for the bioreactor experiment, which examined the ability of the microbial consortium to induce carbonate mineral precipitation using only atmospheric CO_2 as the carbon source. The 'phototrophic' based consortium catalysed and accelerated the precipitation of platy hydromagnesite [$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$] accompanied by magnesite [$MgCO_3$], aragonite [$CaCO_3$], and minor dypingite [$Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$]. Scanning Electron Microscopy-Energy Dispersive Spectroscopy observation-measurements indicated that cell exteriors and extracellular polymeric substances (EPS) act as nucleation sites for carbonate precipitation. In many cases, entire cyanobacteria filaments were observed entombed in magnesium carbonate coatings, which appeared to contain a framework of EPS. Cell coatings were composed of small crystals, which intuitively resulted from rapid crystal nucleation. Excess nutrient addition generated eutrophic conditions in the bioreactor, resulting in the growth of a pellicle that sealed the bioreactor contents from the atmosphere. The resulting anaerobic conditions induced fermentation and subsequent acid generation, which in turn caused a drop in pH to circumneutral values and a reduction in carbonate precipitation. Monitoring of the water chemistry conditions indicated that a high pH (>9.4), and relatively high concentrations of magnesium (>3000 ppm), compared with the natural wetland (up to 1000 ppm), and dissolved inorganic carbon (>20 mM C) are ideal for carbonate precipitation. Under optimum nutrient and magnesium inputs, a mass balance calculation using water chemistry data and hydromagnesite as the sole mineral product resulted in a carbon sequestration rate of 61 t C/ha/year.

Reference

Power I M *et al.* 2007. Biologically induced mineralization of dypingite by cyanobacteria from an alkaline wetland near Atlin, British Columbia. *Geochemical Transactions* **8**, pp. 13.

03EGB-02. FORMATION OF WEATHERING-DERIVED MAGNESITE DEPOSITS IN THE NEW ENGLAND OROGEN, NEW SOUTH WALES, AUSTRALIA: IMPLICATIONS FROM MINERALOGY, GEOCHEMISTRY AND GENESIS OF THE ATTUNGA MAGNESITE DEPOSIT

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Nodular, cryptocrystalline, weathering-derived magnesite deposits in the New England Orogen, Australia, provide a significant source of high-purity magnesite. Common textural features and related isotopic fingerprints indicate a close genetic relationship between weathering-derived magnesite deposits hosted by ultramafic rocks at Attunga and by sediments at Kunwarara while silica-carbonate rock alteration and rare hydrothermal magnesite vein deposits reflect contrasting conditions of formation. Localised weathering of carbonates in a soil environment shifts stable isotopic composition towards low $\delta^{13}C$ and high $\delta^{18}O$ typical for weathering-derived magnesites while intrusion-related fluids do not significantly change the isotopic composition of affected carbonates. At Attunga, magnesite consists of irregular, nodular veins and masses filling faults and cracks in the weathered serpentinite host rock, as well as soft powdery magnesite in pervasive serpentinite alteration zones. The high-grade magnesite at Attunga can be contaminated by amorphous silica and serpentine relicts but does not contain dolomite or ferroan magnesite as observed for its hydrothermal equivalent, the Piedmont magnesite deposit, or other widespread deposits of silica-carbonate rock in the Great Serpentinite Belt. Heavy $\delta^{18}O$ values are compatible with a supergene formation from meteoric waters while low $\delta^{13}C$ suggests C3-photosynthetic plants as the predominant source of carbon for the Attunga magnesites. We infer that weathering-derived, nodular magnesite deposits hosted in ultramafic rocks like the Attunga magnesite deposit have formed in a two-step process involving the hypogene formation of a pre-cursor magnesite deposit and complete supergene overprinting by meteoric waters that acquired carbon from percolation through soil.

03EGC – PETROLEUM PROSPECTIVITY, EXPLORATION AND MODELLING OF PROVEN AND FRONTIER BASINS

03EGC-01. FOSSIL FUELS FOR THE FUTURE

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Despite its rapid growth over the last decade, renewable energy (excluding hydroelectricity) still provides less than 2% of the global energy supply. Fossil fuels, by contrast, provide over 85%. Predictions of an imminent peaking of world oil production have occurred numerous times over the last one hundred years. More recently there have been predictions of “peak coal” and “peak gas”. Despite these predictions and concerns about global climate change, production of fossil fuels continues to increase. Since 2000 there has been approximately a 16% increase in global oil production, a 40% rise in natural gas production, and an amazing 70% increase in coal production. At the same time global reserves of oil and gas are at all time highs as new technologies have made additional resources economically viable.

The development of new technologies for deep-water exploration and production has been an important factor in creating new reserves over the last decade. If successful, current exploration efforts in the deep waters of the Great Australian Bight could make Australia a net exporter of oil.

The most dramatic changes, however, have been in the development of so-called “unconventional resources” in reservoirs with relatively low porosity and permeability lithologies, including shale, coal and sandstones. Unconventional resources now account for over two thirds of the United States natural gas production, and 37% of US oil production. The development of unconventional resources has revolutionised the energy mix in the United States, with substantial decreases in oil imports, domestic coal production, and fossil fuel-related CO_2 emissions. The potential for unconventional resources is only just beginning to be realised elsewhere in the world. Australia is about to become a major supplier of LNG from coal seam gas to East Asian markets. There are also likely very substantial amounts of shale gas, shale oil and tight gas in Australia, though their true potential remains to be ascertained.

Discoveries and developments over the next decade, combined with many countries’ increasing concerns for energy security, will likely change the world’s energy mix and trade patterns substantially. The challenge for Australia is to unlock the potential of its oil and gas resources in a cost-competitive manner while also restricting CO_2 emissions.

03EGD – PETROLEUM PROSPECTIVITY, EXPLORATION AND MODELLING OF PROVEN AND FRONTIER BASINS

03EGD-01. WHY ARE CONJUGATE PASSIVE MARGINS OFTEN ASYMMETRIC? – A NEW ANSWER TO AN OLD QUESTION

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During passive margin formation, continental crust and lithosphere are stretched and thinned until break-up takes place and a new oceanic basin is formed. Many rifted margins feature highly thinned continental crust (thickness <10 km) that is divided between conjugate margin pairs with striking asymmetry. While highly thinned crust can be very wide on one margin (e.g. 70 km in Iberia, 200 km off Angola) it is restricted to few tens of kilometres on the conjugate side. Similar margin asymmetry is evident at many passive margins pairs like Australia/Antarctica, East Australia/Lord Howe Rise, India/Antarctica, Europe/North America, the Central South Atlantic conjugates and possibly at the Australian North West Shelf. Here we suggest that a new process ‘steady-state rift migration’ is the key for understanding both margin asymmetry and the generation of highly thinned crust.

We combine observation form the well-studied Iberia/Newfoundland and Angola/Brazil margins with thermo-mechanical forward models. Our numerical code involves an elasto-visco-plastic rheology formulation that allows for self-consistent generation of faults and ductile shear zones as well as stress- and temperature-dependent viscosity. We constrain our experiments with detailed plate kinematic history of the pre-break up and early seafloor spreading phase, laboratory-based rheology, and melt fraction evaluation of mantle upwelling. Our results are consistent with observed fault patterns, crustal thickness, and basin stratigraphy.

We find that rift migration is induced by strengthening in the rift centre and weakening of a rift side. Both effects generate a lateral strength contrast that forces motion of the rift centre in a steady-state manner. Rift migration is accommodated by sequential faulting in the brittle crust and controlled by lower crustal flow. Thus the extent of rift migration depends on lower crustal viscosity near the rift centre, which in turn is a function of extension velocity, lower crustal composition and initial thermal structure. By demonstrating how lower crustal viscosity and the rate of extension affect the final margin width, we explain the formation of highly thinned crust and the degree of asymmetry in the Central South Atlantic and Iberia/Newfoundland within a single model framework.

Our model holds important implications for deep-water hydrocarbon exploration. It displays sustained transfer of material across the extensional plate boundary predicting that large portions of a wide margin originate from its conjugate side. Moreover, lateral motion of the rift centre causes oceanward migrating peak heat flow, affecting the spatio-temporal hydrocarbon maturation patterns

03EGD-02. THE SPATIO-TEMPORAL EVOLUTION OF SURFACE DYNAMIC TOPOGRAPHY DRIVEN BY DEEP MANTLE PROCESSES SINCE THE CRETACEOUS

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Mantle convection can have a profound influence on basin evolution, but progress has been slow in quantifying this relationship or making these concepts available for exploration. Many regional continental basins and margins have experienced long-wavelength tilting and subsidence/uplift, leading to sea-level change that deviates from a global reference standard. We evaluate the evolution of large-scale surface dynamic topography since 150 Ma using a mantle convection model (TERRA) constrained by a global tectonic model. We impose 150 Myr of plate motion histories, generated by the plate reconstruction software GPlates, as a surface kinematic boundary condition for our global convection simulations. Employing a fine discretisation of ~25 km globally allows us to model mantle convection at Earth-like vigour with a Rayleigh number of 10^9. As initial conditions for our models we approximate the unknown Jurassic mantle structure by applying the oldest plate velocity configuration until a quasi steady-state is reached. We use a radial viscosity profile involving three layers: lithosphere (10^23 Pas), non-lithospheric upper mantle (10^21 Pas), and lower mantle (10^23 Pas). Dynamic topography is derived from normal stresses at Earth's surface after replacing the lithosphere with a homogeneous shell. The models generate a global flow and dynamic topography pattern with hemispheric upwellings focused on the antipodal low-velocity seismic-shear-wave regions above the core–mantle boundary, even though the basal thermal boundary layer evolves dynamically in our models. Subduction along the western Pacific and northern Tethys margins drives a pronounced return flow centred on the reconstructed position of India in the Cretaceous, resulting in positive dynamic topography from India and Madagascar to the south eastern African margin from 120 and 60 Ma. In the mid-Cretaceous a strong surface topography high starts straddling the margins of northwest Africa and western Europe. Our model predicts large-scale dynamic subsidence for both the Arabian Peninsula as well as India during the Cenozoic as they move from a mantle upwelling into the downwelling region associated with the closure of the Meso-Tethys during from 90 to 30 Ma. Our model also predicts large topography variations along-strike passive margins especially where they straddle boundaries between large-scale upwellings and downwellings through time. We use this global model to define "geodynamic rules" for how different surface tectonic settings and associated sedimentary basins are affected by mantle processes. Locations within a ~4000 km distance from subduction zones show large negative amplitudes while everywhere else the signal is positive. We find that rapid variations in vertical motion rates occur at locations along the margins of overriding plates (e.g. Western US) and at points that are located on a plate that rapidly approaches a subduction zone (e.g. India and Arabia). Our models provide a predictive framework linking mantle convection with plate tectonics and sedimentary basin history, to improve our understanding of how subduction and mantle convection affect basin evolution over time.

03EGD-03. TECTONIC CONTROLS ON OIL AND GAS SEEPS AND SHALE GAS ACCUMULATIONS, ONSHORE TIMOR-LESTE

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Oil and gas seeps that occur across Timor-Leste represent underlying structural zones parallel to strike that extend across the half island, from Suai in the SW to near Los Palos in the NE. A particularly linear chain of mainly gas seeps occurs along a NE transect between Suai and Bobonaro, in an area of strong structural control. Adjacent to the seep line on the NW side, the Saburai Range forms a NE-striking linear ridge line bound by steep cliffs of Bandeira Group limestones, in some cases over 600 m high. Extensive fault gouges, in some cases 10s of m thick occur along the base of the ridge line, and multiple fault striae occur on cliff faces, indicating that these faces represent active faults. To the SE of the Saburai Range a remarkably straight, NE-striking section of the Bazol River extends for over 5km before taking a sudden 120° bend, exposing a structural melange along much of its length. This structural melange, of indeterminate thickness, includes dominantly Triassic Babulu Formation shales but also contains blocks of middle Miocene carbonate pelagite, indicating formation of the structural melange occurred post middle Miocene. Gas seeps, represented by spontaneously combusting regions within tracts of Babulu Formation shale occur within or adjacent to these melange zones.

We believe that that recent deformation, manifest as melange zones within incompetent lithologies, bounded by high-angle faults, controls the location of gas seeps from within dominantly shale-rich lithologies. Chains of documented oil and gas seeps occur along these structural zones, a relationship that can be seen across the island.

Melange zones across Timor-Leste always occur in close proximity to young, high-angle faults manifest as vertical cliffs of competent limestones (the “fatu” limestones), and in many cases are accompanied by other evidence of structural control, including hot springs and associated deposits.

This presentation will examine the relationship of known oil and gas seeps to the areas of intensive, young, high-angle deformation that bounds melange zones across Timor-Leste.

03EGD-04. SOURCE ROCK POTENTIAL IN AN ACTIVE CONTINENTAL MARGIN: MYALL TROUGH, SOUTHEASTERN AUSTRALIA

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The southern edge of the late Paleozoic active continental margin of eastern Australia has been studied in terms of its oil and/or gas generation potential. The Carboniferous clastic sedimentary succession in the forearc part of the subduction system provides a great opportunity to assess source rock potential. A suite of twenty nine (29) mudstone samples were collected from the Myall Trough (New England Fold Belt, southeast Australia), and were analysed using the Rock-Eval II pyrolysis method. Attributes such as, quantity, quality and maturity of the organic material are used in order to estimate the regional source rock potential. Organic geochemical data indicate that organic material is present in sufficient abundance and with good enough quality to be considered as potential source rocks. In the study region, the mudstones examined have fair source-rock characteristics with respect to their total organic content. The Rock-Eval pyrolytic yields and calculated values of hydrogen and oxygen indices indicate a regional poor to fair, gas-prone source rock potential. The current investigation revealed that the organic matter is Type III kerogen, indicating gas generation potential. The degree of thermal maturity, assessed from Tmax and PI values, suggests that the sedimentary sequence is mature with respect to gas generation and has experienced high temperature (>100^{o}C) during burial. Outcrop samples commonly exhibit depletion in pyrolysis values because of processes such as weathering and oxidation, resulting in deterioration of organic geochemical parameters. Oxidation potentially removed hydrogen and added oxygen to the kerogen resulting in lower Hydrogen Index (HI) and higher Oxygen Index (OI) values and thus, the study region should be of higher prospectivity.

03EGE – COAL – AN OLD RESOURCE IN A NEW AGE

03EGE-01. ASHFORD COAL MEASURES, ONCE A VALUABLE LOCAL RESOURCE, NOW INTERNATIONALLY ISOLATED AND A GEOLOGICAL ENIGMA

Brian Roach

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The Ashford Coal Measures are comprised of freshwater lithic conglomerates to sandstones generally white in colour, and grey carbonaceous shales. Below the Ashford seam the conglomerates are comprised of rounded pebbles set in a grey shale matrix. Limited studies indicate the source of the Permian sediments appears to be the underlying Carboniferous age formation. The Ashford Coal Measures, it is thought, are the northern remnants of the Greta Coal Measures.

Coal was first discovered near Ashford in 1884 by John McDonald in an exposure in the bed of a tributary of the Severn River at the present site of the Ashford Colliery and Power Station complex. The first commercial use of Ashford coal was in beehive furnaces producing metallurgical coke for the Silver Spur Silver Mine. During WWII it was proposed that the coal could be used to produce aluminium for the war effort, however the war ended and in the 1950’s generation of electricity utilising Ashford Coal was proposed. Power generation commenced in 1959 and continued up until 1997 when the station was deemed uneconomic to run. During the period 1959 to 1990 the Ashford Colliery produced in excess of 1 000 000 tonnes of coal. The coal was purchased under a fixed price and term, which limited the economics; in 1977 it was discovered that the Ashford Seam had exceptional heat value and was also a very marketable coking coal. It became apparent that the power station was in fact “burning a high grade coking coal”.

In 1987 drilling within the mining leases carried out to determine the likelihood of deep coal resources behind abandoned open cuts. The results of the drilling program led to re-evaluation of the potential resources/reserves at Ashford as the drilling clearly demonstrated that the Ashford Coal Measures continue west under the granite overthrust and that coal quality was unaffected by the Severn Fault. The drilling showed the seam dip angle decreases from 25 to 35 degrees to 15 to 16 degrees and the Severn Thrust fault is not 60 degrees, but in fact is tending to be subparallel to coal measures. This indicated that the likely reserves of the Ashford Colliery could be in the range of 10 million tonnes and possibly 20 million tonnes.

Recent (2012) drilling has added new insight to the tectonic model with a granite boss (neck) being defined, which supports the concept that the granite overlying the basin is in fact a sill under which the coal basin has been thrust.

Once a local valuable local resource the Ashford Coal Project is now endeavouring to become a valuable coking coal supply on international markets, however the lack of regional infrastructure hampers this development. "If the North West of NSW had had reliable rail or road transport options in the past the site would be a big hole in the ground by now" to quote one earlier mine geologist.

Hopefully the new demand for coking coal will see the dream of earlier developers realised.

03EGE-02. INORGANIC MATTER IN VICTORIAN BROWN COALS

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The inorganic matter in coals affects their utility in many processes, such as combustion and coking. Inorganic matter in coals comprises crystalline minerals, non-crystalline minerals (mineraloids), and non-mineral inorganics (dissolved salts in the pore water and organically associated elements). The inorganic constituents of the higher rank coals are mainly crystalline minerals. As the coal rank decreases the non-mineral inorganics become more abundant. The non-mineral inorganics are the dominant inorganic constituents in the Victorian brown coals. The identification and quantification of the inorganic matter in the brown coals may provide important insights into problems associated with a number of coal utilisation processes such as the ash-forming reactions that occur during combustion that can lead to slagging and fouling, and emission generation.

X-Ray Diffraction (XRD) is a common technique for the identification of crystalline minerals in coals. XRD analysis is performed on the coal ashes prepared at low temperature by using a radio-frequency plasma asher, which has little effect on the nature of minerals in coal. Low-temperature ashing is performed in order to remove the matter, which would dilute the inorganic components. However, the non-mineral inorganics in the brown coals produce artefacts due to reaction of the organically associated elements with sulfur during low-temperature ashing.

Sequential leaching has been employed in many studies to determine the association of the non-mineral inorganic elements in coals. In addition, the removal of the non-mineral inorganic elements by sequential leaching prior to low-temperature ashing reduces the amount of artefact phases in the ash. Thus, sequential leaching combined with XRD analysis of the low-temperature ash of coal can be an effective method to characterise the inorganic matter in low-rank coals and brown coals in particular.

In this study sequential leaching was used to enable the identification and quantification of the minerals in three Victorian brown coals (Hazelwood (H), Yallourn (Y) and Loy Yang (LY)) and determine the nature of the non-mineral inorganics. The leaching solutions were ultra pure water (Milli-Q), 1M ammonium acetate, 0.1 M diammonium salt of ethylenadiaminetetraacetic acid (EDTA) buffered by NH_4OH to pH 9, 1M hydrochloric acid, and 2M nitric acid. XRD and Scanning Electron Microscopy (SEM) analyses were carried out on the low-temperature ashes.

The abundance of the minerals in the low temperature ashes of the original coals was very low; less than 1% in coals H and Y, and 7.8% in coal LY. Quartz, albite, iron sulfides (marcasite and pyrite) and calcite were the minerals found in the ashes of the original coals. The removal of most organically associated elements and soluble salts enabled the identification and quantification of the less abundant minerals, such as pyrite in coal H, albite in coals H and Y, and orthoclase and kaolinite in coal LY, due to the increase of their relative abundance. The distribution of the organically associated elements in the coals was highly variable and no consistent pattern was observed. This indicates the complex nature of the occurrence of the elements in the coals.

03EGE-03. A NEW SUBSURFACE FRACTURE HEIGHT PREDICTION MODEL FOR LONGWALL MINES IN THE NSW COALFIELDS

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Community concerns regarding subsurface groundwater regime impacts and widely varying subsurface fracture height predictions (and groundwater response definitions) at several longwall mine locations in NSW have prompted a review of published mine site data by the authors.

The current suite of subsurface fracture height prediction models attempt to define the zone of complete groundwater depressurisation and the minimum thickness of overlying rock required to protect highly productive aquifers and permanent waters. Unfortunately, some models developed in one coalfield are not easily transferable for use in other coalfields due to significant variations in mining geometry and geology.

Based on a review of available borehole extensometer and piezometer data (dating back 20 years or more), the definition of the “height of fracturing” appears to have included heights of continuous fracturing (the A Zone) and dilated strata (the B Zone) in some instances. It is also the opinion of the 2nd author that the A Zone should not be assumed to be fully depressurised immediately after mining, as resistance to flow through the disturbed, fractured strata above the caving zone is still likely to control drainage into the mine workings to some degree. Groundwater modelling may be used to determine the degree of desaturation likely to develop in the A Zone.

This paper describes the outcomes of the review of the ‘state-of-the-art’ subsurface fracture zone height prediction models and the development of a new model based on Buckingham’s PI-Term theory and analytical models of strata behaviour during the caving process above longwalls. The new model includes the key fracture height driving parameters of panel width (W), cover depth (H), mining height (T) and local geology factors to estimate the A and B zone horizons above a given longwall panel. The potential bias in the regression equations due to geological affects has been addressed by determining the effective thickness (t’) of the strata where the A Zone height occurred. The geological factor may also be used to calibrate the prediction model to local mine site data. The sensitivity of the A Zone predictions to the selection of the geological factor has also been assessed by comparing results of a mine geometry-only model (i.e. no geological factor was included).

The PI-Term model(s) adopt a stochastic (deterministic + probabilistic) assessment approach and provides mean and upper 95% confidence limits for each zone. The results of the sensitivity analyses on the predicted heights of the A and B zones due to causative factor changes are also presented in the paper.

The development of near surface cracking in unconfined strata (D Zone), the presence or absence of low permeability, thinly bedded strata units (i.e. claystone and mudstone) and persistent geological structure (faults and dykes) are also considered when assessing the potential for connective subsurface fracturing to connect with the surface cracks or A and B zones. Three cases that apparently resulted in surface-to-seam fracture connection were included in the development of the new PI-Term model.

03EGE-04. ADVANCES IN ASSESSING COKE OVEN FEED SAMPLES BY COAL GRAIN ANALYSIS (CGA)

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CSIRO’s Coal Grain Analysis (CGA) system was recently upgraded to better enable characterisation of coal particles. The system (based on coal petrography methods) collects, mosaics and then processes a large number of high-resolution optical reflected light microscopy images providing particle and internal structure size information, composition details and a reflectance fingerprint of each individual particle. This method of collecting and mosaicing images over a large area ensures that whole particles can be analysed and sufficient particles are examined to give a quantitative analysis of the sample. Technological advances in the size of images that can be analysed by this system have enabled particles up to 8 mm in topsize to be imaged and analysed, making analysis of coke oven feed samples at size, a viable option.

During coking, for coals of suitable rank, the vitrinite, liptinite and some of the inertinite macerals are fusible and the minerals and remaining inertinite macerals do not fuse. The amount of fusible inertinite present in a coal varies between coals extracted from differing coal basins/measures and even from coal to coal from similar regions. Inertinite fusibility is related to reflectance, with low reflecting (fusible) inertinite being more reactive than high reflecting (infusible) inertinite. The amount and size of infusible inertinite particles impact on coke quality parameters (i.e. large inertinite, approximately +1.5 mm, adversely affects coke quality).

The reflectance threshold between fusible and infusible inertinites was investigated for four Australian coals by using imaging methods on matching coal and coke surfaces obtained from two halves of individual coal lumps, where one half had been coked. It was discovered that the threshold between the fusible and infusible inertinite was not a fixed value between lumps of the same coal. However, the reflectance range for the fusible inertinite (from the end of the vitrinite reflectance range to the beginning of the infusible inertinite reflectance range) stayed constant between lumps of the same coal. Thus, analysing each lump separately with the same fusible inertinite range but slightly differing reflectance thresholds enabled all components to be identified correctly. The CGA image analysis software was updated so that the inertinite component within each particle was split between fusible and infusible inertinite based on a defined fusible inertinite reflectance range. As each particle within an image is characterised from its own reflectance fingerprint, this range can be accurately applied on a particle-by-particle basis.

Once the reflectance range for the fusible inertinite was determined for the coals the new CGA imaging system was used to analyse size fractions for three matched pairs of coking coals (a low rank pair (0.9–1.1% R_{vran}), medium rank pair (1.1–1.3% R_{vran}) and a high rank pair (1.3–1.5% R_{vran})) from different Australian coal basins. One coal from each pair came from the Rangal Coal Measures and the others came from the Illawarra and German Creek Coal Measures.

For all three pairs the Rangal coal contained a greater amount of large infusible inerts than its sister coal.

INFRASTRUCTURE, SERVICE & COMMUNITY

03ISCA – AUSTRALIAN GEOLOGICAL HERITAGE AND THE NATIONAL HERITAGE LIST; ARE WE BEING OVER RUN BY THE BIOLOGISTS?

03ISCA-01. GEOLOGICAL HERITAGE AROUND CANBERRA – A TEMPLATE FOR NATIONAL RECOGNITION

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Although the Australian Capital Territory is small in area compared with other States and Territories, it now has forty geoheritage sites in the region that are documented to provide user-friendly information as PDF files. To be relevant in the 21st century the information on these heritage sites must be readily available to scholars at all levels, to teachers, land developers, government authorities and the general public. To achieve this, the information for sites around Canberra is now easily available as PDF files through the Geoheritage drop-down menu within the Geological Society of Australia web site. The current site information builds on to older geological heritage descriptions.

There are selection criteria applied to every Canberra region geoheritage site that are similar to those applied in earlier times to heritage sites in Victoria. Sites on the list may be of interest to diverse interest groups at many levels of detail; the specialist Earth science researcher, the historian, the government administrator, the teacher, etc. Sites are classified as being of international, national, regional or local significance. The sites are identified on their scientific, educational or cultural merit no matter what the nature of land ownership or management.

In the last year the Canberra region geological heritage site information has been used: 1) on a geological excursion for international geologists and engineers attending a conference on CO_2 sequestering, 2) by major road construction engineers to design flyover details for the half-billion dollar Majura Parkway near Canberra Airport, 3) to put together an interesting end-of-term excursion for eighty primary school children aged 8–9 years old, 4) to plan the redevelopment of the National Museum of Australia on Acton Peninsula, and 5) to make the case with ACT planning authorities for sympathetic major township open parkland and river corridor design in the new Canberra township of Molonglo, including notable geologist naming rights.

In the public arena, geologists, like others in the various fields of science, must make the case for outstanding geological features to be placed on local, regional or national heritage lists, and work hard to defend their choice and continue promoting their importance to every generation of Australians.

If the selection criteria for Canberra region sites are applied at a national level there is no need for any rivalry or clash with the biological sciences. Cross-discipline criteria for the selection of National Heritage List sites can, in practice, enhance the case for inclusion in national or State/Territory schemes. Rather ordinary-looking limestone outcrops in the middle of Canberra only get onto the Commonwealth Heritage List because of their historical and cultural significance. Inevitably, such schemes have much wider scientific, educational, tourism and cultural selection criteria that have cost implications for Government authorities and tourist promotion industries. Geologists should get involved in any decision-making process.

03ISCB – GEOTOURISM – ENHANCING PUBLIC APPRECIATION OF GEOHERITAGE AND EARTH SCIENCES HISTORY

03ISCB-01. THE GLASS-NEGATIVE PHOTOGRAPHIC COLLECTION OF THE GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

John Blockley[1] & **Angela Riganti**[2]

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From about 1896 to 1928 staff of the Geological Survey of Western Australia carried cumbersome, glass-plate cameras into the field to record rock outcrops, mines, field activities and scenes of general interest. GSWA's collection of 1792 glass-plate negatives, now transferred onto film, contains about 1240 field photos taken during this period; the remaining are photos of laboratory specimens and staff. This remarkable collection represents a little-used archive of images of value to those researching the State's early mining history or interested in retracing some of the arduous expeditions undertaken by its geological pioneers.

The earliest photos with a reliable date were taken by Topographical Surveyor S J Becher who had also served as a Mines Inspector. Although only 12 in number, they show the state of mining at Marble Bar and Nullagine in 1896. H W B Talbot managed to take some 217 photographs while mapping large tracts of the Western Australian interior from the back of a camel during the period 1907 to 1926. Of these, about 52 recorded his 1908 trip along the Canning Stock Route, where he joined Canning's well-sinking party until it reached Halls Creek. Talbot then continued on a side trip to inspect the Tanami gold field in the Northern Territory, spending a total of 426 consecuitve days in the field.

Torrington Blatchford, who spent a total of about 20 years with GSWA in between spells of consulting, rivalled Talbot in contributing 218 negatives to the collection from 1897 to 1927. Of particular interest are the 36 images of mines, scenery and station homesteads that he took during a survey of the Pilbara region in 1912.

Edward de C. Clarke, later Professor of Geology at the University of Western Australia, was also an enthusiastic photographer, contributing 110 negatives to the collection between 1913 and 1918. In 1916, he and Talbot mounted an historic expedition from Laverton to the Western Australia/South Australia border to map the Warburton Range region; they took about 35 photographs despite suffering injuries to party members during an attack by Aborigines.

Other significant contributors to the photographic collection, with the periods covered by their photographs indicated in brackets, include W D Campbell (1901–1909), A D G Esson (1922–1925), C G Gibson (1904–1910), C S Honman (1911–1916), C F V Jackson (1903–1904), J T Jutson (1914–1918), A Gibb Maitland (1907–1915), E C Saint-Smith (1912–1913) and H P Woodward (1905–1916). The efforts of these early geologists succeeded in producing a pictorial record of geological- and mining-related features extending from the Kimberley region to the south coast, and from the west coast to the Western Australian border.

03ISCC – GEOTOURISM – ENHANCING PUBLIC APPRECIATION OF GEOHERITAGE AND EARTH SCIENCES HISTORY

03ISCC-01. A VISION FOR THE NATIONAL ROCK GARDEN

Brad Pillans

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The National Rock Garden (NRG) is located on a 6 hectare site on the western foreshore of Lake Burley Griffin, in Canberra. It is close to the National Arboretum, the National Zoo & Aquarium and the Lindsay Pryor National Arboretum and just a few kilometres from the Australian National Botanic Gardens.

The NRG was launched at the AESC in July 2010, and formally gazetted as a national monument in April 2011. The first display, the Federation Rocks, was opened in October 2013 as part of Centenary of Canberra celebrations. The

Federation Rocks consist of eight large rocks, one from each state and territory, each chosen for special significance to its state or territory of origin.

The vision for the National Rock Garden is to celebrate the geological heritage of Australia by displaying iconic rocks in a park-like setting. Initially, we envisaged a display consisting of 100 large rock specimens from all around Australia, each weighing about 10–20 tonnes, and placed along meandering pathways with sympathetic plantings of native trees and shrubs. Each rock would have a plaque, to explain its significance, and where appropriate, a cut and polished face to reveal its features. A primary consideration, in choosing the rocks, was that they would tell interesting stories of national (and sometimes international) significance that would appeal to a wide public audience, especially school children.

The Federation Rocks display has proved to be a great success, as more and more people hear about it. I have chatted with many people at the display, and their comments are invariably very positive. Wide media coverage, in February, of the theft of one of our rocks (a 1 tonne block of gold-bearing reef quartz from Bendigo), has also raised the profile of the NRG, despite the loss of the rock.

The Federation Rocks display has also served to demonstrate some important principles:

1. People love big rocks, if they have an interesting story to tell and if they are visually appealing.

2. Informative signage is essential, with text that is both understandable and entertaining for the wider public.

3. Display rocks cannot be too valuable, otherwise they will be stolen or pieces will be broken off as souvenirs. We suspect that the Bendigo rock was stolen for its gold content, even though it probably only contained a few grams of gold (and a lot more fool’s gold).

4. The Federation Rocks have whetted people’s appetite for more rocks and will provide a way of enthusing would-be sponsors and donors, as we seek to raise a substantial amount of money to develop the whole 6 hectare site. To that end, we are working with renowned landscape architects, Taylor Cullity Lethlean, to develop an NRG masterplan that will have the ‘wow’ factor to further excite people about rocks. In doing so, we have moved away from our original ‘big rocks in a paddock with a few trees’ idea, to something much more complex and interesting.

03ISCC-02. GEOTOURISM AND GEOHERITAGE – COMPELLING LESSONS FROM SCOTLAND

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Geotourism is not a new phenomenon – in the mid-1700s poet James Macpherson travelled Scotland publishing poems about a landscape that "is more real than the people who inhabit it” and naturalist Thomas Pennant was writing his observations on geography, geology, flora and fauna in what is arguably the first geoheritage field guide – “A Tour in Scotland” (1769). The Scottish landscape also attracted artists to paint the wild and desolate landscapes of the highlands – Turner and Landseer being the most prolific of the time. Indeed, some of Scotland’s early geotourists included some very famous individuals such as, Queen Victoria, Dr Johnson and Mendelssohn who all travelled to the Isle of Staffa in the 19th century, to marvel at Fingal’s cave and associated sea cliffs, all fashioned from columnar basalt.

Scotland is ranked the top European eco-destination and 9th in the world, and visitors to Scotland rank scenery as the main attraction (ahead of history and culture). Geotourism is a growing component of the tourism industry

Scotland has over three billion years of Earth history written in its geology and lays claim to being the birthplace of modern geological science, providing engaging intertwined stories of science and human endeavour. There are now over 250 locations across Scotland that have some Earth heritage interpretation – ranging from explanatory leaflets, trail guides, interpretive boards and entries in guide books, to major facilities such as the Knockan Crag Visitor Centre and the National Trust for Scotland visitor centre at Glen Coe, representing a full geological interpretive experience. From individual sites of major historical geological significance such as Hutton’s unconformity in the centre of Edinburgh to three UNESCO Geoparks covering almost 8000 km^2, geoheritage plays a very significant role in providing tourist experiences that are sought out by growing markets. The on-line environment has opened up significant new avenues not only for promotion but also for delivery of geotourism products such as iGeology and Visit Scotland Landscape itineraries.

The challenge, in a country that is home to a vast array of geodiverse heritage sites, many of which are protected under legislation for their scientific value, has been the tension between protection/preservation and broadening access and engagement through geotourism. Working in partnership with government bodies, national and local tourism agencies and operators, and universities and museums, a range of models has been developed to achieve an array of geotourism solutions that meet the needs of local and national objectives. Fostering a sense of local pride and "ownership" of geoheritage and building an understanding of the critical part it plays in local and national economies has been crucial to the success of this approach.

03ISCD – GEOTOURISM – ENHANCING PUBLIC APPRECIATION OF GEOHERITAGE AND EARTH SCIENCES HISTORY

03ISCD-01. GEOTOURISM AND AUSTRALIAN NATIONAL LANDSCAPES

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Geotourism is emerging as a new global phenomenon that fosters sustainable tourism based upon landscapes. Its definition has recently been refined as a form of tourism that specifically focuses on the geology and landscapes, which shape the character of a region. Geotourism promotes tourism to 'geo-sites', the conservation of geodiversity and an understanding of Earth sciences through appreciation and learning. Thus geotourism is sustainable tourism that focuses on an area's geology and landscape as the basis for providing visitor engagement, learning and enjoyment.

Essential to the development of geotourism is the understanding of the identity or character of a region or territory. To achieve this, geotourism is viewed as being based on the idea that the environment is made up of **A**biotic, **B**iotic and **C**ultural components. This 'ABC' approach comprises the **A**biotic elements of geology and climate, the **B**iotic elements of animals (fauna) and plants (flora), and **C**ultural or human components. Geotourism argues that to fully understand and appreciate the environment, we must know about the Abiotic elements of geology and climate first as these determine the Biotic elements of animals and plants which live there. By extension, the combination of the Abiotic and Biotic components of the environment determine the Cultural landscape of how people lived in the area in the past, as well as how they live there today.

Geotourists can comprise both independent travellers and group tourists, and they may visit natural areas (including mining areas) or urban/built areas wherever there is a geological attraction. This is a key distinction between geotourism and other forms of natural area tourism, as by definition natural area tourism takes place only in natural areas.

Australia's National Landscape Program represents a significant national long term strategic approach to tourism and conservation, which aims to highlight the value of our remarkable natural and cultural environments as tourism assets, improving the quality of visitor experiences in those regions, and in turn, increasing support for their conservation. There are currently 16 designated National Landscapes in Australia. With its integrative focus on landscapes as a whole, the development of geotourism within each landscape offers the opportunity to align with the core focus and sustainable development of each landscape region.

However, as is the case for much of Australia's protected areas, there is very little interpretative information available in these national Landscapes about the Abiotic components of the environment, particularly relating to geology and geomorphology. To address this significant shortcoming, the Geotourism Sub Committee of the Geological Society of Australia, working closely with the new Geotourism Forum of the industry group Ecotourism Australia, can recommend, and to some extent implement, effective measures to rectify this situation.

As geotourism continues to develop both globally and within Australia, these measures offer the potential to create opportunities for geoscientist employment both within government land management agencies and within the tourism industry generally.

03ISCD-03. PROMOTING AUSTRALIA–CHINA RELATIONSHIP THROUGH GEOPARKS

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Geoparks, one of the UNESCO initiatives to protect natural environment, are more than just areas of outstanding geology and landscape. They are set up to promote Earth science, encourage community engagement, foster sustainable development and enhance communication and exchange of experiences. There are currently 100 geoparks in 30 countries around the world. They are accredited with global status by the Bureau of Global Geoparks Network. Twenty-nine of them are located in China and most of the rest are in Europe.

The four-year revalidation system of Global Geoparks Network monitors their quality and ensures the pre-set standards and requirements are correctly being followed. One of these requirements is to establish linkages with other parks for mutual understanding, learning and promotion. During the revalidation process in recent years, this requirement has been taken seriously by most assessors. It therefore encourages many Chinese geoparks to look for partners with similar capacities within and outside the country. In this respect, this paper reviews the efforts of 10 Chinese global geoparks to assess their degree of success in achieving the objective of networking at both national and international levels. Results show that all these geoparks are willing to work together with other parks for the exchange of experiences.

However, many of them are relatively weak in their international networking because of language and cultural barriers. The longer geographical distance and more complicated visa application of European countries, in particular, add extra difficulties in making physical exchange and visits possible among the parks. Australia is a preferred target of collaboration because of its proximity to China and located within the Asia Pacific region. China's natural park management experiences are outstanding and have been well known to the Chinese people. This opens great opportunity for Australian national parks or national landscapes to link up with Chinese geoparks. By establishing 'sister' relationship between national parks and landscapes with Chinese geoparks, the unique attraction of each park and landscape can be promoted without causing extra financial strain on their budgets. This is more effective in highlighting and promoting individual national landscapes together with their park areas and communities to the Chinese tourism market. This supplements Tourism Australia's approach of marketing Australia as well as the national landscapes. Apart from encouraging geotourism, the 'sister' relationship will lead to further cultural and economic exchanges between the two countries and eventually help to create a harmonious and more stable Asia Pacific region.

03ISCD-04. JENOLAN CAVES – AN EVOLVING GEOTOURISM LOCATION

Steve McClean & Dan Cove

Jenolan Caves Reserves Trust

Jenolan Caves is one of the leading geosites in Australia, attracting more than 200 000 visitors every year. It is also significant in that it was the first location in Australia that was recognised for its geological heritage, being protected by the NSW Government with the creation of the Jenolan Caves Reserve in 1866. The presentation of the caves to visitors is a highly specialised and evolving art form that has progressed markedly since the 1970s. Also the range of cave experiences has changed and been enhanced due to the changing wants and needs of the visitor population. Such has been the change that Jenolan has been a finalist and winner in a number of categories at both state and national tourism awards over the last ten years. Visitor statistics indicate that the number of overseas visitors to Jenolan continues to diversify with a recent trend towards greater engagement with Asian visitor groups.

03ISCE – GEOTOURISM – ENHANCING PUBLIC APPRECIATION OF GEOHERITAGE AND EARTH SCIENCES HISTORY

03ISCE-01. KANAWINKA GEOPARK – LATEST DEVELOPMENTS AND BUILDING AN AUSTRALIAN MODEL FOR GEOPARKS

Ian D Lewis & **Bernie Joyce**

Kanawinka Geopark, Western Victoria and southeast South Australia, Australia

Geoparks are a world-wide concept designed to promote the valuing of areas of geological significance. They have the primary aim of raising public understanding, education and appreciation of landscapes and the stories of the Earth processes by encouraging increased visitation to areas beyond the world's large cities. Of the several hundred Geoparks around the world, UNESCO awards special recognition to 90 and many more aspire to this status.

Kanawinka Geopark is by far the biggest of them all (400 x 150 kms), and could contain all the others in one corner of its area. It spans the Newer Volcanic region of Western Victoria and southeast South Australia, has 400 kms of the eolianite and volcanic coastlines west of the Twelve Apostles and contains the extensive karst (limestone) lands of the Mount Gambier region. Kanawinka Geopark takes its name from the large local fault line that divides it near the State border.

Kanawinka Geopark is now 5 years old and is managed by a combination of local council input and community members with special skills, related interests and a pride in their local region. The Geopark concept originated in Europe around small prominent localities but Australians are developing Geopark ideas which are more adapted to a single nation in a large continent with mining and well-established National Parks systems.

However, unlike National Parks, Geoparks are non-regulatory and are not government funded as are the emerging Australian National Landscapes. Instead, in Australia they are evolving into a voluntary model reaching across communities to promote local landscape appreciation and visitation. This presentation will summarise the recent developments within the Geopark and its profile in Australia

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03ISCE-02. QUALITY INFORMATION – THE BASIS FOR SUCCESSFUL GEOTOURISM

Bruce Leaver

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The value of tourism to the Australian economy in 2011–12 was $87b. Over the same period the export value of coal was $46b and iron ore $62b. Tourism directly employs 4.6% of the workforce and mining 2.2%. In many regions of regional Australia tourism is now the primary economic and employment contributor, supplanting the traditional role of primary industries.

Market research has repeatedly shown that the primary motivation for travel to and within Australia is the appeal of its unique natural environment. Recent research shows that the same drivers apply to the rapidly growing Chinese inbound tourism market.

Australian nature experiences are usually presented through images of iconic wildlife. The practical reality is most of our top nature tourism destinations are appealing and distinctive because of outstanding and interesting geological and geomorphological features.

Tourism Australia’s national landscapes program has identified Australia’s 16 top nature tourism destinations as the basis for its international marketing program. Eleven of the 16 (including 4 World Heritage Areas) have a primary visitor appeal based on outstanding Earth history.

Market research has further identified to profile of the ideal visitor. To be successful in the highly competitive international tourism market Australia must offer experiences that exactly match that profile. This visitor is educated, environmentally aware, adventurous and eager to learn about what they are experiencing.

One of the biggest shortcomings in regional tourism is the absence of quality information. Over 80% of the target market uses the internet to research their travel decisions. It is critical that quality information be readily available, tailored to that traveler’s interests in order to influence that decision. That information should also be available in a form that is readily accessible to the visitor when they travel through a region. Given the role of landscape in Australia’s nature based experiences that information must include the geological and geomorphological features that make the area appealing.

In recent years written geology guides have become increasingly available. These can be good start to fill the knowledge gap but the material has to readily accessible to the visitor in a form that matches their interests. This will rarely be a complete geological history of an area but rather focused information as to why significant features are there.

There are examples of Earth history stories specifically designed to appeal to prospective visitors. These examples are becoming readily available in written downloadable formats, summarised as particular journeys of discovery and, more recently, as downloadable packages using a smart phone application. The latter, Geotreat, is a project that is a partnership between the Geological Society of Australia and the Swedish Geological Survey, the developers of the software.

Heritage that is economically valuable is heritage preserved. By enhancing the value of outstanding physical landscapes to the regional tourism economy there becomes an economic imperative to ensure that this heritage is preserved, protected and properly managed.

03ISCE-03. MINING GEOHERITAGE ACTIVITIES IN THE AUSIMM

Sandra E Close & **Geoff Sharrock**

Surbiton Associates Pty Ltd, Melbourne, Australia

The Australasian Institute of Mining and Metallurgy's (AusIMM) interest in mining heritage is primarily carried out *via* the Heritage Committee.

The Heritage Committee's function has been to deal with enquiries and to support any Branches that have been involved in heritage matters. Also, several volumes on heritage themes have been published. In addition, the bi-monthly AusIMM Bulletin has for many years featured articles on mining heritage, which are well received by members – these have included personal stories, details of past mining operations and description of sites containing mining relics.

Despite keen interest from a relatively small group, many AusIMM members have little awareness of heritage matters, let alone the wide range of topics, which fall under the banner of mining heritage.

More recently, there has been a renewed focus on heritage and new initiatives are being introduced to raise members' awareness of the importance of heritage to the mining industry. The guiding principle is, "Heritage is You", highlighting the fact that mining heritage reflects the work and achievements of members past and present, emphasising that if those in the mining industry do not value what has been achieved then they cannot expect others to do so.

The wide acceptance of the internet and the updating of the AusIMM web site and its web-based services have now opened up several opportunities to raise the profile of "heritage" and to provide relevant services to members. Some heritage aspects are essentially "internal" to The AusIMM in that they are concerned with providing information for members only, while "external" aspects have a broader reach.

Perhaps the major legacy of a "professional" organisation such as AusIMM is the technical information, which has been published – as this essentially enables exchange of knowledge between members and also details their achievements. The AusIMM has undertaken the major step of digitising all of its Proceedings/Transactions back to its inception in 1893, as well as papers from conferences. These are now all available free to members *via* OneMine, a global online library, which also provides similar material from several other relevant professional organisations. As well, digitisation of other heritage material such as film, colour slides and audio tapes has recently been carried out.

Another "internally focused" initiative, which is currently underway, is the Personal History Project, to record personal career-oriented information from mature members. While initial data was provided when membership details were first recorded, little ongoing information on an individual's career and achievements has subsequently been collected. Such information will provide a source of biographical material and also enable academic research on, for example, what motivates people to take up the various mining related professions. This will of course be subject to privacy considerations.

A more externally focused project is also currently underway which aims to provide a source of information on mining heritage information in general, as well as information on specific mining heritage sites. This project is not intended to reinvent the wheel but rather to make use of links to existing data where possible, as well as to gather original material when appropriate. As part of this initiative interested AusIMM Branches are being encouraged to undertake specific projects in their region. A pilot project involving the possible use of phone apps, based on existing Geological Society of Australia (GSA) experience is also being assessed.

Another externally focused initiative of the Heritage Committee is to foster interaction with other groups. Cooperation and mutual support and information sharing is beneficial with kindred groups such as GSA and Engineering Australia, while dialogue with a range of government bodies is also essential.

03ISCE-04. GEOTOURISM AROUND CANBERRA – BASED ON A GEOHERITAGE WEBSITE CATALOGUE

Douglas Finlayson

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Canberra, as the nation's capital city, is a tourist destination for people from all round Australia and oversees seeking to visit national institutions, engage in sporting events and participate in conferences and symposia of all types. Schools throughout the nation endeavour to take students on a Canberra excursion once during the school years.

Canberra tertiary institutions provide stimulating environments for conference delegates. The tourist industry is very much involved. Conference delegates always like a break from formal presentations to experience the local places of interest.

Tourism of all kinds, geotourism or otherwise, requires information on destinations that will be attractive for visitors. Promotion is very, very important. Canberra does not have the huge attractions like the Great Barrier Reef, Uluru, or the Bungle Bungles, but there are many geoheritage sites that can be woven into interesting excursions in and around the city for a variety of patrons, young and old. Parliament House, a focus for many tourists, has a huge number of building stones as a focus for tourists. The public visitor entrance hall is visually stunning. Also, tours of the normally off-limits Capital Hill rocks under House of Representatives chamber are always sold out as soon as they are advertised through Ticketek during the annual Canberra Enlighten Festival.

In and around Canberra a catalogue of forty geoheritage sites on the GSA web site can be used as a geotourism resource. The catalogue includes the heritage in the 19th century mining town of Captains Flat, the spectacular Siluro-Devonian placaderm fish fossils and limestones of Wee Jasper, and the climate record and tectonic history of Lake George with its often dry lake bed. All can be a focus for geotourism with a local cool climate winery thrown in for good measure for adults or a dinosaur museum for the younger family members.

Geoscience Australia's "Geological Time Walk" and geoscience information centre is now firmly on the educational tour circuit for school student excursions to Canberra from around Australia, along with the War Memorial, Questacon and Parliament House.

Geological heritage sites, whether around Canberra or elsewhere, must be documented and catalogued to be of use to tour operators on a commercial basis or to the public on a casual basis. Some excursions may have professional Earth science guides for large groups but others may not. Geological information for the Canberra region is now readily available through a web site or in a readily available guide book at the National Library, National Arboretum Canberra, Parliament House, National Botanical Gardens, Namadgi National Park, etc. The general public may prefer self-guided geotours. Tourist operators and conference organisers often have a particular client group in mind so that excursions can be tailor-made for clients/customers if necessary.

Canberra does not spring immediately to mind when considering a geoheritage excursion. Don't be put off. All the detailed information for such excursions is now readily available for the professional tour operator, conference organiser, or for the general public in book shops and on the GSA web site.

RESOURCES

03REA – UNCOVER - SEARCHING THE DEEP EARTH

03REA-01. 'PROSPECTING DRILLING': A TECHNOLOGY-ENABLED REVOLUTION IN MINERAL EXPLORATION

Richard Hillis

Deep Exploration Technologies Cooperative Research Centre, Adelaide, Australia

The Deep Exploration Technologies Cooperative Research Centre (DET CRC) is an Australian-based $AUS 120M research initiative to transform mineral exploration technologies and address declining success in mineral exploration beneath barren cover. It is funded by the Australian Government and the mining industry. This presentation will focus on the potential for DET CRC's coiled tubing drilling and real-time sensing projects to enable a revolutionary new approach to mineral exploration beneath barren cover, i.e. 'prospecting drilling'.

Tier 1 mineral resource discoveries are critical to maintaining Australia's, and indeed the world's mineral resource inventory without continuing decline in the grade of mined resources. Such discoveries are becoming less common because, increasingly, remaining prospective, under-explored areas are obscured by deep, barren cover. Improving the rate of Tier 1 discoveries obscured by deep, barren cover requires a step change in mineral exploration techniques that may be provided by 'prospecting drilling', i.e. extensive drilling programs that map mineral systems beneath cover, enabling vectoring towards deposits. The rationale for 'prospecting drilling' is provided by two examples: (i) a dataset of antimony from the Kalgoorlie district of Western Australia, which shows that subsampling at a 2 km spacing would map the mineral system and enable vectoring towards the contained deposits; and (ii) analysis of hypogene alteration systems of IOCG deposits in South Australia, which presents the possibility of vectoring towards the deposits within such systems starting from >10 km distant. The technological platform for ‘prospecting drilling’ must include low cost drilling due to the dense subsurface sampling required. Low cost drilling may be provided by transferring coiled tubing (CT) drilling technology, with its continuous drill pipe on a reel, from the oil and gas sector. Key challenges to the deployment of CT drilling in mineral exploration, i.e. its rate of penetration in hard rocks, the durability of CT and the recovery of cuttings, are being assessed and addressed by DET CRC researchers. The optimum technology platform for ‘prospecting drilling’ would be CT drilling complemented by downhole and top-of-hole sensing providing real-time petrophysics, structure/rock fabric, geochemistry and mineralogy. The first manifestation of real-time, downhole sensing is DET CRC’s newly developed autonomous sonde that is deployed by the driller and logs natural gamma radiation as the dill rods are pulled. Experimentation on real-time, top-of-hole sensing (on drill cuttings from diamond cored holes) has demonstrated cost-effective, rapid, repeatable (objective) and accurate determination of geochemistry and mineralogy with the necessary depth-fidelity. At the target cost of $50/metre, CT drilling could cost-effectively undertake ‘prospecting drilling’ in large, covered provinces such as the IOCG-prospective Gawler Carton of South Australia.

03REA-02. THE NULLARBOR: FIRST IMAGES OF THE EUCLA-GAWLER DEEP SEISMIC REFLECTION LINE (13GA-EG1)

Richard Blewett[1], Ian Tyler[2], Steve Hill[3], Brian Kennett[4] & Tanya Fomin[1]

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The Eucla–Gawler deep seismic reflection line (13GA–EG1), which was completed in February 2014, forms the ‘missing piece’ in a now complete east–west transect of the continent. The new line joins the previously acquired Albany–Fraser Orogen line (12GA–AF3) at Haig (WA), extending the seismic coverage for a further 834 km eastwards to Tarcoola (SA). The data were acquired by Geoscience Australia, the Geological Survey of Western Australia, and the Geological Survey of South Australia as part these institutions’ precompetitive data acquisition programmes, with data–infrastructure investment from AuScope to complete the line. The investment provides new, fundamental data in a hitherto little-known region of Australia with the aim of encouraging exploration investment and ultimately new mineral resource discovery, as well as improving knowledge of the structure and evolution of the continent.

The Eucla–Gawler region (Nullarbor Plain) is a major geological frontier, with very little information available on the subsurface geology. The region lies between two of the most prospective geological regions in the world, with the Yilgarn Craton to the west and the Gawler Craton to the east, however, the extensive sedimentary cover associated with the Eucla Basin has led to the bedrock underlying this region being very poorly represented and understood.

Some of the geological unknowns in this region include the:

- deep crustal structure of the sub-Eucla Basin basement geology as a whole and the likely geological processes that drove Mesoproterozoic tectonic assembly between the West Australian Craton and the South Australian Craton;
- deep crustal structure of the eastern margin of the Albany–Fraser Orogen and western margin of the Gawler Craton;
- nature of the Mundrabilla Shear Zone as a crustal-scale structure;
- nature and character of the Moho;
- margins of the Coompana magnetic feature and associated magnetic lineaments;
- structural relationships between tectonic units mapped at the surface (such as neotectonic features); and,
- structural elements of the Eucla Basin and underlying basins, which may host hydrocarbons.

A wide range of interpreted geological settings in this region have the potential to be highly prospective for regional, greenfields mineral exploration. This includes the:

- cratonic margins, such as the western margin of the Gawler Craton, which are settings that typically host conduits for deeply sourced mineralising fluids and depositional sites;
- Coompana magnetic feature and its margins in the southwest of South Australia. Previous interpretations suggest parallels with geological systems hosting Cu–Ni sulfides elsewhere, such as in Western Australia (e.g., the Nova deposit immediately to the west);
- highly prospective (e.g., Ni–Cu) mafic rift sequence in the western Gawler Craton associated with the Fowler Domain; and,

- provenance and transport pathways for heavy mineral sands (HMS) that have accumulated in Eucla Basin sediments and are presently mined at Jacinth-Ambrosia.

The data are of excellent quality, despite limestone and karst conditions in the Eucla Basin. This talk will present the unmigrated field stacks of the full crustal sections (20 second two-way-time); answering some of the geological unknowns.

03REB – UNCOVER - SEARCHING THE DEEP EARTH

03REB-01. THE CHARACTER OF THE LITHOSPHERE–ASTHENOSPHERE TRANSITION BENEATH THE AUSTRALIAN CONTINENT

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The base of the lithosphere is rarely a sharp interface and in consequence a variety of proxies are employed to try to gauge lithospheric thickness. The asthenosphere is expected to lie in a convective thermal regime and so seismic wavespeed gradients can be employed to provide an indication of the transition from a conductive thermal regime in the lithosphere to a more adiabatic state in the asthenosphere. Further, the character of seismic anisotropy can provide additional information since the more mobile asthenosphere is expected to be affected by current plate motions.

The broad outlines of the variations in the thickness of the lithosphere can be extracted by using a variety of criteria, e.g. fixed perturbation from a reference model, but this approach does not provide information on the sharpness of the transition to the lithosphere. By using information on both absolute shear wavespeed and its radial gradients, upper and lower bounds on the depth to the base of the lithosphere can be found, and the difference represents a measure of the thickness of the lithosphere–asthenosphere transition (LAT). We use a radially anisotropic 3-D shear wave model derived from multi-mode surface waves with the inclusion of finite frequency effects.

The thickness of the transitions is large beneath cratonic areas with fast wavespeed, but much thinner in the suture zone between cratons, particularly in the Musgrave block in central Australia. The lithosphere–asthenosphere transition is quite sharp beneath the Phanerozoic eastern margin of Australia. Anomalously fast SH wave speeds are found both above and beneath the areas with sharper to the asthenosphere in central Australia; these features link to frozen anisotropy in the lithosphere beneath the Mesoproterozoic suture zone as well as the anisotropy induced by shear flow in the asthenosphere beneath the fast drifting Australian continent.

03REB-02. RECOGNISING SIGNIFICANT REGIONAL METALLOGENIC CONTROLS WITH SUBTLE SIGNATURES

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Spatial distribution of mineral deposits in many geological provinces suggests the presence of regional-scale metallogenic controls, which do no not have an obvious expression in standard geological datasets. This can be due to a combination of the problem of scale and types of typical geological observations. A mineral prospectivity analysis not recognising such regional metallogenic controls as distinct targeting criteria is likely to produce results significantly biased towards more obvious identified features and thus leading to erroneous or at least suboptimal exploration targeting decisions. Systematic analysis of the spatial distribution of known mineral deposits may reveal the presence and characteristics of such regional metallogenic controls with only subtle expressions in standard geological datasets. They can also be inferred on the basis of significant spatial changes in the regional geochronology and geochemistry of magmatic rocks, metamorphic grades, isotopic geochemistry (including Sm–Nd and Hf isotopes), etc.

As an example, exploratory statistical spatial data analysis indicates that the regional spatial distribution of orogenic gold mineralisation in the Hodgkinson Province of north Queensland and the Western Lachlan Orogen in central Victoria, Australia, are strongly heterogeneous. The bulk of major gold deposits in each region are concentrated in relatively narrow (20 to 40 km wide) metallogenic zones oriented obliquely to most recognised major surface structures. While smaller gold deposits occur outside those zones, largest ore fields in each province are mostly confined within them. Notably, there is no clear spatial association between major deposits and regional-scale faults.

The richly endowed metallogenic zones in both the Hodgkinson Province and the Bendigo Zone of the Western Lachlan Orogen spatially correlate with boundaries between greenschist and sub-greenschist metamorphic zones and igneous sub-province boundaries. This evidence, combined with interpretations of deep seismic data, suggests that the metallogenic zones probably correspond to major crustal-scale heterogeneities in the middle to lower crust with only subtle and indirect surface expressions.

Similar significant metallogenic controls associated with deep crustal and lithospheric domain boundaries are commonly not expressed as major faults. Early recognition of such cryptic controls is critical for regional exploration targeting under cover but remains a serious challenge.

03REB-03. CRUSTAL ELECTRICAL RESISTIVITY HETEROGENEITY: A VECTOR TO MINERALISATION?

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The eastern Gawler Craton and Stuart Shelf region is one of the most prospective mineral provinces on Earth. However, the mineral system and the crustal architecture that provides its framework are poorly understood because the (*ca* 1590 Ma) prospective rocks are largely covered by Neoproterozoic-to-recent sediments. Magnetotellurics (MT) is an electromagnetic geophysical technique able to penetrate the cover sequences. The method can image the entire mineralising system in three-dimensions effectively frozen in place from 1590 Ma, from the base of the crust and uppermost mantle to the near surface, and from reduced to oxidised conditions.

From an array of ~200 long-period MT sites spaced about 10 km apart, we present new 3D crustal resistivity models of the eastern Gawler Craton and Stuart Shelf covering an area approximately 300 km by 100 km, and to a depth of 50 km. The resistivity models image an extensive conductive cover sequence, but also show large variations at mid and lower crustal depths. The Achean core of the Gawler Craton is electrically resistive (>1000 Ohm.m), while Proterozoic basement beneath the Stuart Shelf is two to three orders of magnitude more conducting. Major mineral deposits, including Olympic Dam and Carapateena, are coincident with the maximum gradients in mid and lower crustal resistivity, which may delineate significant deep crust and mantle fluid pathways. However, other significant resistivity gradients are also imaged, suggesting that these 3D models may provide a new approach to defining regional prospectivity.

We also present a detailed 200 km transect across the Olympic Dam deposit, and other prospective areas including the Vulcan deposit. In the second half of 2013, an 80-site broadband MT survey was conducted along an 80 km profile with a NE–SW orientation along the eastern margin of the Stuart Shelf, centred over the Olympic Dam deposit. The newly collected data provide much higher resolution of upper and mid-crustal resistivity than have been seen before, and have been integrated with existing 5 km spaced long-period MT data over 200 km. Conductive pathways are imaged through the resistive basement, connecting the highly conductive surface sediments with a large conductive zone at approximately 20 km depth. The conductive heterogeneity of the crust is proposed to help constrain region of potential mineralisation, and indicates that such conductive upper-crustal pathways may be a vector to mineralisation.

We show that regional broadband and long-period MT may unlock vital clues as to the fluid pathway architecture of the Stuart Shelf and to the nature of the mineralising systems within it. This will have direct implications for the understanding of IOCGU systems with applications for mineral exploration within South Australia and Australia.

03REB-04. INVESTIGATING THE ELECTRICAL LITHOSPHERE OF THE FLINDERS RANGES USING MAGNETOTELLURICS

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The link between the ancient Gawler Craton and the Curnamona Province lies beneath the Flinders Ranges, which bisects these two regionswhich that may have been connected prior to rifting. Seismic reflection and passive teleseismic studies have addressed these problems, but have not fully resolved the deep crustal and upper mantle architecture. Little is known about the lithospheric-scale electrical properties but these may yield vital constraints on the thermal and fluid evolution of this region. Magnetotellurics (MT) can be used to fill gaps in knowledge here regarding the tectonic history of the intra-plate deformation that is the Flinders Ranges.

Long period magnetotelluric data have been collected at 29 sites in an array spanning the Flinders Ranges and some parts of the adjacent Stuart Shelf and Frome Embayment, as part of the AusLAMP regional MT mapping program.

This new dataset complements numerous existing magnetotelluric transects within the region, which contain useful information about local structure, but these transects do not allow investigation into the deep lithosphere, nor do they offer an inclusive resistivity model of the crust and upper mantle beneath the Flinders Ranges.

New data were recorded in October and November 2013, at a frequency of 10 Hz, at 35–50 km spacing. Instruments remained in the field for three weeks, resulting in MT responses in the period range of 10–10 000 s for most sites. Such a large period range allows investigation of the entire lithosphere, from near surface to the lithosphere–asthenosphere boundary.

The data can be represented as geomagnetic induction arrows that map large regional trends in the lithospheric resistivity structure. An arrow is generated for each station at a given period (the longer the period the greater the depth), with each arrow tending to point toward conductive regions, and with length related to the magnitude of the conductive gradient. We show that at a bandwidth of 1000–4000 s, which yields information of scale lengths of about 100 km, induction arrows indicate a significant conductive central region within the Flinders Ranges that has been previously identified as the Flinders Conductive Anomaly.

Significant distortion is observed in the MT responses at longer periods, most likely due to the complex deformational history of the region, with small amounts of distortion also being attributed to the topography within the region. With significant portions of this dataset also involving three-dimensional effects, the greatest benefit will be obtained from three-dimensional inversions covering a volume of about 300 by 400 km, and to a depth of about 200 km.

03REC – UNCOVER - SEARCHING THE DEEP EARTH

03REC-01. GEOCHEMISTRY EXPANDS THE EXPLORATION FAIRWAY FOR THE MINERALISED COPPER PORPHYRIES IN WESTERN VICTORIA

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Mineralised Cu–Mo–Au porphyries were discovered in belts of Cambrian andesite in the Stavely region of western Victoria in the early 1990s. Deep weathering complicated early geochemical exploration and only a small number of diamond holes to several hundred metres depth were drilled. These encountered sub-economic grades in mostly propylitic alteration. New work shows they only drilled into porphyry dykes emanating up into the host andesites, rather than intersecting the actual porphyry bodies where economic grades could exist in the potassic zone. This lack of early success, combined with no historic artisanal mining and uncertainty over the geological context meant there was little appetite to persevere.

In the mid 2000s university whole-rock geochemical research suggested that the plate tectonic setting had been an Andean-type convergent margin – very attractive for copper porphyries – rather than a region of arc–continent collision as previously preferred. The geochemistry recognised boninites that can only form in supra-subduction zone settings. The andesite belts, themselves, and some associated granodiorite intrusions also possessed a geochemical subduction fingerprint with relative depletion of HFSE. A government funded deep crustal seismic transect across the region in the late 2000s imaged a crustal geometry consistent with the Andean-type convergent margin model. The faulted belts of andesite exposed at surface can be traced down into what appears to be a larger arc edifice buried in the subsurface.

This greater confidence for Andean-like mineralised porphyries has triggered a new round of exploration and research. A major breakthrough in prospectivity was taking some of the mineralised porphyry drill core and doing whole-rock geochemistry for comparison against the existing academic geochemistry. This shows the porphyries are related to the granodiorite intrusions rather than the belts of andesite as previously thought. This boosts prospectivity in two important ways: 1) the intrusions are younger than the steep dipping fault slices of andesite so that the mineral systems are upright for easy vectoring rather than being variably titled and/or fault dissected; and 2) the porphyries can occur anywhere within the entire Stavely region rather than being narrowly restricted to a few fault slices of andesite. A government stratigraphic drill program is being planned to better define the margins of Stavely Geological Zone.

Like many mineralised porphyry systems there is complexity for explorers. Current mapping shows the most obvious targets are where the porphyries intrude into the andesites with phyllic overprinting causing demagnetisation haloes (historic Victor prospect). Less obvious are porphyries intruding into siliclastic sandstone outside of the andesite belts with some of these still preserving the prograde potassic cap for a magnetic high (historic Junction prospect). The intrusions occur in clusters with a multiphase intrusion history, some mineralised and some barren. The clusters seem to be concentrated in late conjugate faults cutting across the paleo-arc trend to define corridors of enhanced prospectivity. Current explorers are collecting gravity and IP to generate good exploration targets through the deep weathering and cover, whilst they raise money for the deep drilling (up to 1 km) that will finally test the economic viability of this very poorly known porphyry mineral province.

03REC-02. GEOMICROBIOLOGICAL PATHWAYS TO MINERAL EXPLORATION IN THE DEEP

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The discovery of new ore deposits is becoming increasingly difficult in Australia, because many un(der)explored regions are covered by thick layers of regolith. To improve exploration success in these terrains a detailed understanding of microbial species distribution and functioning is now being utilised to develop bioindicator and biosensor systems. Bioindicators employ genetic markers from soils, deep regolith and groundwaters to provide information about buried mineralisation, while biosensors allow in-field analyses of metal concentrations in complex sampling media.

Generally, regolith materials are highly active zones of the environments hosting large microbial communities. Here, these communities are the primary drivers of C-, N-, S- and P- cycling. They also drive metal cycles, because many metals are used as micro-nutrients or for energy generation. If the contents of mobile heavy metals*, e.g.*, Ag, Cu, Au, Ni, Pb, U and Zn, in these regolith materials exceed certain thresholds, metals become cytotoxic. This leads to changes in the microbial community composition, some species thrive while others decline. Generally, thriving species display an increased capability of dealing with metal toxicity by expressing more genetic metal resistant determinants. This allows them to detoxify their cell immediate environments and is commonly linked to the immobilisation of metals *via* the formation intra- and extra-cellular biominerals. Using next-generation sequencing and microarray approaches, these genetic differences can now be detected and linked to environmental parameters. A number of recent studies of soils overlying VMS-, Au-, and Cu–Au–U- deposits in Western Australia, the Northern Territory, South Australia and New South Wales have shown that microbial communities structures and the presence of metal resistance genes were closely linked to the underlying mineralisation (expressed as elevated content of mobile heavy metals in top soils), as well as regolith landforms and regional geology. A multi-institutional project to define the composition of microbial communities on a continental scale is currently underway, *i.e*., the Biomes of Australian soils project (BASE). This project will define characteristic microbial communities across a wide range of Australian soil ecosystems and link them to environmental and physicochemical parameters. This dataset can then be used as backdrop to compare microbial community responses in soils from heavy metal-rich shallow and deep regolith environments important for mineral exploration.

Microbial communities mediating Au cycling occur on Au grains from (sub)-tropical, (semi)-arid, temperate and subarctic environments. Some bacteria, *e.g.*, *Cupriavidus metallidurans*, and *Salmonella typhimurium*, have developed biochemical responses to deal with highly toxic Au complexes; these include Au-specific sensing and efflux. This has led to the development and testing of a whole-cell biosensor for Au. Tests with real regolith materials have shown that the concentration of Au can be accurately measured, down to a detection limit of two parts-per-billion with the same accuracy as an ICP-MS. Currently, research is underway to develop protein-based biosensors for Au, which if successful will lead to 10 to 1000 times increased sensitivity and allow in field real-time measurement of Au from any material.

03REC-03. MEAT ANTS (IRIDOMYRMEX PURPUREUS) ARE BETTER METAL PROSPECTORS THAN TERMITES

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The geochemistry of meat ant (*Iridomyrmex purpureus*) nests and termite nests (unidentified species) were studied in a semi-arid climate of mixed eucalypt forest with a barren sandstone covering (<1 ppm Ag, 10 ppm Pb, <25 ppm Zn, and <44 ppm As) between 40 to 60 m above buried epithermal silver–lead–zinc–arsenic–manganese mineralisation of Kingsgate Consolidated Limited's Bowdens Silver Deposit (BSD) near Mudgee in eastern NSW.

Six insect nest 'mounds' were sampled (four meat ant nests and two termite nests) and metal values compared with soil samples taken adjacent to each of the nests. Silver and base metal contents of meat ant nests are in most cases much higher than in the soils and outcropping/subcropping rock adjacent to the meat ant nests. Meat ant nests are anomalous in Ag, Pb, Zn, As, Mn and Cd and reflect the composition of the mineralisation in underlying strata separated by barren cover. Termite nests did not contain any significant anomalies of metals that occur in the buried deposit.

The BSD is a large epithermal silver–lead–zinc deposit, which is hosted in early Permian rhyolite. Early mineralisation is disseminated and occurs within siliceous fill-cemented breccia. Later mineralisation is commonly quartz–carbonate–sulfide assemblages in thin crustiform vein sets. Recent resource estimates reported by Kingsgate Consolidated Ltd total 88 million tonnes of 47.7 grams per tonne silver, 0.29% lead and 0.39% zinc (total Measured, Indicated and Inferred).

All of the insect nests are located within an area of thin soils and rocky quartz sandstones and siltstones, which overlie buried mineralisation in the northeastern portion of the deposit (Main Zone North). Each of the six nests was sampled at depths of several centimeters to minimise possible surface contamination from drilling activity. Meat ant nests comprised unconsolidated, free-flowing sand. Termite nest debris consisted of fine-grained, compacted silt material that required breaking and crumbling. Soil samples were also collected at each nest location.

The observed differences in metal distribution between meat ant and termite nests have been influenced by habitat and very different lifestyles of the insects. Termites are cellulose feeders and source food and moisture from vegetation. They accumulate metals in their bodies through ingestion of elevated metals in foliage cellulose. Meat ants are also widespread throughout Australia and are omnivorous opportunistic scavengers that are not limited to deriving and accumulating metals from foliage. Meat ants are known to have extensive underground nests and we believe that in periods of prolonged drought they supplement their moisture uptake by accessing the underground water table through joints and cracks, some opened by penetrating eucalypt roots. Moisture collected by foraging meat ants can be stored in the ant crop (or social stomach) and carried to the nest where it is fed to other members of the colony by trophallaxis. Over time metals accumulate in nest debris through accumulation of insect excrement and body parts.

This study showed that meat ant nest sampling can be an effective exploration tool to detect covered base metal mineralisation.

03RED – 3D GEOSCIENCE: METHODS, APPLICATIONS AND CHALLENGES IN IMAGING AND ANALYSING SOLID EARTH SYSTEMS AT DIFFERENT SCALES

03RED-01. 3D EARTH IMAGING OF REGIONS AND CONTINENTS: THE CHALLENGE OF DATA FUSION ACROSS MULTIPLE SCALES

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3D Earth imaging is an increasingly sophisticated process. It often involves the formation of ‘volumes’, representing a lithology group or other categorical entity, from a continuous, and usually indirect, observable. These volumes may be separated by geometric structures such as a bedding plain, fault or fold. In reconnaissance, we are happy to deduce an architecture or fabric based on a single observable, for example, seismic velocity. As our investigations progress, the need arises to synthesise results using multiple geophysical observables, including magnetic intensity, gravity and conductivity. In most cases, the top surface or shallow layers of our model boasts a special category of data: directly observed categorical geology, commonly in great detail. Hence, we are faced with the challenge of making a useful integration of a high number of data dimensions of mixed type, and possibly discovering knowledge from the interpretation of patterns inherent between those data dimensions.

Taking as a starting point Earth models derived from seismic tomography, this presentation explores conceptual and practical strategies for progressing from single-observable reconnaissance towards 3D images based on multiple observables. Visualisation strategies that facilitate data inference will also be explored with the idea that visualisation is part of the inference process, not only a way of displaying a final result.

The first case study, from southeast Australia, will show an example of inference and imaging strategies on a regional scale, focussing on Bass Strait and northwest Tasmania. This is a relatively data rich location, although with patches of extremely high data density, and some areas that are extremely data poor. Strategies for learning from multiple datasets, and making refinements to the volumes comprising the 3D images based on those learnings, will be presented together with a range of visualisations. This case study also provides examples of new knowledge resulting from a data fusion investigation.

A continent-scale example is shown as second case study, focussing on Antarctica. 3D imaging is now characterised by adequate data coverage for a first order understanding of much of the lithosphere, however, there are significant implications in the sole reliance on this scale of data. Strategies for meaningful data interpolation and extrapolation will be presented, again with a range of visualisations. This large-scale case study provides an example of an approach to Earth imaging based on model predictions and uncertainty evaluation.

03REE – 3D GEOSCIENCE: METHODS, APPLICATIONS AND CHALLENGES IN IMAGING AND ANALYSING SOLID EARTH SYSTEMS AT DIFFERENT SCALES

03REE-01. HIGH-RESOLUTION X-RAY COMPUTED TOMOGRAPHY: APPLICATION TO IGNEOUS PETROLOGY AND ORE DEPOSITS

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Conventional petrographic studies commonly rely on the analysis of two-dimension thin sections, blocks or mineral separates, using techniques such as optical microscopy, scanning electron microscopy (SEM), electron microprobe analysis, mineral liberation analysis (MLA) SEM, or quantitative evaluation of materials SEM (QEMSCAN). Although all these techniques are important to characterise the mineral assemblages or compositions, they do not reproduce the real three dimensional views of the samples and can lead to incomplete or biased interpretation of the textural relationships, mineral sizes and abundances. High-resolution X-ray computed tomography (HRXCT) is a non-destructive technique that allows the exploration of three-dimensional mineral, alloy or pore distributions in natural and synthetic samples, leaving the samples intact for further sample characterisation. The recent development of HRXCT allows the three-dimensional characterisation of samples at a detail resolution down to 0.7 µm. The data generated by HRXCT not only provide some striking three-dimensional images but can also be processed and analysed to provide *in-situ* quantitative three-dimensional mineralogical and textural measurements that are impossible to assess accurately by any other method. This, combined with the development of dedicated workflows, algorithms, and softwares, is opening notably new doors for the quantitative three-dimensional characterisation (at the sample scale) of igneous and metamorphic rocks, ore materials (either natural or synthetic) or meteorites. The presentation will describe the basic principles and methodology of HRXCT, from the data acquisition to the three-dimensional quantitative measurements and will present several examples of its application to igneous petrology and ore geology.

03REE-02. USING SYNCHROTRON X-RAY MICROTOMOGRAPHY TO IMAGE STRUCTURE AND POROSITY IN SHEARED NEOARCHEAN GRANITE, YILGARN CRATON, WESTERN AUSTRALIA

Klaus Gessner[1,2], Ivan Zibra[1], Jie Liu[2], Martin Paesold[3], Virginia Toy[4], Xianghui Xiao[5], Klaus Regenauer-Lieb[2] & Luca Menegon[6]

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On the 10 to 100 km scale the structure of the Neoarchean Yilgarn Craton is characterised by a network of high-strain zones within highly deformed, elongate granitic bodies and transposed greenstone belts. This shear zone network developed during prolonged magmatic activity that led to a nearly complete reworking of the felsic continental crust. Strong spatial and temporal correlation with hydrothermal gold mineralisation suggests that the shear zone network may have acted as a pathway for mineralising fluids.

Here we present results of 3D fabric analysis of deformed granite from the Neoarchean Cundimurra Shear Zone in the Murchison Domain of the Youanmi Terrane. The fabrics we document relate to the late part of a protracted history of structurally controlled granite emplacement in a transpressional kinematic setting. The granite protolith shows a pre-existing lower amphibolite facies foliation that experienced fracturing related to the emplacement of tourmaline-bearing veins. The rock subsequently was deformed in greenschist facies mylonitic to ultramyonitic shear zones that are typically tens of millimetres to tens of centimetres in width. We analysed samples across a shear zone margin where the ductile strain gradient is expressed by a transition from granite to ultramylonite. The analysis of the 3D volumetric model produced by reconstructing the Synchrotron X-ray data complemented by Electron Backscatter Diffraction data that allows us to better characterise the deformation fabric by integrating quantitative measurements of the shape fabric and the crystallographic orientation. Preliminary results show that with increasing ductile strain and crystal–plastic grain size reduction, porosity becomes significantly smaller, and in some cases can decrease by three orders of magnitude. Whereas our results are consistent with a reduction of pore space due to closer packing of smaller grains, they do not reproduce an increase in porosity with increasing ductile strain as has been reported in previous studies.

High fluid flow rates are required to sustain advective mass transport in hydrothermal mineral systems. The lack of primary porosity in crystalline rocks at mid-crustal levels and its destruction by grain size reduction is a major limiting factor for dynamic permeability. Our results suggest that crystal–plastic deformation processes may not always increase dynamic permeability in mid-crustal shear zones, and that therefore the potential of shear zones to act as pathways of mineralising fluids needs to be assessed carefully on a case by case basis.

03REE-03. 3D CRUSTAL ARCHITECTURE OF THE EAST ALBANY-FRASER OROGEN IN WESTERN AUSTRALIA FROM PASSIVE SEISMIC DATA

Christian Sippl[1], Hrvoje Tkalčić[1], Brian L N Kennett[1], Catherine V Spaggiari[2] & Klaus Gessner[2]

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The east Albany-Fraser Orogen, situated at the southeastern margin of the Yilgarn Craton in Western Australia, comprises a series of NNE–SSW trending structural domains associated with both extensional and compressional, Paleoproterozoic to Mesoproterozoic tectonothermal events. With no major tectonic activity in the region since nearly 1.1 Ga, the features of this orogen are exceptionally well preserved. Although outcrop is sparse due to cover by regolith and younger basins, through a combination of field, geochronological and geochemical analysis and aeromagnetic and gravity data interpretation, the surface geology has been reasonably well defined. However, knowledge about geological structure at depth, which could provide important insights into the processes that drove the tectonic evolution of the Albany–Fraser Orogen, is currently very poor, particularly in 3D.

To resolve the deep crustal structure of this region, a 40-station passive seismic array, installed in November 2013, covers all of the units of the east Albany-Fraser Orogen from the Yilgarn Craton to the Nornalup Zone. After a year of continuous recording, the array will be shifted southwards along the strike of the orogen at the end of 2014, where it will record data for another full year.

Four seismic reflection profiles, collectively known as the Albany-Fraser seismic survey, were shot perpendicular to the major structural grain of the orogen in 2012, and their interpretation in a collaborative effort between the Geological Survey of WA, Geoscience Australia, The Australian National University, The University of Western Australia and AngloGoldAshanti, has recently become available. Our passive seismic array fills the *ca* 300 km lateral gap between two of these profiles, allowing us to trace the lateral extent and variation of the units interpreted from the 2D profiles. The higher resolution of the reflection profiles provides an important benchmark for the passive seismic dataset, showing for example which unit boundaries we can resolve, and the extension of information from 2D to 3D.

Preliminary results from the analysis of the first two batches of data, collected in February and June 2014, will be presented. We use ambient noise tomography to retrieve a three-dimensional model of regional shear wavespeeds, and receiver functions, jointly inverted with surface wave dispersion curves, to get 1D profiles of shear wavespeeds and the depth of major velocity discontinuities beneath the stations. Small local earthquakes identified in the seismic records are also tested for their usefulness in probing the regional crustal structure.

03REE-04. INSIGHTS INTO THE STRUCTURE OF THE MCARTHUR BASIN USING THE IMPLICIT 3D MODELLING METHOD: PRELIMINARY RESULTS

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Three-dimensional modelling is extensively used in petroleum and mining industries to fill the gap between subsurface reality and scarce geophysical and geological datasets. Given this context, dramatic improvements in 3D modelling methods have been achieved over the last decade. The implicit modelling method is one of these advances and is capable of reducing the time-cost and difficulty of building a structural model.

The McArthur Basin is located in northeastern Northern Territory (Australia). This Paleo- to Mesoproterozoic basin covers an area of approximately 600 × 800 km with a preserved thickness of up to 10 km of primarily sedimentary rocks with subordinate volcanic rocks. The basin succession has been subdivided into five lithostratigraphic packages based on similarities in age and lithology, each separated by a regional scale unconformity or disconformity. Two of these packages, the Glyde and the Wilton packages, are highly prospective for base metals, iron ore and hydrocarbons. The Barney Creek Formation, a thick layer of mixed black-shales and dolomites within the Glyde package, hosts the world class McArthur River Zn–Pb–Ag deposit and is considered as a potential source rock and reservoir for both conventional and unconventional hydrocarbons.

The present-day structure of the basin displays a polyphased and complex history emphasised by multiple reactivations of deep basement structures. At the basin scale, these intense deformations appear restricted to the north–south Walker-Batten Fault Zones and the east–west Urapunga Fault Zone.

The main questions raised by the present work are: (i) how to integrate and compile heterogeneous data to provide the most consistent structural framework for an implicit modelling method, and (ii) how the 3D model would increase knowledge of selected subsurface economic target geometries and improve the fundamental understanding of the geological history of the McArthur Basin.

Results are based on a series of 1D and 2D geophysical and geological datasets. Due to the basin size a classification of faults as first and second order hierarchy has been established, based on the synthesis of outcrop and subsurface data and/or their interpretation and is designed to serve the 3D modelling process. The subsurface geometry of the faults has also been interpreted and integrated into the modelling process. The basin displays both shortening and extensional deformation. Faults linked to these deformations display generally low dip angle and imbricate structures (sequences and duplexes). The associated deformation style implies two main triggering mechanisms: thin and thick skin deformation styles. The thin-skin deformation style led to the identification of potential décollement layers or weak interfaces within the sedimentary series that have been integrated into the 3D structural model. Horizon modelling has also been attempted in the highly deformed Batten Fault Zone. Here, the Barney Creek Formation was constrained using cored wells, outcrop data and structural measurements. The result gives an approximation of the depth-to-reservoir for this particular formation and will be extended across the entire area as additional data becomes available.

DYNAMIC PLANET

03DPA – FLUIDS AND MELTS FROM CORE TO CRUST

03DPA-01. WAS THE EARLY EARTH STAGNANT?

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Geodynamic modelling of the early Earth suggests high mantle temperatures would have resulted in weak slabs, and insufficient stress within slabs, to sustain subduction. A number of authors have suggested that a stagnant, or episodic, mode tectonism was more appropriate to the early Earth than plate tectonics.

Here we address the ability of stagnant lid tectonics to explain a number of observations of the Hadean/Archean Earth. We show that mixing in stagnant lid regimes is over an order of magnitude less efficient than mobile lid mixing, and for plausible Rayleigh numbers and internal heat production. This suggests an explanation for the long mixing time of ^{142}Nd and ^{182}W anomalies, which have been documented in <*ca* 2.7 Ga rocks, but should have been homogenised on those timescales in a plate tectonic regime. This scenario also 1) posits an explanation for the delay between accretion of the late veneer – between 4.5–3.8 Ga on a stagnant surface – and its fully mixed signature apparent in elevated PGEs in 2.7 Ga komatiites, 2) provides an explanation for the 400 Ma of immobility of the mafic protolith from which the Jack Hill zircons were sourced, 3) retards early heat loss from the mantle, providing a solution to the "Archean thermal catastrophe" of parameterised Earth evolution models, and 4) provides an explanation for the low paleointensities (and thus magnetic field strength) observed in >4 Ga zircon grains.

03DPA-02. A MANTLE XENOLITH PERSPECTIVE ON KIMBERLITE PETROGENESIS

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Kimberlites are enigmatic, rare, small volume igneous rocks that are important because they are the primary host rock to diamonds and because kimberlite parental melts originate from deep within the Earth (> 150 km, i.e. within the diamond stability field). In addition, kimberlite magmas have entrained abundant fragments of mantle and deep crust wall rocks en route to the surface, thus providing the major source of information about the petrology and geochemistry of the deep lithosphere in continental areas. Due to their hybrid and volatile-rich nature and widespread alteration by deuteric (i.e. late-stage magmatic), meteoric and hydrothermal fluids, the primary composition of kimberlites has proven difficult to constrain.

The study of melt inclusions in primary magmatic minerals of kimberlite rocks, such as olivine and spinel, has provided evidence that the composition of kimberlite magmas prior to late-stage modification might be close to carbonatitic. However, this interpretation contrasts with the broadly ultramafic composition of kimberlite rocks and has been widely criticised because the trapped melt inclusions may or may not be representative of the composition of primary kimberlite melts.

Given that not all pulses of kimberlite magmatism reach the surface, the investigation of reaction textures between mantle wall rock fragments (i.e. xenoliths) entrained by kimberlite magmas and primitive or precursor kimberlite melts may provide an alternative approach to gain constraints on the petrogenesis of kimberlite melts. Micro-textural, mineralogical, geochemical and melt/fluid inclusion analyses of these reaction zones can provide a wealth of information on the composition of kimberlite magmas at depth, i.e. before their composition is extensively modified by processes such as outgassing and crustal alteration.

This presentation will review existing studies of mantle xenoliths that preserve evidence of metasomatism coeval with kimberlite magmatism. These studies include detailed examinations of carbonate-rich metasomatic assemblages commonly occurring in veins and pools and overprinting pre-existing mantle minerals; and investigations of mantle polymict breccias, which are widely regarded as failed kimberlite intrusions that halted at lithospheric mantle depth. Where abundant data are available for both the entraining kimberlite magma and the metasomatic mantle agent, a direct comparison between the two melts can be drawn. We will show this is particularly significant for the Bultfontein kimberlite (Kimberley, South Africa), where an alkali-carbonate composition for the primary kimberlite magma has been deduced from our coupled investigation of kimberlite host rock and entrained mantle xenoliths. We conclude that the study of reaction textures in mantle xenoliths produced just prior to or during kimberlite entrainment represents a novel and exciting direction towards a new understanding of the petrogenesis of kimberlite melts.

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03DPB-01. HOW SUPERCONTINENT CYCLES AFFECT THE VIGOUR OF OCEANIC HYDROTHERMAL CIRCULATION AND SEAWATER CHEMISTRY

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The major ion chemistry of the world's oceans has oscillated at least five times in the Phanerozoic Eon and is represented by changes in composition of marine carbonates, bromine concentrations and composition of inclusion fluids, deposition of marine evaporates and mass-balance calculations. The oscillations between the so-called "aragonite" seas during which aragonite and high magnesian calcite precipitate, as in today's oceans, and "calcite" seas during which low magnesian calcite precipitates can be related quantitatively to supercontinent cycles. We reconstruct relatively young mid-ocean ridge flanks aged 0–65 m.y. from 200 Ma to the present and compute oceanic heat and fluid flow, ocean floor area and mean crustal age of the ocean crust over the last 200 million years. Geological uncertainties of our reconstructions are explored by comparing alternative age–area distributions, reflecting gradual advances in our knowledge and in the complexity of ocean basin reconstructions. Three alternative reconstructions for 100 Ma reflect the stepwise inclusion of more complex mid-ocean ridge systems, modelling the breakup of the Ontong Java, Manihiki and Hikurangi plateaus, and the subsequent inclusion of back-arc basins in the eastern Tethys and Southeast Asia. The seafloor age histograms, mean ages and ridge flank areas of these reconstructions have only undergone relatively minor changes, supporting the robustness of our approach. Both fully dynamic plate tectonic-mantle convection models and our kinematic reconstructions suggest that over a Wilson cycle there are variations by a factor of 2 in the rate of production of new seafloor. A stable supercontinent is accompanied by a rectangular age–area distribution, with breakup and dispersal leading to a skewed distribution, reflecting the progressive creation of new crust at the expense of much older crust being subducted, while the triangular distribution we observe today reflects a near constant production of oceanic lithosphere compared to what is destroyed. We show that variations in hydrothermal flux calculated as a function of the changing age–area distribution of ocean floor after supercontinent break-up and dispersal correlate with major transitions in ocean chemistry in the Late Jurassic and in the Oligocene, in broad agreement with geological observations. The onset of a major period of calcite precipitation is linked to the break-up of Pangaea, leading to a doubling in the length of the global mid-ocean ridge system and a 50% increase in hydrothermal fluid flux. Increased hydrothermal flux enhances alteration of fresh basalt, resulting in lowered Mg/Ca ratio of the seawater and ultimately hypercalcification. Formation of massive chalk deposits in the Upper Cretaceous coincided with the maximum area of relatively young ocean floor that drives hydrothermal flux. The transition towards present-day Mg-rich aragonite seas correlates with a reduction in spreading rates, and a decrease in the area of young ocean floor due to progressive subduction of ridge flanks along the Pacific rim. As late Archean and Proterozoic seawater experienced similar oscillations in Mg/Ca ratios our improved understanding of the underlying tectonic processes controlling the major ion chemistry of oceans can provide insights into the earliest and poorly constrained cycles of coalescence and dispersal of continents.

03DPB-02. ACCRETION OF ANDESITIC CRUST ALONG A HIGH-TEMPERATURE OCEANIC DETACHMENT FAULT IN THE OMAN OPHIOLITE (BAHLA MASSIF)

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The Oman ophiolite is considered as a fossil analog of fast oceanic spreading centers, especially from the structure and composition of its lower crust. However, a glance at former studies reveals that this conclusion is based on observations conducted on a few spots in the ophiolite. A clear observational and sampling bias exists against areas where the lower crust is strongly faulted. These areas are preferentially located along the thrust front of the ophiolite and their structures have been attributed to syn- and post-emplacement tectonics. However, the recent discovery of syn-magmatic faults in the ophiolite led us to reconsider this interpretation.

To better constrain the accretion history of the Oman ophiolite, we undertook a combined structural, petrological and geochemical study of the lower crust (layered cumulates) and the mantle peridotites in one of these frontal areas (Bahla massif). We found that the structure of this massif is inherited from crustal accretion along a major high-temperature ridge-parallel normal fault located at the mantle/crust boundary. Fault rocks are affected by intense plastic deformation under very high-temperature conditions (from gabbro solidus to amphibolite facies) and the evolution of this deformation is broadly correlated with steepening of the cumulate layering and the mantle/crust boundary. This 15 km-long ductile fault is interrupted by a strike-slip shear zone, also synchronous with the accretion, as attested by the intrusion of syn-tectonic plagiogranite. This 10 km-long shear zone is characterised by intense mylonitic deformation at temperatures rising from greenschist facies in the crust to granulite facies in the mantle. The architecture of this massif is quite similar to that of oceanic core complexes developed along syn-accretion detachment faults at slow-spreading ridges.

Parent melts of the Bahla crust, were more siliceous for a given MgO content than mid-ocean ridge basalt (MORB), as deduced from the abundance of early-crystallising orthopyroxene (opx) in the layered cumulates. Some lithologies, such as opx-bearing troctolite and cumulative harzburgite, have not been reported previously in the Oman crust and appear to be specific to Bahla. The major- and trace-element composition of the cumulates can be explained by mixing in various proportions between MORB-like melts and depleted melts of andesitic–boninitic affinity. These latter may have been produced by hydrous remelting of the lithospheric mantle, with fluid migration down to mantle depths being enhanced by intense faulting. Most mantle dykes (former melt channels feeding the crust) from Bahla belong to this andesitic kindred, which may explain the high proportion of this component in the hybrid parent melts of crustal cumulates.

These results lead to the conclusion that the Oman ophiolite cannot be blindly compared to modern rapidly spreading oceanic ridges. Compared to massifs studied up to now, the specific structural and petrological characteristics of Bahla appear related to its position at the front of the ophiolite, closer to the continental margin at the time of spreading. We can thus assume that slow spreading conditions and a marginal setting probably prevailed during the early stages of the accretion of the oceanic basin from which the ophiolite was derived.

03DPB-03. HOW DEFORMATION AFFECTS REACTION RATES: NEW INSIGHTS FROM PHASE TRANSFORMATION EXPERIMENTS IN THE KBR–KCL–H_2O SYSTEM

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Many natural processes such as weathering, diagenesis, metasomatism and metamorphism involve phase transitions in mineral–fluid systems. Recent experimental studies on feldspars, apatite and zircon show that mineral reactions in the presence of a reactive fluid occur by solvent-mediated phase transformation over extremely short timescales, ranging from hours to weeks. This has important implications for geological processes, which are classically viewed as occurring over millions of years.

However, to date all phase-transformation experiments have been carried out on undeformed perfect crystals, while in nature chemical alteration in minerals is clearly associated with deformation microstructures such as subgrain boundaries, twins and crystal defects. Understanding the effects of deformation microstructures on the rates of mineral phase transformations is essential for our fundamental understanding of large-scale geodynamic processes on Earth; in nature, reaction and deformation commonly go hand-in-hand.

We present first results from a series of hydrothermal experiments designed to examine effects of deformation microstructures on reaction rates in single crystals of salt (KCl). The experimentally deformed crystals exhibit subgrain boundaries, bent lattices and hair fractures. Two main sets of static experiments have been performed: (a) replacement experiments on large sample volumes and (b) see-through experiments on thin sample slices, allowing real-time observation of reaction progress under the reflected light micrsocope. In the static experiment series, undeformed and pre-deformed (13% strain) KBr single crystals were reacted with saturated KCl–H_2O solution at room temperatures (24°C ± 0.5°C) and atmospheric pressures for durations of 5, 10, 30, 60 and 120 min.

The reaction resulted in a development of a highly porous KCl rim around the relict core of the KBr crystal. The volume and external morphology of the original crystal was preserved in all cases and the reaction interface was sharp even on the microscale. Deformed samples developed reaction rims that are 8–15% thicker compared to the undeformed samples, suggesting a considerable increase in reaction rates associated with deformation microstructures. In see-through experiments the reaction front showed a distinctly different behaviour in deformed *vs* undeformed samples.

The results of this study suggest that deformation microstructures can significantly enhance reaction rates and influence the microstructures that develop during phase transformations.

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03DPC-01. METAL SOURCES AND TRANSPORT MECHANISMS AT CRUST–MANTLE BOUNDARY CONDITIONS: NEW SEARCH SPACE FOR DEEP-SEATED MAGMATIC MINERAL SYSTEMS

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Most known world-class magmatic nickel–copper sulfide deposits formed relatively close to the Earth's surface and it can be argued that most, if not all, of the easily accessible deposits have already been found. Consequently, it is necessary to open new exploration possibilities to guarantee a steady metal supply in the future. One promising approach involves the exploration for magmatic nickel–copper sulfide deposits that are hosted by rocks formed by magmas of mantle origin and intruded around the crust–mantle boundary. However, little is known about how and where these deposits form.

For this purpose we integrated (i) a series of high-pressure and high-temperature experiments with (ii) the analysis of mineralised mafic and ultramafic rocks collected from a series of pipe-like conduits in the Ivrea-Verbano Zone in northwest Italy. As well as providing exposures of the subcontinental lithospheric mantle, this domain shows the crust–mantle boundary where deep-seated mineralised intrusions were emplaced in the early Permian. These pipes have a strong alkaline affinity and provide a unique opportunity to study the tantalising relationships between fluid-rich mafic magmas and sulfide mineralisation at crust–mantle boundary conditions.

The pipes consist of massive amphibole- and phlogopite-rich peridotite and pyroxenite with minor hornblendite and gabbro and an extensive accessory mineral assemblage including apatite, zircon, baddeleyite, carbonates, titanite, ilmenite, rutile, spinel and graphite. Ni–Cu–PGE mineralisation occurs mainly along the outer rim of the pipes, forming randomly distributed polyphase sulfide nodules with sizes from <100 µm up to several millimetres. The sulfide assemblage consists mostly of pyrrhotite, pentlandite, chalcopyrite, with minor cubanite, mackinawite and pyrite and is closely associated with a wide range of platinum-group minerals such as merenskyite ($(Pd,Pt)(Te,Bi)_2$), moncheite ($(Pt,Pd)(Te,Bi)_2$), sperrylite ($PtAs_2$) and irarsite (IrAsS).

Our geothermometry estimates suggest that the pipes were emplaced at ~900–950°C, close to the water-saturated peridotite solidus. Water-rich conditions in the parental melt are also suggested by our high-pressure and high-temperature experiments and by SHRIMP-SI analysis of pyroxenes from the pipes, which yielded ~500 ppm H_2O, corresponding to ~4 wt% water in the melt. Whole-rock and minero-chemical data suggest that the parent magma to these pipes was most likely derived from the asthenosphere and then later "contaminated" by low-melting point fractions of lithospheric melt caused by previous metasomatic activity. The evolving volatile-rich melt then intruded the Ivrea-Verbano Zone as a series of open-system feeder conduits that subsequently reached sulfide saturation and formed widespread Ni–Cu–PGE mineralisation.

The integration of experimental and field-based data shows that even if H_2O-rich fluids are less efficient to transport and concentrate metals than sulfide liquids and basaltic melts at crust–mantle boundary conditions, they may nonetheless play a very important physical role in facilitating the establishment of plumbing systems where mass transfer of metals between the mantle and crust can occur and where economic metal sulfide deposits can form along magmatic open system conduits. These findings represent the first step towards a new generation of exploration models that will allow recognition of deep-level metal sulfide deposits and identification of prospective regions in areas that were previously considered to be non-prospective.

03DPC-02. ARCHEAN LITHOSPHERIC MANTLE: THE FOUNT OF ALL ORES?

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Magma-related ore systems form economic deposits that underpin our human civilisation. The single largest influence on the formation of Earth's ore deposits has been the generation of the Archean subcontinental lithospheric mantle (SCLM). The magmas related to the redistribution of metallic elements are derived from the asthenosphere, then traverse and interact to varying degrees with the SCLM.

Convergent geochronology datasets including Hf-isotope model ages for zircons and Re–Os model ages for mantle sulfides, reinforced by other geochemical and tectonic criteria, indicate that over 75% of the SCLM and its overlying crust (now mostly lower crust) formed at 3.5–3.0 Ga, probably in a global overturn event (or series of events) that marked a change in Earth's fundamental geodynamic behaviour. This primitive SCLM, the roots of the Archean cratons, was geochemically highly depleted, but has been variously refertilised by multiple fluid infiltration events that commonly can be recognised in the crustal tectonic record in diverse orogenic environments. These fluids can metasomatise the original SCLM domain, and add or scavenge elements of economic relevance depending on the conditions.

The primitive SCLM subsequently has played a major role in crustal metallogeny for many ore types [1]. *Firstly,* the high degree of buoyancy of this ancient SCLM relative to the asthenosphere, due to the Mg-rich and Fe-poor composition, results in the persistence today of low-density, rheologically coherent Archean domains (including relict blobs in rifted ocean basins [2] and commonly, the preservation of old crustal domains (the "life-raft" model). *Secondly,* the enduring (and volumetrically dominating) Archean lithospheric mantle domains represent a reservoir for metasomatic enrichment over their 3.5 billion year history, creating a potentially metallogenically-fertile mantle impregnated with critical elements (including Au, Cu, Ni? and platinum group elements [3, 4]). *Thirdly,* the formation of Archean cratons provided an architectural mantle-scape of regions with contrasting rheology, composition and thickness. These cohesive Archean domains control magma and fluid pathways around their margins and along old sutures between blocks, and may act as both sinks and sources for ore-forming elements depending on the geodynamic evolutionary stage. *Fourthly,* if this first stabilisation of lithospheric mantle at 3.5 Ga signalled the end of an overturn regime (either uniquely, or intermittent with subduction), then this is when long-lived tectonic regimes conducive to mineralising systems (e.g. back-arc basins, passive margins, cratonic boundaries) became available [5].

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03DPC-03. EVOLUTION OF EARTH'S EARLY CRUST – COUPLING PETROLOGICAL AND 2D NUMERICAL MODELLING

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Plate tectonics can explain the assembly and break-up of supercontinents, how and where major mineral deposits formed and maybe even why there is life on Earth. However, it remains unclear when plate tectonics began in its present form and why it does not occur on other terrestrial planets in our solar system. Most data suggest that plate tectonics has operated at least since the Neoarchean, but to what extent these processes occurred during the first two billion years of Earth history is fiercely debated.

Petrological and thermal models suggest ambient mantle potential temperatures in the Archean were > or >> 1500°C. Such high temperatures would have led to a higher degree of partial melting of the mantle and the generation of a thick (up to 45 km) MgO-rich primary crust that was underlain by highly residual mantle. However, the preserved volume of this crust is low, which suggests most of it has been recycled into the mantle. Was this thick crust capable of being subducted, or was some other mechanism responsible for it's recycling?

We couple calculated phase equilibria for hydrated and anhydrous crust compositions and their residues for Moho temperatures of 1000 and 900°C with parameterised 2D geodynamic models to investigate the stability and evolution of early Archean lithosphere. Petrological modelling shows that, with increasing MgO content, the density of primary crust increases more dramatically than the density of complementary residual mantle decreases. MgO-rich primary crust was ultramafic (i.e. it lacked plagioclase) and, depending on the degree of hydration, would have become gravitationally unstable at thicknesses of between ~35 km (anhydrous) to ~45 km (fully hydrated). The results of 2D thermomechanical modelling suggests that delamination of this thick crust is dynamically plausible. Delaminated crust would have refertilised residual mantle or melted, and return flow causes adiabatic melting to form new crust, further driving delamination by magmatic thickening. Ultimately this new crust could have melted to produce the tonalite–trondhjemite rocks that characterise the exposed Archean continental crust.

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03DPD-01. TIBETAN CHROMITITES: TO THE TRANSITION ZONE AND BACK?

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Microdiamonds, exsolution of diopside, coesite and FeC, and a range of inclusions including native metals and alloys, are present in podiform chromitite bodies from the Luobusa peridotite massif, Tibet [e.g. 1, 2]. This trace-mineral assemblage suggests that the chromitites have formed at ultra-high pressures (UHP) corresponding to the Transition Zone under super-reducing conditions (SuR-UHP). However, trace-element signatures of the chromites are indistinguishable from those of typical ophiolitic chromitites such as those from the Antalya Complex, Turkey. These trace-element signatures suggest primary crystallisation from typical arc-type melts at shallow depths [3]. New data on geochronology and Fe oxidation state may explain this conundrum.

Rhenium-depletion model ages of laurite grains, and U–Pb ages and εHf values of euhedral zircons separated from massive chromitite, suggest that the chromitites formed at least 325 Ma ago. We propose that a lithospheric mantle slab containing the crystallised chromitite was subducted to the Transition Zone (>440 km, corresponding to >12.5 GPa) [4], where chromite inverted to the high-pressure polymorph Ca-ferrite, and reacted locally with reducing fluids to form the SuR-UHP trace-mineral assemblage. Os model ages (TRD) of Os–Ir alloy nuggets in chromitites suggest that this had occurred by *ca* 235 Ma [5]. $Fe^{3+}/\Sigma Fe$ obtained for chromite in massive chromitite from Luobusa using Mössbauer spectroscopy are higher than those for chromite in nodular chromitite (McCammon, C., unpublished). This may reflect sequestration of Fe^{3+} in the UHP Ca-ferrite polymorph stable in the deep upper mantle, to help to produce the low-fO_2 conditions in the Transition Zone. Massive chromite preserves a higher Fe^{3+} content during ascent because no significant amount of a reducing agent (e.g. Fe^0) is available. In nodular chromite, there is more interstitial silicate, in which Fe^{3+} can accept electrons to produce Fe^{2+}, resulting in a higher Fe^{2+} content in the chromite [6].

Os model ages suggest that after *ca* 100 Ma in the Transition Zone, material from the buoyant, depleted slab appears to have been transported to shallow depths and incorporated into the lithosphere. Geodynamic modelling suggests the ascent from >440 km was rapid (*ca* 6–8 Ma), likely driven by rollback of the Indian plate slab. This process may occur in other collision zones; if so, mantle samples from the Transition Zone may be widespread.

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03DPD-02. TRANSITION-ZONE METAMORPHISM IN "Ophiolitic" CHROMITITES: INSIGHTS INTO COLLISION-ZONE DYNAMICS

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Diamonds have been reported from Tibetan "ophiolites" for ≥30 years, but widely dismissed as contaminants. However, the diamonds have now been found *in-situ* in both the chromitites and the peridotites of "ophiolites" along the Yarlung-Zangbo suture (Tibet) and the Polar Urals. These massifs are dominated by depleted spinel harzburgite; some yield whole-rock Re–Os T_{RD} ages back to 3.4 Ga, suggesting that they represent ancient SCLM.

LA-ICPMS analyses of the diamonds show LREE-enriched trace-element patterns parallel to those of kimberlitic fibrous diamonds; the "ophiolitic" diamonds thus have a geochemical signature indicating they are natural. However, they also show negative anomalies in Sr, Sm, Eu, and Yb; very low Fe; high Ta; inclusions of $Ni_{70}Mn_{20}Co_5$ alloy. They are part of an assemblage of alloys, native metals, carbides and silicides, defining fO_2 down to IW = –8. Exsolution of coesite, diopside and enstatite from chromite implies P = 15–18 GPa at Transition Zone (TZ) temperatures [4]. The highly reduced assemblage appears to reflect interaction of the chromitites with low-fO_2 fluids in the TZ.

The trace-element signatures of the chromites are identical to those of typical ophiolitic chromitites, and imply primary crystallisation at shallow depths. *In-situ* analyses of PGE sulfides give T_{RD} = 290–630 Ma, peaking at 325 Ma. Euhedral zircons separated from the chromitites give U–Pb ages of 376 ± 7 Ma, and εHf = 9.7 $\pm$ 4.6 (T_{DM} *ca* 2 Ga), suggesting some crustal component. However, T_{RD} model ages of Os–Ir nuggets in the chromitites are much younger: 234 ± 3 Ma. We interpret the sulfide + zircon ages as dating the shallow formation of the chromitites, while the Os–Ir model ages may record the timing of reduction and recrystallisation in the TZ following deep subduction, related to early events in the paleo-Tethys. Dynamic modelling suggests that the rise of the peridotites from the TZ to the crust during the early Cenozoic/Late Cretaceous was rapid (*ca* 6 Ma), and probably was driven by the rollback of the Indian slab after it had stalled in the TZ.

One striking observation is the *absence* of eclogites or similar UHP crustal rocks along the 3000 km of the Yarlung-Zangbo suture. If these peridotite massifs represent oceanic mantle, or ancient SCLM that became seafloor, their deep subduction was driven at least partly by the negative buoyancy of an eclogitic crust. If that detached from the slab in the TZ, it would sink deeper into the mantle, while the buoyant harzburgites would try to rise. These super-reducing ultra-high pressure (SuR-UHP) massifs carry unique information on global geodynamic processes including the tectonics of collision zones, and the physical and chemical makeup of the Earth's Transition Zone.

03DPD-03. SUBDUCTION REFERTILISATION OF OROGENIC LITHOSPHERE DETECTED BY TRACE ELEMENTS IN OLIVINE

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Mantle lithosphere is newly formed during accretionary orogens in which the closure of small ocean basins leads to the amalgamation of small crustal blocks into new continents. This process has been widespread throughout Earth history, but may have been prominent during the late Archean (3200–2500 Ma) when a large proportion of the current continental crust and lithosphere was formed, but high mountain ranges formed by continental collision were probably rare.

The Mediterranean region is a modern example of this process, where mantle lithosphere is newly created and composed of intimately mixed strongly depleted peridotite and crustal material from the forearc region. Potassium-rich volcanic rocks emplaced more than 30 Ma after the formation of this lithosphere tap the new lithosphere, carrying evidence for the presence of extremely depleted peridotite in their sources, but also for mica-bearing pyroxenites formed by reaction between subducted continental sediments and peridotite [1].

Olivines crystallised from the magmas and as megacrysts within the enriched mantle have elevated concentrations of Li and Zn that correlate positively with $^{87}Sr/^{86}Sr$ of the rocks, indicating the involvement of continental crust-derived sediments in the source region during melting. High Ni is characteristic of olivine derived from olivine-free source rocks, but does not distinguish between several possible origins of these rocks. Lithium is a distinctive element for identifying continental crustal recycling: Li concentrations in olivines from Mediterranean lamproites range from 10–45 ppm, in contrast to <1 to 5 ppm characteristics for basalts and mantle rocks. Furthermore, xenocrysts in the Mediterranean rocks also show elevated Li contents (up to 15 ppm), demonstrating that this is a source feature. Coupled increases in Li and Zn at low Ti concentrations appear characteristic for source regions in which recycled continental crust plays a role. This “orogenic” crustal component was first recognised from its very radiogenic $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{204}Pb$ and unradiogenic $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$. Correlation of high Li with further elements such as Zn, Na, Ti and Ca will help to identify minerals in the source assemblages, such as phlogopite, spinel, garnet, amphiboles and carbonates, and thus the source of the olivine-free assemblages [2]. The Mediterranean xenocrysts affected by continental crust at source cover a similar range in lithium contents to pyroxenites found within orogenic peridotites. Whole-rock Li concentrations show similar ranges for oceanic and continental clastic sediments, whereby the highest Li known for sediments is for Mediterranean flysch.

If much of the continental crust is formed by accretionary orogens of this type, then extensive tracts of the continental lithosphere may contain recycled crustal material. A high proportion of subducted sediment is probably not completely returned to the convecting mantle, but becomes stored within the subcontinental lithosphere, explaining the rarity of geochemical traces of recycled continental crust in the convecting mantle on the geochemical signatures of ocean island basalts.

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03DPD-04. SULFUR DIOXIDE DEGASSING DURING ARCHEAN KOMATIITE VOLCANISM

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Komatiites are ancient submarine lavas that erupted over 2.5 billion years ago. These hot and highly turbulent flows entrained discrete sulfide liquids that concentrated nickel, copper and the platinum group elements locally to economic proportions. Our multiple sulfur isotope measurements on sulfides from komatiites and local volcanogenic and sedimentary country rocks indicate that sulfur degassing during komatiite volcanism may have played a key role in the mineralising process. Data from variably mineralised komatiite units in the north Eastern Goldfields, Western Australia, indicate pervasive (>90%) sulfur loss from sulfide-saturated komatiite lavas, dominantly in the form of SO_2 gas. In addition to economic mineralisation, this komatiite ‘redox filter’, whereby reduced sulfur in the sulfide liquid was exchanged for oxidised sulfur in the fugitive gas, had the potential to influence the geochemical evolution of the atmosphere and ocean on Archean Earth.

In this presentation, we will lay out the ‘redox filter’ mechanism in detail, demonstrate its multiple S isotope consequences, and compare these predictions to the observed dataset. In addition, we will explore how this process, when scaled to global proportions, may be responsible for the ‘bloom’ in mass-independent fractionation of sulfur isotopes that is observed in the sedimentary record at *ca* 2.7 Ga.

COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIUM

03CPOA – COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIA

03CPOA-01. DO OROGENIC PROCESSES DIFFER FROM WEST TO EAST? A COMPARATIVE ANALYSIS OF CIRCUM-PACIFIC OROGENS

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Local variables strongly influence what happens at any moment in time in an orogenic belt, but the regional stress field must also play a role. An orogen must respond to changes in the regional stress field, and some responses amplify (as opposed to resist) the onset of instability, e.g., a period of compressive orogeny can result in thrusting of slices of back-arc lithosphere over adjacent terranes. Thrusting may continue until new subduction zones initiate, and the newly subducting slabs themselves begin to roll back. Depending on relative rates, the orogenic system overlying the retreating slab may find itself once again extending, thus terminating the compressional epoch. Another example might be found in the evolution of a subduction system in which slab transforms have developed. A small change in the orientation of the regional stress field can place slab transforms under compression, with thrusting continuing until new subduction zones initiate. These new subduction segments themselves may begin to roll back, terminating the compressional epoch. Such switches in tectonic mode allow ready explanation for several common manifestations of the orogenic process, for example the emplacement and then stranding of ultramafic sheets, or the tectonometamorphic stratigraphy commonplace in all a major orogenic belts.

The question then arises as to why switches in tectonic mode seem to be synchronised on a planetary scale, here shown to include events in the Circum-Pacific orogens. If emerging evidence for synchronicity is accepted (and there are still many aspects to be disputed) how do we explain self-organisation of what appears to be criticality in the behaviour in the global assemblage of tectonic plates? Inherently longer time-scale processes in the underlying asthenosphere do not have the capability to explain instabilities that synchronise on time intervals less than one million years. To answer this question we must address the nature of the feedback loops between local, regional and planet-scale tectonic processes in the lithosphere. Two laws of planetary mechanics then become evident. The first law recognises that the regional stress field must vary in consequence of any changes that are taking place in the planetary assemblage of lithospheric plates, and since torque balance must be maintained at all times, globally synchronised changes must occur when mechanical resistance is increased anywhere in the plate tectonic system, e.g., as the result of accretion of oceanic plateaux or continental fragments. The second law is derivative from the first and might be stated in an almost Gaia-type formalism, asserting that everything (in the planetary tectonic system) depends on everything else. However the Gaia hypothesis is biased in that a self-regulating, complex system is considered only in that it may contribute to maintaining the conditions for life on the planet. In contrast, global changes that accompany tectonic mode switches can drive planet-scale catastrophe, including biological mass extinction. Feed-back loops in a complex system are not of necessity self correcting, and change (including change that is gradual and continual) can lead inexorably to collapse of one pattern of organisation, and the instalment or recreation of another.

03CPOA-02. NEOPROTEROZOIC GLOBAL GEODYNAMIC REARRANGEMENT RECORDED BY HF ISOTOPES IN ZIRCON: BIRTH OF THE CIRCUM-PACIFIC AND DAWN OF THE PHANEROZOIC

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It has become apparent that the Earth can be divided into two convective mantle supercells in the Phanerozoic, but it is not clear when or why they began. The boundary of the supercells is marked by the position of the circum-Pacific subduction system, which is a semi-hemispheric belt that separates an exclusively oceanic cell from the other which contains continental blocks. Within the continental cell, the Alpine-Himalayan orogenic system is a 10,000 km-long suture zone where continental fragments of Gondwana to the south are transported northward and trapped against the growing Eurasian continent to the north. The evolution of each system exhibits distinctive εHf arrays based on contributions from increasing magmatic arc proportions of juvenile mantle (circum-Pacific) or a repeated mixture of mantle and evolved crust (as with Wilson cycles). The identification of these two εHf signals has been applied to Neoproterozoic orogenic systems on a global scale in an effort to understand geodynamic conditions leading to the formation of Gondwana.

Compilation of a worldwide εHf database was conducted on Neoproterozoic orogenic belts located in peri-Gondwanan terranes around West Gondwana, including Avalonia-Cadomia and the Arabian Nubian Shield. Neoproterozoic belts also exist within the Tarim, North and South China cratons and, around northern Baltica (Timanide and Arctida) and Siberia (Baikalides). The classic “Pan African” belts were also included. Neoproterozoic orogens were categorised as part of either internal or external systems based on their εHf signature and palaeogeographical location.

The database depicts a global change in εHf signal at 600-550 Ma. Prior to this, throughout the Mesoproterozoic and early Neoproterozoic, most εHf arrays reflect a crustal reworking trend of decreasing εHf with time. However, for each major geological entity, εHf arrays contract to more juvenile compositions between 600-550 Ma.

The global change toward juvenile compositions in the Late Neoproterozoic mimics the trend observed by the circum-Pacific system (in Japan, New Zealand, Australia, Antarctica and South America). It implies that normal subduction of ocean-under-continent became a global phenomenon at this stage, rather than collisional orogenic processes. We interpret this global change to reflect establishment of a circum-Pacific-type subduction system around the newly-formed supercontinent of Gondwana. The change coincided with termination of the Pan-African orogens as Gondwana amalgamated, eliminating the slab pull effect on plate motion as slab breakoff occurred beneath the supercontinent. However, convective mantle downwelling continued as the slabs sank progressively deeper into the deep mantle. It appears that once the fundamental driver of Gondwanan amalgamation was finally lost as all fragments collided, a new global arrangement of subduction systems was required to maintain conservation of momentum in the mantle supercell beneath. Thus began the Pangean supercontinental cycle as the circum-Pacific subduction system initiated, heralding the dawn of the Phanerozoic.

03CPOB – COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIA

03CPOB-01. ZEALANDIA'S 0.5 GA SUBDUCTION HISTORY

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Whether as part of Pangea and Gondwana or as a separate continent, Zealandia has always occupied a position between eastern Australia and the oceanic plates of the paleo-Pacific Ocean. As such the onland and offshore New Zealand geological record directly informs on the migration and changing nature of one of the Earth's continent–ocean boundaries (COBs) over a 500 million year time span.

Inferring the subduction polarity, accretionary style and overall geometry of the Cambrian to Devonian COB is highly speculative due to the small strike length and width of preserved terranes and plutons. The Carboniferous to early Permian COB in New Zealand appears to have been passive. A late Permian accretionary episode arguably involved Dun Mountain Ophiolite and Brook Street magmatic arc and there is clear evidence for a Late Triassic magmatic arc in the Median Batholith. However no accretionary wedges of demonstrable Permian or Triassic deformational age are preserved. From the Middle Jurassic to Early Cretaceous, the SE Gondwana COB was a major accretionary margin and represents a major continental growth increment. Magmatic arc, forearc basin, and accretionary wedge components are all well preserved as Darran and Separation Point Suite plutons, Murihiku Terrane and Torlesse Terrane–Haast Schist respectively.

Subduction ceased off South Zealandia at about 100 Ma, probably with the collision of the Hikurangi Plateau Large Igneous Province (LIP). Some time between 100 and 45 Ma, subduction re-initiated off North Zealandia and was accompanied by at least 1000 km of slab rollback and backarc basin formation. The timing and cause of subduction re-inititation and its polarity are controversial – but ultimately resolvable. Offshore data show that Pacific slab rollback was at its most rapid in the late Oligocene and early Miocene (25–18 Ma), was static from 17–6 Ma and has only commenced again since 5 Ma.

The present day festoon of SW Pacific arcs and remnant arcs is 'pinned' at its south end by the Hikurangi LIP and at its north end by the Ontong Java LIP. It provides a modern analogue for the lateral termination of orogenic belts.

03CPOB-02. PRE-CRETACEOUS BASEMENT OF CHATHAM ISLAND: STRATIGRAPHY, DEFORMATION, METAMORPHISM, AGE AND CRUSTAL HERITAGE

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Basement of Chatham Island, 800 km from Christchurch, occurs in a complexly folded 4750 km-thick section, partly resembling NZ Torlesse strata, interpreted as submarine fans in the Pacific Gondwana margin. Unique coastal exposures represent <0.2% of the area of the Chatham Rise segment of the Zealandia continent.

Major rock types: CAQS Medium/coarse-grained quartz–albite–phengite schist with clasts of plagioclase and blue quartz to 1 cm diameter, lacking clastic micas and carbonaceous matter like greywackes. Graded bedding, and composition suggest dacitic pyroclastic material redeposited in deep marine environment. **GAS** Green argillaceous schist like CAQS with more phengite. **BAS** Black argillaceous schist. Fine-grained quartz–albite–phengite–chlorite schist with carbonaceous matter and pyrite cubes, likely reduced marine black shale. **GW** Greywacke/greywacke schist, graded-bedded with abundant quartz, rock fragments, clastic mica and metamorphic source evidence, like Torlesse, East Otago. **Minor rock types: GS** Greenschist, 1–5 m-thick beds of albite–quartz–phengite–chlorite–epidote–pumpellyite–sphene schist, interpreted as water-laid basaltic tuff. **MC** Metamorphosed chert, rare 0.2–1 m beds, some with trace spessartine. Pumpellyite–actinolite facies gabbro xenoliths in Cretaceous volcanic breccia, could be older basement from below.

Stratigraphy (base-to-top): Teraki Formation 2000 m, interbedded 30% CAQS, 35% GAS and 35% BAS with 14 distinctive GS beds. CAQS dominates lowest 500 m in SW coast cliffs. Base not exposed. **Kaingaroa Volcanics** 2000 m, interbedded 70% CAQS, 20% GAS, 10% BAS with interbedded MC in lowest 500 m. Base is at first greenschist of Teraki. **Matarakau Greywacke** 750 m, dominant GW and BAS with minor GS, MC, GAS, CAQS. Base gradational with Kaingaroa; top unexposed.

Three structural phases occur in complete western section. I: Obscure NW-trending minor folds/lineation, metamorphic foliation. II: Main phase AP foliation dips N at low angle to bedding; gentle E–W minor folds/lineation. Fold asymmetry suggests upper limb of major N-directed recumbent fold; movement line 310, 25. On SW coast, II is strongly overprinted by III crenulations/slip-cleavage dipping 45–55°S, synchronous with broad warping of II foliation. In the east, II lineation and foliation is offset/rotated along the Titore Fault with early extension, late thrusting. Matarakau on south has SW-dipping foliation; lineation plunging 20–45°SW/W. Kaingaroa on north has steep N-dipping foliation; lineation plunging 30–50°E.

Metamorphism at pumpellyite–actinolite facies, consistent with T 270–340^{o}C, P 0.48–0.7 GPa, occurred at 198–180 Ma (Early Jurassic) from 6 Rb–Sr whole-rock ages, 193–155 Ma (mainly Late Jurassic 162–157 Ma) from 21 rock/mica K–Ar ages. Greywackes show textural grades I-IIB, consistent with Otago pumpellyite stability.

Zircons (58) from a Kaingaroa Volcanic CAQS sample, were analysed for U, Th, Pb, and Hf isotopes by laser ICPMS; major/trace elements by EMP, and compared to 51 earlier age results from Matarakau Greywacke. Youngest probability density peaks at 244, 256 *vs* 232, 237 Ma suggest maximum Middle and Late Triassic ages, respectively, with abundant Early Triassic–Permian and significant older grains in Silurian (Kaingaroa), Ordovician, Neoproterozoic, Mesoproterozoic. Trace elements from Kaingaroa suggest protoliths from granite to gabbro. Dominant Permo-Triassic zircons, with felsic trace elements, could be consistent with Middle Triassic turbidites shed from an eroding felsic arc on the Gondwana margin with limited other sources before Matarakau time.

03CPOB-03. AUSTRALIAN CRUST IN A PACIFIC ISLAND ARC

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A substantial proportion of zircon grains separated from igneous rocks of the Western Belt in the Vanuatu intra-oceanic arc reveal age populations at *ca* 330–220 Ma, 530–430 Ma, 850–700 Ma, 1.75–1.5 Ga, 2.0–1.8 Ga and 2.8–2.5 Ga. This inheritance signature is unlike anything formerly identified from the oceanic realm of the southwest Pacific. U–Pb ages generally match the major crustal blocks of the Australian continent, with the exception of a significant portion (~20%) of zircon grains corresponding with the Rodinia breakup age (*ca* 800 Ma), which previously has not been found in eastern Australia or the southwest Pacific. New Ar–Ar dating of hornblende from several andesites and U–Pb dating of magmatic zircon from a tonalite demonstrate that exposed igneous rocks of the Western Belt formed between 35 and 16 Ma. These ages conform with previous interpreted ages of early arc growth in Vanuatu. Geochemical information from the same rocks shows that they are typical arc igneous rocks, which exhibit trace element patterns and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic compositions that are similar to adjacent islands formed during present-day magmatic activity [1]. These results highlight the complexity of the convergent boundary between the Australian and Pacific plates in the southwest Pacific and may place the distinguishing geochemical characteristics of other intra-oceanic arcs under scrutiny.

As the name implies, intra-oceanic arcs are considered to be far removed from large continental masses, so the contribution from continental derived material to the geochemical signature of these rocks is often assumed to be negligible. Crustal additions to arc magmas are often inferred to be associated with the subducting slab and processes occurring within the underlying mantle, rather than from any pre-existing crust or crustal basement. In contrast with the entirely intra-oceanic origin proposed for the Vanuatu arc, we suggest that the Vanuatu arc basement comprises Australian continental material transported from northern parts of Australia prior to the late Eocene. Inherited U–Pb ages matching Australian continental ages in zircon-undersaturated oceanic arc rocks implicitly shows that continental material is influencing the geochemical characteristics of at least some of the Vanuatu arc magmas. Furthermore, these results advance our understanding of circum-Pacific tectonics and arc evolution, as we suggest that the Vanuatu arc was in part built upon a fragment of Australian continental crust that was displaced during the retreat of the southwestern Pacific subduction margin. These results also have significant implications for the evolution of other parts of the western Pacific, including Tonga, Fiji and the Solomon Islands.

Reference

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03CPOB-04. OROGENS OF SOUTHEAST ASIA AND THEIR LINK TO TETHYAN AND (PROTO-) PACIFIC TECTONIC EVOLUTION

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Southeast Asia has been shaped by long-term convergence between the Eurasian continent, Tethyan terranes and the (proto-) Pacific plates and island arcs. Each accretionary event has been recorded in regional unconformities, basin inversions and ophiolite obduction on Sundaland. However, the timing and geodynamic driving mechanisms for these major events have a wide range of interpretations. We address and reconcile these ambiguities by creating a new generation of plate reconstructions for the region that moves beyond classical “continental drift” schematics, and instead present a plate motion model with dynamically closing plate boundaries that are informed by surface geology and constraints from the deep Earth using numerical mantle convection simulations. We restore ancient and now-subducted ocean basins and account for sutures and orogenies that link the Tethyan, Eurasian and Pacific realms related to the collision of Gondwana and east-Asian continental fragments to Sundaland since the Jurassic.

Firstly, we model the latest Jurassic rifting and seafloor spreading along northern Gondwana that transferred eastern Borneo, East Java and West Sulawesi continental blocks northward to collide with Sundaland in the Late Cretaceous. Secondly, we account for the change from Andean-style subduction on the east Asian margin in the Late Cretaceous by presenting a model of back-arc opening of the Proto South China Sea, which is recorded in the tectonic subsidence curves of east Asian basins and the supra-subduction zone ophiolites emplaced on Mindoro. The back-arc opening detaches the Semitau (Luconia) and South Palawan continental fragments, and transfers them onto northern Borneo by the mid Eocene, analogous to the opening of the Tyrrhenian back-arc system in the Mediterranean. Lastly, following the accretion events on Borneo, the Sundaland continental promontory undergoes significant oroclinal bending, evident in the large counter-clockwise rotation of Borneo from robust regional paleomagnetic studies and curved lineaments on Sumatra, the Java Sea and southern Borneo. We present the first oroclinal bending model for Sundaland, and we use paleomagnetic data, potential field constraints and basin evolution histories to account for ~80° counter-clockwise rotation of Borneo since 50 Ma.

The resulting global plate motion model, with evolving plate boundaries and seafloor age distributions, is then linked to mantle flow simulations to track the evolution of regional subduction zones and the fate of subducted slabs in the mantle. Orogenic events resulting from terrane collisions and suturing typically terminate subduction and induce slab break-off events, which is a major variable controlling the depth of slab material observed at present-day. We compare the predictions of our mantle flow simulations with anomalously fast seismic velocity anomalies imaged by mantle tomography to test our plate motion model and help refine subduction and suturing events in the region, and compare the styles of convergence to both the circum-Pacific and the Mediterranean and Tethyan convergent margins.

03CPOC – COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIA

03CPOC-01. CONTROL OF SUBDUCTION ZONE SIZE ON SLAB ROLLBACK, STYLE OF MANTLE FLOW AND OVERRIDING PLATE DEFORMATION

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Subduction zones provide a major control on plate motion and mantle flow. They can cause devastating earthquakes (e.g. Japan 2011), and they are linked to massive mountains (e.g. Andes) and ocean basins (e.g. North Fiji Basin).

Previous work has shown that the size (width, i.e. trench-parallel extent) of subduction zones and the presence of slab edges provide a major control on plate velocities, plate boundary velocities, the slab geometry, and the style of mantle flow. In this contribution I will present results from dynamic subduction models that demonstrate how the size of subduction zones controls the style of overriding plate deformation, and outline the mechanism responsible for such deformation. In the central part of wide subduction zones, subduction is dominated by poloidal and is accommodated mostly by subducting plate motion, while the subduction zone hinge is relatively immobile. The poloidal mantle tractions at the base of the overriding plate cause the overriding plate to move trenchward at a rate that is faster than the rate of trench retreat, causing shortening and mountain building at the leading edge of the overriding plate as it collides with the subduction zone hinge. At narrow subduction zones and near subduction zone edges, subduction is accompanied by mantle flow that has a large toroidal component with return flow around the lateral slab edges, and subduction is accommodated significantly by trench retreat and slab rollback. The toroidal mantle flow induces shear stresses at the base of the overriding plate that increase trenchward and cause trenchward overriding plate motion at a velocity whose spatial average is below the trench retreat velocity. This combination causes trench-normal deviatoric tension and backarc extension in the overriding plate. Ultimately, the geodynamic models demonstrate that backarc extension is favoured for narrow slabs and near lateral slab edges, and is driven by rollback induced toroidal mantle flow, while backarc shortening is favoured for the centre of wide slabs, and is driven by poloidal mantle flow resulting from downdip slab motion.

These geodynamic models of overriding plate deformation provide an explanation for the large-scale trench-normal deformation observed at many subduction zones. For example, the Andes mountains can be explained by their tectonic setting bordering one of the largest subduction zones on Earth, the South American subduction zone. Maximum shortening occurs in the centre of the subduction zone where the leading edge of the overriding plate collides with the relatively immobile subduction zone hinge, as the overriding plate is forced to move westward by subduction-induced basal tractions. In contrast, at subduction zone segments including Tonga, New Hebrides and Hellenic, or narrow subduction zones such as Scotia, slab rollback and toroidal mantle return flow are facilitated by the presence of lateral slab edges, and the toroidal basal tractions drive overriding plate extension and backarc basin formation, such as the Lau, North Fiji, Aegean and Scotia backarc basins.

03CPOC-02. EVOLUTION OF THE LONG-WAVELENGTH TOPOGRAPHY OF SOUTH AMERICA SINCE 150 MA IN RESPONSE TO EASTERN PACIFIC SUBDUCTION

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The subduction zone west of South America spans 6000 km along strike and has been active for over 250 Myr. The influence of this subduction on the evolution of South America has been profound, underlying mountain building and arc volcanism in the Andean Cordillera. Here, we investigate the long-wavelength changes in the topography of South America associated with this subduction and its interplay with the lithospheric deformation associated with the opening of the South Atlantic. We pay particular attention to the topographic expression of flat-lying subduction zones.

We developed time-dependent geodynamic models of mantle flow and lithosphere deformation to investigate the evolution of South American dynamic and isostatic topography since the late Jurassic (150 Ma). In our workflow, we impose the kinematics of global plate reconstructions accounting for continental deformation in forward global mantle convection models with compositionally distinct crust and continental lithosphere embedded within the thermal lithosphere. The shallow thermal structure of subducting slabs is assimilated, allowing us to investigate the evolution of dynamic topography around flat slab segments. The predicted temperature field is compared to mantle tomography since the initial and boundary conditions are based on independent plate reconstructions.

Multiple cases are used to investigate how the evolution of South American dynamic topography is influenced by mantle rheology, the kinematics of the opening of the South Atlantic and alternative scenarios for recent and past flat-slab subduction. We predict that the migration of South America over sinking oceanic lithosphere resulted in a tilt of the continent to the west until *ca* 45 Ma, which then inverted in a tilt to the east. This first-order result is consistent with the reversal of the drainage of the Amazon River. We investigate which scenarios of flat-slab subduction since the Eocene are compatible with geological constraints on the evolution of the Solimoes Basin, the Chaco Basin, the Sierras Pampeanas and the Central Patagonian Basin. We compare our modelling results to mantle tomography and to the total subsidence inferred from well data offshore Argentina and Brazil to broadly constraining the viscosity structure of the mantle.

03CPOC-03. TECTONIC EVOLUTION OF THE NORTH AMERICAN CORDILLERA: A WESTERN PACIFIC PERSPECTIVE

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The North American Cordillera records a history of accretionary orogenesis extending from the Neoproterozoic to present. It consists of an inboard domain of Cambrian to Triassic backarc basins, which provide a sensitive record of Cordilleran extension and contraction, and an outboard domain of stretched continental ribbons, arc–backarc assemblages of oceanic and continental affinities, and accretionary prisms. Although the Paleozoic–early Mesozoic history has similarities to western Pacific tectonics, the late Mesozoic and Cenozoic history appears to have involved large-scale strike-slip motion, involving migration of far-travelled terranes back-and-forth along the Cordilleran margin. These major translational features spawned the suspect terrane hypothesis, which dominated global tectonics for at least a quarter-century after 1980.

Following Neoproterozoic rifting during Rodinia breakup, subduction began on the western Laurentian margin, possibly as early as the Cambrian. Throughout the early Paleozoic, sporadic oceanic arc and backarc assemblages reflect outboard arc migration during a major retreat phase associated with E-dipping subduction. However, it was not until the Devonian that widespread continental arc magmatism is evident, followed by a retreat phase that produced continental ribbons and backarc basins along the entire margin. Thus, in the Canadian cordillera, Yukon-Tanana (Y-T) and Kootenay continental ribbons developed outboard of the Cache Creek and Slide Mountain oceanic backarc basins, respectively. Both ocean basins can be traced southward from Alaska, at least to the Sierra Nevadas in California. During this extensional stage, arc assemblages re-established on the outboard fringe of the stretched Y-T ribbon (Alexander to the north and Stikinia to the south). Outermost terrane, Wrangrellia, probably initiated farther north than the Y-T ribbon.

Protracted closure of the ocean basins occurred between the late Permian and Middle Triassic. The Slide Mt backarc basin closed first, between *ca* 280–240 Ma, during W-dipping subduction, which generated the Quesnellia arc system. During final Slide Mt closure, the Cache Creek backarc began to subduct eastward beneath Quesnellia. Closure of Cache Creek occurred between the Early Triassic and Middle Jurassic (*ca* 160 Ma). In the US Cordillera, this event was recorded as craton-verging, Luning-Fencemaker fold and thrust belt, part of the Late Jurassic (150–140 Ma) Nevadan Orogeny.

Closure of the late Paleozoic Cordilleran oceans was caused by the Y-T ribbon moving southward after being transferred onto the subducting ocean plate. This induced sinistral transpression along the Canadian Cordillera. NE-trending folds and thrusts in the LFFB indicate the bulk shortening direction was NW–SE at this stage, consistent with sinistral transpression and southward migration of outboard terranes.

Short-lived extension–contraction accretionary events occurred in the Early Cretaceous, before the major mid-Cretaceous magmatic flareup along the Cordillera. This was associated with significant crustal thickening during the Sevier Orogeny, which just pre-dated the Laramide orogeny in the US. Subsequent Eocene extension produced the classic Cordilleran core complexes, extending from Arizona to Alaska, associated with re-establishment of an outboard arc system. Thereafter, the outboard terranes began migrating northward as part of an orogen-scale dextral transpression event, culminating with translation of Yakutat terranes from the USA to Alaska. These apparent major terrane translation processes, coined the Baja British Columbia hypothesis, contrasts with the tectonic evolution of the Tasmanides, and may be associated with ridge–trench interaction, as presently seen with opening of the Gulf of California.

03CPOD – COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIA

03CPOD-01. THE TASMANIDE BENAMBRAN LINE: A REFERENCE FOR HISTORICAL INTERPRETATION OF OROGENIC ZONE DEVELOPMENT IN EASTERN AUSTRALIA

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The Benambran line, marking the eastern limit of crustal addition to the Tasmanides in a widespread early Silurian episode of orogenesis, provides a useful reference in charting the history of the Tasmanides as a whole. For the northern Tasmanides the line is positioned within the inboard margin of the Mossman Orogen. For the southern Tasmanides, it lies east of the exposed Lachlan Orogen and beneath the overprinting inboard part of the New England Orogen. For the central Tasmanides the line is less well constrained but it lies east of the Anakie Inlier and east of the continuation of the early Paleozoic magmatic arc into southern Queensland. It most likely is also positioned beneath the overprinting inboard part of the New England Orogen.

Thus the Benambran line imposed in the early Silurian can be followed continuously, with only minor changes in orientation, along the full length of the Tasmanides. Crust to the east of the line consists of active margin assemblages (largely outboard subduction complex rocks) within the Mossman and New England orogens developed at the east Gondwana fringe in mid to late Paleozoic time with shortening structure imposed in the Tabberabberan and Hunter-Bowen orogenies. In contrast, crust to the west of the Benambran line is remarkably diverse. In the northern Tasmanides the line is little separated from a buttress of Mesoproterozoic craton to the west. Rocks in the narrow strip of lower Paleozoic rocks tectonised in the Benambran episode were exhumed from a variety of crustal levels attesting to a complex pre-Benambran crustal history involving extension, which has left a pervasive structural signature in several metamorphic complexes. Lower Paleozoic rocks now preserved largely represent only the inboard part of an active margin assemblage and its outboard part, if it has escaped subduction erosion, is now beneath the Mossman Orogen that occupies the upper crust to the east. For the central Tasmanides, Paleozoic crust to the west of the line is expansively developed as the Thomson Orogen. This system is thought to consist of inboard active margin sedimentary and igneous rocks of late Cambrian–Ordovician age affected by Benambran overprint, overlying Neoproterozoic–lower Cambrian passive margin rocks tectonised in the late Cambrian Delamerian Orogeny. For the southern Tasmanides, Proterozoic craton lies far to the west of the Benambran line. The full crustal section of the Lachlan Orogen was in late Sulurian time comprised of lower Paleozoic sedimentary rocks and oceanic island arc added to East Gondwana in Benambran crustal shortening. An active margin association is indicated and detrital mineral age signatures of both assemblages indicate they formed proximal to Gondwana but the details of plate geometry involved in their formation remain contentious.

This along-strike diversity of lower Paleozoic crust west of the Benambran line attests to very different pre-Benambran histories of extension. How these regimes were partitioned remains unresolved. The Clarke River–Diamantina Fault Zone likely represents a first-order translational structure within the early Paleozoic extensional geometry of the Tasmanides.

03CPOD-02. MID PERMIAN–MID TRIASSIC FLAT SUBDUCTION IN THE SOUTHERN NEW ENGLAND OROGEN

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Despite a conducive geological environment (Pacific-type margin, widespread calc-alkaline magmatism, specific arc indicators) and research spanning four decades, debate still surrounds the role of subduction in the Permian–Triassic development of the southern New England Orogen (sNEO) and its contemporary fringing basins. Contentious issues include: (a) correlating the orogen and adjacent basins; (b) inferring recurrence from basinal stratigraphic records; (c) focus on granitoids rather than preceding volcanism; (d) assuming classic (free) rather than flat subduction; (e) any evidence of rollback; and (f) likely slab overlap.

Volcanism is considered the key to recognising geological recurrence and to differentiating subduction episodes and modes. Mid-Permian–mid Triassic volcanism and associated activity in the sNEO differ from the continuum of weak to strong extensional activity expected from free subduction, viz:

- Volcanism is distinctly episodic (continuum expected) with discrete episodes in the late lower Permian ("Owl Gully arc"), middle Permian (Drake Volcanics), middle–upper Permian (Wandsworth Volcanic Group), Middle Triassic (Nymboida Coal Measures), and the early Upper Triassic (Chillingham Volcanics);
- The Wandsworth Volcanic Group (VG) occurs anomalously inboard (outboard progression expected);
- The Wandsworth VG exhibits an anomalously NNE trend oblique to the other four trends (similar or gradually changing trends expected);

- In *all* five cases, volcanism follows compressive deformation (compressive deformation unexplained), commonly with significant delays;
- Volcanism commonly overlaps or is followed by outboard granitoids, then by later inboard Sn–F bearing leucogranitoids (outboard younging expected); and,
- The overall tempo of activity is anomalously fast.

In contrast, flat subduction seems better able to accommodate these anomalies as well as overlapping slab influences (by slab stacking). The most convincing candidate for flat subduction control is the Wandsworth VG and associated activity due to: (a) the very wide zone of activity; (b) the inboard distance from any subduction zone; (c) the anomalous NNE trend of the Wandsworth VG; (d) the duration of preceding (intermittent) deformation and the delay from its onset till the onset of volcanism; (e) the duration of associated activity (extending to the early Middle Triassic) compared to other regimes; (f) its overlap in time and space of the preceding Drake and ensuing Nymboida regimes; and (g) the economy of a single protracted regime compared to the complexity of alternative interpretations. The link between flat subduction and magmatism is speculative, but may have involved: (a) fluid transfer to the upper plate in preparation for later calc-alkalic magmatism; (b) asthenosphere access due to loss of slab buoyancy (± upper slab delamination) to generate widespread calc-alkalic volcanism; (c) slab breakoff generating outboard, latest Permian granitoids; and (d) later (Middle Triassic), inboard magmatism to initiate leucogranitoids with Sn–F mineralisation, plausibly due to descent of the detached slab inducing localised, inboard asthenospheric upwelling and Laki-style F-fractionation beneath thick(?) crust.

The two subsequent regimes are also likely candidates for flat subduction control due to factors such as the width of the active zone, inboard distance, deformation before volcanism, and late, inboard leucogranitoids with Sn–F mineralisation. Evidence relating to the two earlier regimes is less compelling.

03CPOD-03. GEOCHEMISTRY AND GEOCHRONOLOGY OF THE IGNEOUS ROCKS WITHIN THE LORNE BASIN, SOUTHERN NEW ENGLAND OROGEN, NSW, AUSTRALIA

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The circular Lorne Basin, located in the southern New England Orogen (NEO), contains plutonic and volcanic rocks linked to the basin's evolution. These are the youngest igneous rocks associated with the development of the NEO. SHRIMP U–Pb zircon geochronology was conducted on igneous rocks to constrain basin development. A volcanic clast from the Jolly Nose conglomerate in the lower part of the basin's stratigraphy indicates an eruption age of 217 ± 10 Ma indicating basin initiation in the late Triassic. Detrital zircons from the same horizon show derivation from mostly Carboniferous (*ca* 320 Ma) sources, with older Gondwanan-aged grains (latest Neoproterozoic and *ca* 1 Ga) also present. The Diamond Head rhyolite from higher in the basin's stratigraphy has a zircon age of 217 ± 10 Ma, indistinguishable from the age of the felsic volcanic clast in the Jolly Nose conglomerate. Plutonic rocks that cut the felsic volcanic units have yielded marginally younger ages. A quartz-diorite from the North Brother intrusion yields an age of 212 ± 4.4 Ma. A similar rock from the Middle Brother intrusion has been dated by Geoscience Australia at an indistinguishable age of 212 ± 4.4 Ma. These results indicate the rapid evolution of the Lorne Basin spanning less than 10 Ma during the late Triassic.

The plutonic rocks range from diorite to quartz-rich granitic composition. The majority of the igneous rocks are highly fractionated, with enrichment in SiO_2, Al_2O_3, Na_2O, K_2O, FeO*t*, Zr, Ba, Pb and Sr with low abundances of TiO_2, P_2O_5, MgO, Cr and Ni. Harker diagrams indicate linear trends for many elements, with hornblende and plagioclase crystallisation controlling composition. The 10 Ma timespan of emplacement and geochemical signatures including low Ni and Cr counter those expected in impact generated melts, ruling out the impact structure hypothesis. In discrimination plots, the Lorne Basin igneous rocks straddle the divide between I- and A-type rocks. Primitive mantle normalised trace element spectra ('spider diagrams') indicate enrichment of the light REE (La and Ce) compared with Y, being used as a proxy for the middle–heavy REE. They also show depletion of Nb and Ti, and enrichment of Pb. These traits are characteristic of magma compositions governed by fluid flux melting of a mantle wedge, above a subduction zone. There is some evidence of crustal assimilation, as shown by the overall evolved compositions and the presence of pre-Triassic xenocrystic cores in igneous zircon in the Lorne Basin rhyolites.

The late Triassic Coastal Suite of granites and volcanics post-date the Hunter-Bowen Orogeny (Permo-Triassic). The previous phase of granitic intrusions in the NEO are the Permo-Triassic Clarence River Suite some 20 Ma earlier. We suggest that collision of the island-arc Gympie terrane was responsible for the Hunter-Bowen Orogeny and that renewed continental margin subduction following a subduction flip may be responsible for the late Triassic Coastal Suite.

03CPOD-04. RAPID ADVANCE FROM HYDROUS TO BIOTITE-DEHYDRATION MELTING OF A METASEDIMENTARY SOURCE IN THE FORMATION OF THE JIUFENG PLUTON, SOUTHERN CHINA: A RESULT OF BASALTIC UNDERPLATING DURING SLAB FOUNDERING?

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Jurassic granitoids are widespread in southern China (with a total outcrop of 62 700 km^2), constituting one of the largest magmatic provinces in the world. Many petrological and geodynamic models have been proposed to account for material and heat sources for the formation of this province. It has become clear that granitoids were mainly derived from crustal melting and intruded in a continental rift environment. However, it remains enigmatic how the magmatism was corresponded to deep mantle processes. Field and geochronological studies of the Jiufeng pluton in southern China reveal a phase transition from *ca* 160 Ma muscovite granite, two-mica granite (phase I) and amphibole-bearing biotite granite to 157 Ma two-mica granite (phase II). All granites are felsic (SiO_2 >69 wt%) and enriched in K_2O. They also have evolved Sr–Nd–Hf isotope compositions (whole-rock I_{Sr} >0.712, εNd(t) = –12.6 to –9.5; zircon εHf(t) = –12.0 to –6.3) and high zircon $\delta^{18}O$ (6.6‰–9.4‰). The combined data suggest that the Jiufeng pluton were mainly derived from melting of a metasedimentary source at a depth of >20 km as recorded by high-TiO_2 (>0.4 wt%) muscovite. Locally distributed amphibole-bearing granite was derived from magma mixing/mingling, consistent with its variably higher εNd(t) and εHf(t) and lower zircon $\delta^{18}O$. We interpret the phase transition of the Jiufeng pluton primarily a result of rapid advance from ~650°C hydrous melting (for the genesis of *ca* 160 Ma muscovite granite) to >800°C biotite-dehydration melting (for the genesis of phase II 157 $\pm$ 1 Ma two-mica granite) and incremental assembly of magma batches at shallow depth. Rapid increase of melting temperature (>50°C/Ma) at mid-crustal levels was most likely a response to basaltic underplating resulted from a flat-slab foundering beneath the Mesozoic South China orogenic belt.

THURSDAY 10 JULY

PLENARY

PLEN4-01. DEVELOPING an UNDERSTANDING ABOUT AUSTRALIA'S PAST, PRESENT AND FUTURE FROM RESEARCH INTO THE WORLD HERITAGE FOSSIL DEPOSITS OF RIVERSLEIGH

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While Riversleigh fossils in northwestern Queensland came to world attention in 1994 following listing of Riversleigh as a World Heritage property, fossils from limestones in this region have attracted researchers' attention for more than 150 years. Our ARC-supported research, begun in the late '70s, has involved more than 100 researchers in 26 institutions in 11 countries. It has more than trebled previous knowledge about the paleodiversity and phylogenetics of Australian terrestrial vertebrates. Some of the deposits are also rich with invertebrates and plants. Many of the discoveries represent the first fossil records for entire families of modern vertebrates. Considering just mammals spanning the last 26 million years, hundreds of new species, genera, families and even a new order of very weird mammals have been described. Oligocene to Miocene mammal faunas are more diverse than any elsewhere in Australia today or at any time in its past. Forest birds being discovered compliment understanding about water birds known from 26–24 Ma deposits in central Australia. Currently as much research focuses on structure and function of vertebrates represented by articulated skeletons, as on paleobiodiversity. Riversleigh paleohabitats and their faunas have changed over the last 25 Ma from cool temperate forest in the late Oligocene, to perpetually wet rainforests in the early to middle Miocene, to cool, dry increasingly more open vegetation in the late Miocene, to a brief interval of wetter conditions in the early Pliocene, and then back to increasingly drier, more modern habitats through the Pleistocene. The record spans 2.5 climate change cycles. More than 200 distinct fossil deposits have been identified including Oligocene–Pliocene lacustrine and karst deposits and Quaternary karst and fluviatile deposits. Five faunal zones and five depositional phases are recognised. U/Pb radiometric dates now being obtained from paleospeleothems in conjunction with the University of Melbourne are testing and in general corroborating previous age determinations based on biocorrelation. This research has resulted in over 300 publications and about 32 Honours and 45 PhD theses with most of these students obtaining professional jobs. Transcendent programs building on this understanding include assessment of long-term conservation status of contemporary lineages and use of increased understanding about paleoecological resilience to develop translocation strategies to thwart extinction of climate-change threatened species. Recent research based on remote sensing by satellites has unexpectedly revealed that there are more fossiliferous deposits west of the World Heritage area than occur within that area. A grant from the National Geographic Society funded a helicopter to enable us to explore a small part of this new region in 2013. The current biggest challenge is how to resource exploration of the 75% of the remote 'New Riversleigh' region that has not yet been examined. As important as the scientific discoveries that have been, our whole team and the public volunteers who work with us have always had a tremendous amount of fun making and interpreting these discoveries at Riversleigh, which so far, show no signs of slowing down.

ENVIRONMENT

04EVA – COAL SEAM GAS AND GROUNDWATER

04EVA-01. THE USE OF SIMPLE HYDROCHEMICAL INDICATORS TO IDENTIFY CSG GROUNDWATERS AND DELINEATE GROUNDWATER FLOW PATHS WITHIN AND BETWEEN AQUIFERS

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KEY WORDS *CSG groundwaters, hydrochemistry, multivariate statistics, Walloon Coal Measures, inter-aquifer connectivity*

While the simple sodium–bicarbonate or sodium–chloride–bicarbonate hydrochemical signature of coal seam gas (CSG) groundwaters is universal and well known (Grossman *et al.* 1989; Harrison *et al.* 2000; Van Voast 2003; Hamawand *et al.* 2013), the wide range of processes that influence CSG groundwater hydrochemistry suggests that the hydrochemical signatures/responses along individual pathways may be different. Furthermore, water types with similar hydrochemistry to CSG groundwaters may evolve in other groundwater environments (Foster 1950; Rengasamy *et al.* 1991, 1993; Venturelli *et al.* 2003; McNeil *et al.* 2005). As a result, delineating the hydrochemical evolutionary flow paths associated with CSG groundwaters, and other aquifers can be problematic.

The assessment of hydrochemical data in the Surat and Clarence-Moreton basins has shown that simple indicators such as the hydrochemical type or electrical conductivity are ineffective as indicators of the presence of CSG groundwaters for delineating groundwater flow paths and assessing aquifer connectivity. Consequently, there is a need to identify other simple hydrochemical characteristics of CSG groundwaters and non-CSG groundwaters in associated flow paths in order to address a range of gas exploration and groundwater management issues, including investigating CSG flow paths, developing strategic groundwater monitoring programs, and to investigate aquifer connectivity. This paper proposes a simple method of assessing CSG groundwater types and groundwater pathways within coal-bearing formations and adjacent aquifers based on major ion data. Multivariate statistics are first applied to describe the broad hydrochemical facies. Simple hydrochemical trends are then defined to delineate specific hydrochemical characteristics of groundwaters in different aquifers. Three conceptual hydrochemical process models are proposed to infer the presence of different hydrochemical pathways within the Walloon Coal Measures (major target for CSG development) and other bedrock aquifers of the upper Condamine River catchment, which could then also be applied to investigate interactions between the alluvium and bedrock aquifers. Results are compared to other CSG groundwaters in the Surat Basin, Bowen Basin and Illinois Basin, as well as to non-CSG $NaHCO_3$ groundwater types to assess the applicability of applying these conceptual process models to CSG groundwater more broadly.

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04EVA-02. DEVELOPING AN IMPROVED MONITORING APPROACH FOR SPRINGS POTENTIALly IMPACTED BY COAL SEAM GAS DEVLOPEMENT IN THE SURAT CUMULATIVE MANAGEMENT AREA, QUEENSLAND

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This paper explores the range of monitoring tools and methods that may be appropriate for monitoring components of the water balance of springs (as gaining wetlands) in the Surat Cumulative Management Area (CMA, within the Surat Basin). The focus is on a framework to guide selection of monitoring indicators and monitoring approaches.

The work was funded and undertaken in collaboration with the Office of Groundwater Impact Assessment (OGIA). OGIA is responsible for the assessment of the cumulative groundwater impacts in areas of intensive petroleum and gas development in Queensland. The assessment includes regional groundwater modelling and the development of integrated management arrangements, such as monitoring of ecological assets dependent on groundwater. Management arrangements are established in an Underground Water Impact Report (UWIR), which includes a Spring Research Program to advance existing knowledge in relation to gaining wetlands in the Surat CMA.

In conjunction with traditional pressure monitoring, the purpose of gaining wetland monitoring is to establish an understanding of the natural variability in flow and to detect future changes in flow in response to pressure impacts.

Groundwater discharge within the Surat CMA occurs as discrete springs or as watercourse springs where discharge occurs along bedding plains within waterways. Subtle differences in the landscape setting and geomorphology of groundwater discharge zones creates several sub-types of springs that require different approaches to monitoring. Springs have been conceptualised as gaining wetlands.

The ecological value of gaining wetlands is intrinsically linked to the maintenance of the water balance within the wetland environment. The water balance provides a useful frame for selection of monitoring indicators and monitoring approach, so that changes of the water balance can be detected and used to infer a change in the hydrologic condition of the gaining wetland.

The following monitoring indicators are suggested:

- groundwater level/pressure;
- wetland area;
- wetland discharge; and
- water chemistry.

The project has identified many tools and approaches that could be used to measure changes in the gaining wetland water balance. The approaches include on-ground measurement (e.g. estimating evapotranspiration with on-site climate instruments) and remote sensing techniques using satellite or aerial data. Selection of appropriate monitoring approaches for a particular site will depend on the physical attributes of the selected gaining wetland environment. Specifically, selection will depend on the characteristics and processes related to the gaining wetland water balance. This allows the approach to monitoring to be linked to a system of typology for gaining wetlands.

The strengths and weakness of the tools and approaches identified indicate that it is unlikely that a single monitoring approach will satisfy the monitoring objectives. When inherent uncertainties and likely practical issues of each method are also considered, a multiple line of evidence approach is recommended. The work is being used to design a pilot monitoring trial to be implemented by OGIA and industry in the Surat CMA.

The outcomes from this work provide a basis for enhancing existing approaches to monitoring gaining wetlands. The paper provides a summary of the outcomes from a literature review and the role of conceptualisation and typology in the selection of appropriate indicators of change in the hydrologic environment.

04EVA-03. HYDROCHEMICAL CHARACTERISATION OF INTERCONNECTIVITY BETWEEN the WALLOON COAL MEASURES AND MAJOR AQUIFERS IN THE SURAT CMA

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The Condamine Interconnectivity Research Project (CIRP) led by the Office of Groundwater Impact Assessment (OGIA) is aiming to improve the existing understanding of the hydraulic interconnection between the Condamine Alluvium (CA) and the Walloon Coal Measures (WCM). Outcomes of the study will help in improving hydrogeological conceptualisation for the next generation of cumulative groundwater impact assessments in the Surat CMA. The CIRP is taking multiple lines of investigations. One of those lines of investigations is to make best use of available data to test a hypothesis if there has been interflow of water between the CA and the WCM resulting from differences in the water pressure caused by water extraction from the CA for agricultural purposes over recent decades. The study analyses the existing hydrochemical data (>5000 samples) from Condamine Alluvium valley. Significant differences in major ions and ion ratio chemistry between CA and WCM indicates insignificant inflow of water, if any from the WCM into the CA, suggesting that the hydraulic connectivity between the CA and the WCM is likely to be low. The multivariate principal component and K-means cluster analyses has been very useful in not only characterising the groundwater quality but also elucidating the processes and evolution of groundwater chemistry for the WCM and CA in the Condamine valley. The groundwater chemistry of the WCM, particularly in CSG wells, is dominated by very low concentrations of Ca^{2+}, Mg^{2+} and SO_4^{2-}, but very high concentrations of Na^+, pH, SAR and F^- compared to the CA groundwater. A major percentage of Ca^{2+} and Mg^{2+}, 70% and 30%, respectively, in the CA groundwater is derived from weathering of rock-minerals, compared with only 30% Ca^{2+} and 7% Mg^{2+} for the WCM. This suggests Ca^{2+} and Mg^{2+} for the WCM is mostly derived from atmospheric deposition of oceanic water through rainfall followed by cyclic concentration through evapotranspiration, salt mobilisation and leaching. Comparisons between closely located paired WCM and CA bores also showed significant ($P<0.001$) differences in groundwater chemistry irrespective of water pressure gradients between the bores, however most of the time the CA has greater water pressure than the WCM. Additionally, analyses of the existing hydrochemical data (>15 000 samples) from various formations across the Surat CMA further highlights significant differences in the groundwater chemistry between the WCM and other major formations in the Surat CMA, except high level of similarities in the groundwater chemistry between the WCM and the underlying Hutton/Marburg Sandstone; this suggests a good degree of hydraulic connectivity between these two formations. There are also some indications of similarities in the major ion and ion-ratio chemistry between the overlying Springbok Sandstone and the WCM in the Surat CMA. The ^{14}C assessment of groundwater age for a few selected WCM bores indicate 40 000 to 50 000 year old groundwaters, whereas the groundwater age of the top most stratigraphic layer of the CA is expected to be much less than the WCM due to frequent recharge from rainfall and river base flow.

04EVB – COAL SEAM GAS AND GROUNDWATER

04EVB-01. IMPROVING LOCAL HYDROGEOLOGICAL UNDERSTANDING AT SPRINGS; INFORMING THE FUTURE ASSESSMENT OF RISKS TO SPRINGS IN THE SURAT BASIN, QUEENSLAND

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This paper presents recent work undertaken by the Office of Groundwater Impact Assessment (OGIA) to enhance the local scale hydrogeological understanding of springs (gaining wetlands) in the Surat Cumulative Management Area (CMA). OGIA have applied a hypothesis testing and multiple lines of evidence approach that incorporates desktop and field investigations to advance understanding at selected sites.

In Queensland, the coal seam gas (CSG) industry is rapidly expanding in the Surat and Bowen basins. In this area, OGIA is responsible for the assessment of the cumulative groundwater impacts from CSG activities. Broadly, the assessment includes regional groundwater modelling, the development of integrated management arrangements and the assignment of responsibilities to individual petroleum tenure holders. Management arrangements are established in an Underground Water Impact Report (UWIR), which is revised every three years to incorporate new and emerging knowledge.

In the UWIR, OGIA identified a number of research projects relating to gaining wetlands. The principal objective that underpins the research is to improve the local hydrogeological understanding. The results from the project will improve confidence in the predicted impacts at the sites and provide a foundation for advancing the management arrangements in the revised UWIR in 2015.

Six spring complexes were selected as part of the project. The sites were selected based on their proximity to active tenures, currently predicted impacts, the complexity of local geology and where multiple aquifers remain plausible contributors to groundwater discharge.

The project comprises the following three phases:

Stage 1: Establishing a framework for local scale conceptualisation of springs.

Stage 2: Preliminary conceptualisation and hypothesis identification.

Stage 3: Review, synthesis and reconceptualisation.

Under Stage 2, a traditional hydrogeological desktop assessment comprising geological, hydrologic and hydrochemical assessments was completed at each of the study locations. A key outcome was the identification of multiple conceptual hypotheses, which represent the plausible mechanisms of spring genesis based on the available information. Up to four potential hypotheses were identified at each location.

The multiple hypotheses at each site guided the development of a targeted work program to validate and test the hypotheses. At each site, the work program incorporates a combination of activities including the collection of hydraulic head measurements, elevation surveys, wetland and water bore chemistry, geological surveys, ground geophysical investigations and at one location, investigation bores are installed. Wherever applicable, complimentary work in this area from CSG operators is also incorporated.

The project highlights the benefits of applying a hypothesis testing approach to investigate complex natural systems. The target field investigations provide a basis for reducing plausible hypotheses and provide a platform to increase confidence in the prediction of future water pressure impacts and the suitability of monitoring arrangements.

The outcomes from this project will inform the next generation UWIR in 2015.

04EVB-02.THE ROLE OF THE OFFICE OF GROUNDWATER IMPACT ASSESSMENT IN PREDICTING AND MANAGING THE IMPACT OF CSG WATER EXTRACTION IN QUEENSLAND

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In Queensland, the coal seam gas (CSG) industry is rapidly expanding in the Surat and Bowen basins. CSG production involves pumping water from the coal seams to release the gas adsorbed to coal. The reduction in water pressure in the coal seams will cause a reduction in water pressure in overlying and underlying aquifers to some degree, because there is always some interconnectivity between formations. The Surat Basin is a sub-basin of the Great Artesian Basin, which contains aquifers of high economic, environmental and cultural value. The Condamine Alluvium is also an important water resource that overlies parts of the eastern margin of the Surat Basin. The paper describes the role of the Office of Groundwater Impact Assessment (OGIA) in managing the impacts of CSG water extraction on groundwater resources, within the broader regulatory framework.

The Queensland regulatory framework has a general requirement for petroleum tenure holders to make good any impairment of water supply from private water bores affected by CSG water extraction, and to collect baseline data from water supply bores before production commences. Petroleum tenure holders are also required to: assess potential impacts of planned water extraction on aquifers; establish groundwater-monitoring programs; and establish spring monitoring programs.

In areas of intensive development the impacts of groundwater extraction from individual CSG projects can overlap. In such areas a cumulative approach is needed for assessment and management. Such areas can be declared a 'Cumulative Management Area'. When such an area is declared the OGIA becomes responsible for preparing and periodically updating an Underground Water Impact Report (UWIR) which contains: a cumulative assessment of water level impacts; a regional groundwater monitoring strategy; a regional spring impact management strategy; and rules for the assignment of management responsibilities to individual petroleum tenure holders within the area. The costs of OGIA are met through an industry levy.

The first Surat UWIR was approved in December 2012. OGIA is now supporting petroleum tenure holders in the implementation of the management responsibilities established under the report and developing new knowledge to support the updating of the Surat UWIR in late 2015.

04EVB-03. ENVIRONMENTAL TRACER MEASUREMENTS ALONG NORTH–SOUTH TRANSECTS IN THE HUTTON SANDSTONE

Axel Suckow[1,2] & the GISERA baseline team

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Depressurisation of the coal seam gas fields in the Walloon Coal Measures in Queensland may influence aquifers both over- and underlying the formation. While the Gubberamunda Aquifer, overlying the Walloon Coal Measures and being starting point of the flow system of the Great Artesian Basin, is comparably well studied, less information is available on the Hutton Sandstone underlying the Walloon Coal Measures. In October/November 2013 we obtained samples for environmental isotope and tracer analyses ($^{18}O/^{2}H$, CFCs/SF_6, Tritium, noble gases, $^{13}C/^{14}C$, ^{36}Cl, $^{87}Sr/^{86}Sr$, ion chemistry) from bores along two different north–south transects in the Hutton Sandstone. The northern boundary is the outcrop area north of the latitude of Taroom and the southern extent is defined by the availability of wells with screens in the Hutton Sandstone, which is down to the latitude of Roma–Miles. At this latitude the Hutton Sandstone Aquifer is found at a depth around 1000 m below ground.

First results of the environmental tracer measurements confirm earlier difficulties of obtaining flow directions within the Hutton Sandstone. Nearly all bores contain only very low amounts of radiocarbon (^{14}C being below 10 pMC). This is not necessarily an indication of old water but can also indicate oxidation of fossil carbon (e.g. methane) since total dissolved inorganic carbon (TDIC) increases by a factor of ten from north to south in this aquifer. Dissolved helium in groundwater should show accumulation of this noble gas with increasing residence time in the aquifer. Helium increases as expected on the western transect from north to south and has highest values around Reedy Creek. For the eastern transect, however, high helium values are found very close to the outcrop, which was assumed to be the infiltration area. Our results show that deep groundwater flow fields with long time scales and complicated geochemical influences can only be studied successfully with a combination of several tracers allowing conclusions on very different time scales (decades: tritium, CFCs, SF6; millennia: ^{14}C, helium; up to one million years: helium ^{36}Cl, ^{81}Kr).

04EVC – COAL SEAM GAS AND GROUNDWATER

04EVC-01. HYDROCHEMICAL AND ISOTOPIC FINGERPRINTING OF THE WALLOON COAL MEASURES AND ADJACENT AQUIFERS IN THE CLARENCE-MORETON AND EASTERN SURAT BASINS IN SOUTHEAST QUEENSLAND

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The Clarence-Moreton and the Surat basins in Queensland and northern New South Wales contain the coal-bearing sedimentary sequences of the Jurassic Walloon Coal Measures, composed of up to approximately 600 m of mudstone, siltstone, sandstone and coal. In recent years, the intensification of exploration for coal seam gas (CSG) resources within both basins has led to concerns that the depressurisation associated with future resource development may have adverse impacts on water resources in adjacent aquifers.

In order to identify the most suitable tracers to study groundwater recharge and flow patterns within the Walloon Coal Measures and their degree of connectivity with over- or underlying formations, samples were collected from the Walloon Coal Measures and adjacent aquifers in the northern Clarence-Moreton Basin and eastern Surat Basin, and analysed for a wide range of hydrochemical and isotopic parameters. Parameters that were analysed include major ion chemistry, $\delta^{13}C$–DIC, $\delta^{18}O$, $^{87}Sr/^{86}Sr$, Rare Earth Elements and Yttrium (REY), ^{14}C, $\delta^{2}H$ and $\delta^{13}C$ of CH_4 as well as concentrations of dissolved gases (including CH_4).

Dissolved CH_4 concentrations range from below the reporting limit (10 µg/L) to approximately 50 mg/L in groundwaters of the Walloon Coal Measures. However, the high degree of spatial variability of methane concentrations highlights the general complexity of recharge and groundwater flow processes, especially in the Laidley Sub-Basin of the Clarence-Moreton Basin, where numerous volcanic cones penetrate the Walloon Coal Measures and may form pathways for preferential recharge to the Walloon Coal Measures. Interestingly, dissolved CH_4 was also measured in other sedimentary bedrock units and in alluvial aquifers in areas where no previous CSG exploration or development has occurred, highlighting the natural presence of CH_4 in different aquifers.

Radiocarbon ages of Walloon Coal Measure groundwaters are also highly variable, ranging from very young (~82 pMC) to very old (0.43 pMC). While groundwaters sampled in close proximity to the east and west of the Great Dividing Range are mostly young, suggesting that recharge to the Walloon Coal Measures occurs through the basalts of the Great Dividing Range; there are otherwise no clearly discernable spatial patterns and no apparent relationships with depth or distance along inferred flow paths in the Clarence-Moreton Basin.

In contrast to this strong spatial variability of CH_4 concentrations and groundwater ages, REY patterns and $^{87}Sr/^{86}Sr$ isotope ratios of Walloon Coal Measure groundwaters appear to be very uniform and clearly distinct from groundwaters contained in other bedrock units. This difference is attributed to the different source material of the Walloon Coal Measures (mostly basalts in comparison to other bedrock units which are mostly composed of mineralogically more variable Paleozoic basement rocks of the New England Orogen).

This study suggests that REY and $^{87}Sr/^{86}Sr$ ratios may be suitable tracers to study the hydraulic connectivity of the Walloon Coal Measures with over- or underlying aquifers, although more studies on the system are required. In addition, this study also highlights the need to conduct detailed water chemistry and isotope baseline studies prior to the development of coal seam gas resources in order to differentiate between natural background values of CH_4 and potential impacts of coal seam gas development.

04EVD – GENERAL CONTRIBUTIONS

04EVD-01. RARE EARTH AND OTHER ELEMENT PATTERNS IN THE SOILS OF CYPRUS

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A soil geochemical atlas, based on analysis of over 11 000 samples, has been conducted across the republic of Cyprus by a team from the Geological Survey of Cyprus and UNSW. This work is an extension of the regional and global geochemical mapping programs being undertaken by consortia of geological surveys around the world.

REE and other element patterns are largely controlled by the parent lithological composition, which includes the famous ultramafic to mafic Troodos Ophiolite Complex (TOC) and the surrounding younger pelagic carbonate-dominated Circum-Troodos Sedimentary Sequence (CTSS).

Similar concentrations between top soil (0–25 cm) and subsoil (50–75 cm) samples indicate limited REE mobility during weathering. Aqua regia extractable (*ar*–) REE concentrations generally range between 40 and 80% of the total REE content, with a progressive decrease in extractability from La to Lu. There is no correlation between La and Ca in the TOC unit soils and even a weak negative correlation in the CTSS. There is no correlation between La and Fe in the TOC but a strong correlation, despite low Fe values, in the CTSS units. The REE are strongly correlated with Th in all units but not to any great extent with U. For the totals analyses, LREE are closely correlated with Zr and HREE are less positively correlated, but the opposite is the case with the *ar*– data. Chondrite-normalised *ar*-REE patterns display negative Eu anomalies and relative LREE enrichment, apart from the basaltic volcanics for which the pattern is flat. Unlike the shallow marine Pakhna Formation, the deep marine Lefkara Formation displays Ce and Eu depletion.

Major faults in the TOC are characterised by elevated *ar*-REE and/or offset REE trends. The most westerly of these structures has the strongest *ar*-REE anomaly, which coincides with elevated soil Cu values in both the pillow basalts and underlying mafic intrusive sequence containing the sheeted dyke complexes. In soils from the TOC units the main source of REE appears to be zircons and Fe-oxyhydroxides with the REE originating in a range of primary silicates. In the CTSS the REE and other redox-sensitive element (U, Bi, Mo) patterns indicate precipitation from seawater and or association with Fe-oxyhydroxides with a change from deep marine and reduced environments (Lefkara Fmn) to progressively more oxidised marine environments (Pakhna and younger formations).

04EVE – UNDERSTANDING AUSTRALIA'S COASTAL ENVIRONMENT

04EVe-01. CONCEPTUAL AND ACTUAL CHANGES OF COASTAL DUNES DUE TO SEA LEVEL AND CLIMATE CHANGE

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This presentation will present a range of scenarios, some conceptual and data poor, some field based and relatively data rich, of how coastal dune types and coastal dune systems (particularly dunefield barriers), behave or evolve as sea level rises and/or climate changes.

Foredunes will translate landwards and upwards given space and follow Robin's rule rather than the overly simplistic Bruun Rule. Foredunes achieve this *via* a series of steps involving scarping during storm events, post-storm scarp filling and the development of eolian ramps, eolian transport up ramps to deliver beach sediments to the foredune crest and lee slope, partial to full vegetative stabilisation by pioneer vegetation, followed by another erosion event. Significant storm events lead to overwash and immediate shorewards translation in the case of low foredunes and barriers, with possible full-scale destruction of the foredune/landwards dune system and potential re-establishment landwards. Blowouts are eccentric and develop during periods of dunefield stabilisation (driven by increased rainfall and/or decreased wind energy), and during periods of dunefield destabilisation as rainfall decreases and/or winds increase. Blowouts will develop more commonly than present as the coast and seawardmost dunes erode due to wave processes coupled with eolian processes. Higher wind strengths, or increased storminess, will lead to greater development of blowouts than present. Blowouts also commonly evolve into parabolic dunes, and these will develop and/or be more prominent where the climate is drier and more windy, but also where coastal erosion is more rapid as when sea level transgression rates increase. Parabolic dunes will be more commonly developed as opposed to transgressive dunefields if the vegetation cover is higher due to climate changes. Largely active (mobile) trangressive dunefields will stabilise as climate changes towards wetter and/or less windy conditions, and the reverse will occur when the climate becomes more arid and more windy (but with significant hysteresis in the system).

Responses will be complex due to the prevailing climate when conditions begin to change (arid environments will not change as much), and add to sediment supply. Some coasts will change little, and may prograde if the sediment supply is high despite sea level rise.

04EVF – UNDERSTANDING AUSTRALIA'S COASTAL ENVIRONMENT

04EVf-01. THE COMPREHENSIVE AUSTRALIAN TSUNAMI DATABASE – JUST WHEN YOU THOUGHT IT WAS SAFE TO GO BACK IN THE WATER

James Goff[1] & Catherine Chagué-Goff[1,2]

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This new database incorporates peer-reviewed publications, critical reviews and searchable web-based datasets and as such represents a complete re-organisation and restructuring of previous work. These new data take the number of events from 57 (including two “erroneous events”) to 145. Several significant errors have been corrected, not the least of which are mistaken run-up heights for the 19 August 1977 Sumba Island, Indonesia event that suggested it was the largest historical tsunami in Australia’s history. This honour now goes to the 17 July 2006, Java, Indonesia tsunami that had a run-up height of 7.90 m at Steep Point, Western Australia. Although estimated wave heights of 40 feet (~13 m) were noted for the 8 April 1911 event at Warrnambool, Victoria, no run-up data were provided and so its full effects remain uncertain. One of the more interesting findings has been the occurrence of at least 11 deaths, albeit for events that are generally poorly defined.

Data gathered during the construction of this database were rigorously reviewed and as such several previous paleotsunami entries have been removed and other potentially new ones discarded. The reasons for inclusion or exclusion of data are discussed and it is acknowledged that while there has been an almost three-fold increase in the number of entries, the database is still incomplete. With this in mind the database architecture has been brought in line with others in the region with the ultimate goal of merging them all in order to provide a better understanding of the national and regional tsunami hazard (and risk) and to move towards an open source Australasian database.

04EVf-02. ESTIMATING THE INUNDATION LIMITS OF SMALL HISTORICAL TSUNAMIS

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There has been considerable progress in tsunami research in recent years, yet most work has been focussed on identifying and understanding the evidence of large events. This talk discusses the evidence for small historical tsunamis in Lyttelton Harbour, New Zealand. The study area has been inundated by numerous relatively small historical tsunamis without depositing any notable sedimentary evidence. However, excavations of shallow soil profiles revealed discontinuous layers of small grey mud clasts, most likely transported from the nearby harbour, at various depths across the study area. The origin of these mud clast layers was investigated using a multi-proxy approach comprising sedimentological, geochemical and diatom analyses complemented by radiometric dating and historical data. Subtle variations consistent with inclusions of marine mud, such as a decrease in organic content and magnetic susceptibility and increases in geochemical markers (e.g. potassium, calcium) were found in the sedimentary profile. Variations in diatom assemblages suggesting marine influence were also recorded at similar depths, aligning with layers of mud clasts. Using ^{137}Cs dating and historical data, these deposits were attributed to the 1960 Chile and possibly 1964 Alaska tsunamis. Sedimentary evidence for the 2010 Chile tsunami was not found at the study site, but geochemical analysis of surface samples revealed marked changes in calcium, chlorine, strontium and titanium concentrations, indicative of a change from terrestrial to marine influence. This was used to identify the landward extent of inundation. Ultimately, this study shows that a broad multi-proxy analysis can distinguish even the subtle signatures of an inconspicuous deposit laid down by a small tsunami.

04EVf-03. HOLOCENE RECORD OF LONG- AND SHORT-TERM ENVIRONMENTAL CHANGES IN A COASTAL WETLAND, NEW ZEALAND

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Long- and short-term environmental changes in Moawhitu Wetland, D'Urville Island, New Zealand, were reconstructed using a multi-proxy approach. A local Māori oral tradition describes a giant wave destroying a community in the 15th century, however, except for a study in 1962, little geological work had been carried out to investigate this event or to establish a record of paleoenvironmental changes in the area. Three sedimentary sequences sampled across the wetland over a distance of 2 km were analysed for grain size, organic content, geochemistry (ICP-AES, ICP-MS and ITRAX), diatom assemblages and mineralogy, while the chronology was obtained using ^{14}C and ^{210}Pb dating, corroborated with pollen biostratigraphy.

Results of this study indicate that the sand dune barrier at Moawhitu formed *ca* 7400–7200 years BP at the time when sea levels stabilised following the last deglaciation. This led to the establishment of a freshwater lake in the southern area, which gradually infilled to form a wetland with subsequent peat accumulation. In the central part of Moawhitu, lake and peatland sequences alternated. By *ca* 1200 years BP, with the exception of the existing lagoon at the northern end of the study area, conditions favourable to peatland formation were found throughout Moawhitu and continued into the 20th century when they were disrupted by drainage activities.

Evidence for a tsunami 3300–3000 years BP was found in the northern part of Moawhitu wetland (based on sedimentological, geochemical and microfossil data). Geochemical signatures and marine diatom assemblages provide a record of tsunami inundation in the middle part of the wetland, beyond the extent of any sand deposit. No geochemical evidence could be found at the site further inland in the southern part of the wetland. Evidence for a contemporaneous tsunami deposit has also been reported ~100 km N, on Kapiti Island, on the west coast of the North Island of New Zealand, and the event has been attributed to a local fault rupture. So far, no sedimentological, geochemical or micropaleontological evidence for a giant wave in the 15th century has been found in the sedimentary sequence of Moawhitu wetland. However, pebble layers extending across large areas of the dunes have been recorded and these have also been associated with Maori occupation, thus inferring that the sand dune may indeed have acted as an effect barrier to any 15th century tsunami.

This study indicates that more than one tsunami has affected Moawhitu, and further work is planned to document environmental changes in the area.

04EVf-04. THE 'LAKE MANNUM' MUDS: A LACUSTRINE ORIGIN FOR THE LOWER MURRAY RIVER GORGE'S UPPERMOST VALLEY FILL

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Middle to late Holocene age, horizontally laminated clays and muds of lacustrine origin predominate the uppermost layers of the valley-fill sequence deposited in the lower Murray River's bedrock gorge upstream of the set of lakes which separate Australia's largest river, The Murray-Darling, from its discharge point to the Southern Ocean. The top surface of these Coonambingal Formation muds is developed at a constant elevation approximately coincident with the Holocene sea-level maximum and the mud deposit thins progressively in thickness upstream from ~30 m to ~10 m over a distance of 150 km due to a gradual, upstream rise in the elevation of the unit's base. Radiocarbon ages for wood and charcoal fragments recovered from two cores indicates that uppermost 6 m or so of these muds were deposited after the mid-Holocene sea-level maximum, at below sea-level elevations indicating that the discharge of the Murray River was contained and effectively dammed by an obstruction of some kind developed between (or near) Lake Alexandrina and Goolwa where the present-day river mouth is located. This feature is suspected to be the precursor of the present-day dune and beach-barrier system, which occasionally blocks the river mouth and diverts fresh-water flow into the Coorang Lakes. Muddy sediment from the entire Murray-Darling catchment was effectively trapped in the Lower Murray Gorge paleolake, herein named Lake Mannum, during the mid to late Holocene. High rates of sedimentation (one to two metres per thousand years) produced exquisitely fine-scaled (1 mm to 1 cm) lamination in the upper Coonambingal Formation. This material has not been disturbed by bioturbation and presents a sediment record with the potential for to yield a high-resolution record of the Murray-Darling Catchment's discharge for much of the Holocene.

The present-day lower Murray River channel currently presents a meandering but constant planform geometry upstream of Lake Alexandrina that developed as a thalweg incised down into, and entrenched itself within the Coonambingal muds as a somewhat delayed response to the 2 m fall in sea-level after the mid-Holocene maximum. The onset of this incision apparently occurred towards the end of the Holocene. Further widening of the present-day channel is expected.

ENERGY

04EGA – COAL – ADVANCES IN THE MULTIPLE FACETS OF COAL GEOSCIENCES

04EGA-01. A NEW LOOK AT AN OLD FUEL: ADVANCED TECHNOLOGIES FOR EVALUATING MINERAL MATTER IN COAL

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In addition to the organic components, or macerals, coal contains a variable but usually significant proportion of mineral matter. This material includes both crystalline inorganic particles (minerals in the geological sense) and a range of inorganic elements that occur in non-crystalline form, such as dissolved ions in the pore water and inorganic elements bonded in some way to the organic components. The minerals themselves may include detrital admixtures and authigenic precipitates incorporated into the original peat deposit, later-stage precipitates infilling cleats, fractures and pore spaces, and in some cases products of hydrothermal alteration that has affected the coal seam. Many of the practical problems associated with coal, such as unfavourable environmental impacts from stockpiles and waste dumps, difficulties with flow and drainage of seam gases, and operational issues in preparation and utilisation plants, are derived at a fundamental level from the mineral matter.

Advances in geological science have provided a steadily increasing array of techniques to analyse this mineral matter and evaluate its mode of occurrence, allowing improved interpretations of coal formation and better understanding of how the different mineral components might behave when the coal is used. As well as advances in chemical analysis, especially for trace elements, these include quantitative X-ray diffraction, electron microscopy (both alone and combined with image analysis), X-ray micro-tomography, electron microprobe studies, and detailed scanning of cored intervals by X-ray fluorescence techniques. Australian geoscientists have been at the forefront of many of these developments, partly because of the wide variety of coals that occur in Australia and partly because of the significance of the coal industry to the Australian economy.

The conditions under which particular minerals form and interact with each other are often well understood from other branches of the geological sciences. Indeed, in some cases they are better understood than the processes that have produced the different organic components. Drawing on this understanding, in conjunction with information from the petrology of the organic constituents, may thus provide better interpretations of the environments in which particular coals were formed, and also of the changes that have occurred within the coal at different stages of its post-depositional history.

As well as the coal itself, many of these techniques can also be applied to the products of coal utilisation, such as fly ash and furnace deposits, enabling better understanding of the processes that form them, and also their possible value as by-products, from a geological point of view. The high-temperature conditions to which coal and the associated mineral matter are exposed during utilisation have many similarities to the conditions associated with igneous activity. An understanding of magma crystallisation, although derived from research well outside the traditional fields covered by coal geology, can therefore be integrated with mineral matter studies to understand the formation and properties of ashes and furnace deposits. This has implications for both improved efficiency of utilisation and better understanding of the materials in environmental impact assessment.

04EGA-02. THE APPLICATION OF USING THE HYLOGGER™ HYPERSPECTRAL DATA FOR A CHEMOSTRATIGRAPHIc FRAMEWORK OF THE RANGAL AND FORT COOPER COAL MEASURES, BOWEN BASIN

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The application of hyperspectral scanning of core has been extensively tested by the mineral industry, but less so by the petroleum industry. It has potential to test stratigraphic correlations through chemostratigraphic analysis, and to identify deleterious clay minerals that may react with drilling fluids and/or reduce the borehole integrity. It also yields information for the interpretation of provenance, diagenesis and alteration within different strata. This presentation reports preliminary analysis of HyLogger™ data for a suite of cores intersecting the Triassic and upper Permian Rewan Group and underlying Rangal and Fort Cooper Coal Measures (CM) in a structurally complex area of the eastern Bowen Basin. Initial interpretations of the various wavelength data sets, have established mineral signatures of the different formations. Within the Fort Cooper CM, the lower Fairhill Formation and overlying upper Burngrove Formation can be easily differentiated by the mica group alteration phases from phengite to paragonite, respectively. This may reflect a change in provenance, but more likely is evidence of hydrothermal alteration and low-grade metamorphism of the sediments. The fluid is interpreted to be iron rich in the lower Fairhill Formation and transitioning to a sodium rich fluid in the Burngrove Formation, indicated by the transition from phengite to paragenite in the interburden. The results also suggest waves of alteration, possibly due to deep weathering in the Rangal CM, interpreted from a shift in the percentage of white micas to kaolinite minerals within the spectra. These phases of weathering can be traced throughout the project area, indicating initially a SE to NW transition in the lower Rangal CM and then after a hiatus, a NW to SE transition across the project area. This weathering could be climatic or reflect relative changes in uplift. This corresponds to a shift in coal maceral group composition from vitrinite to inertinite dominance in the upper coal seams of the Permian before the Triassic coal gap.

04EGB – COAL – ADVANCES IN THE MULTIPLE FACETS OF COAL GEOSCIENCES

04EGB-01. FORMATION OF FURNACE DEPOSITS DURING COAL COMBUSTION: PRODUCTION OF SYNTHETIC MAGMAS DURING COAL UTILISATION

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Most of Australia's electricity generation takes place in pulverised-fuel (pf) furnaces, where the feed coal is milled to fine powder and burnt to produce heat, which in turn makes steam to drive the turbines and generators. The coal used in these furnaces incorporates varying proportions of mineral matter, including detrital and authigenic minerals similar to those found in sediments, elements linked to the organic matter, and post depositional minerals that occur in veins and fracture fillings. The major minerals in Australian feed coals are usually clay minerals, typically kaolinite and interstratified illite/smectite, with variable proportions of quartz and carbonates such as siderite, calcite and dolomite/ankerite. Pyrite is more common in northern hemisphere coals. As the coal burns, the minerals and other inorganic elements reach temperatures of up to 1200^{o}C for low rank coals and 1600^{o}C for higher rank coals. Most of the minerals are transformed at these temperatures to other species, some of which may adhere to the metal of the furnace tubes and accumulate as furnace deposits, which decrease the rate of heat transfer and hence reduce the efficiency of the steam-raising process.

The mineral interactions associated with the formation of these deposits are similar to the processes that take place in magmas and other high-temperature geological environments. Although a lesser compositional range occurs than is seen in natural magmatic settings, and the systems are essentially anhydrous, significant understanding of the processes controlling deposit formation can be gained by applying the techniques and principles of igneous petrology to the materials involved. The deposits range from sintered masses of ash particles to vesicular glasses representing material that has melted and fused in the furnace environment. They may also contain a range of crystalline materials, which include unaltered coal minerals and minerals produced during cooling of the molten deposits, analogous to processes that occur during igneous rock formation and low pressure extreme thermal metamorphism. Not all the mineral matter in coal may take part in the various reactions, and thus the ash chemistry alone cannot be used to identify the potentially reactive and non-reactive minerals in the coal feed; specific data on the coal's mineralogy, obtained for example by X-ray diffraction, is the most effective starting point for deposit evaluation.

Detailed investigations of deposits formed from different coals and under different conditions have shown that furnace deposits build up in a series of stages. Particles of some ash components become attached to the metal of the furnace tube to form an initiation layer, after which additional particles adhere to that layer and to each other to form a sintered deposit. With rising temperatures due to the impeded heat flow, solid state reactions akin to metamorphism, and in some cases melting and crystallisation akin to igneous processes, may then take place to form bonded and fused "mature" deposits. The development and amelioration of these deposits can thus be investigated from integration of mineralogical and textural data, interpreted in the light of processes that form similar pyroclastic and igneous and rock materials.

04EGB-02. THE CHARACTERISATION OF COAL AND COAL UTILISATION PRODUCTS USING SCANNING ELECTRON MICROSCOPY IMAGE ANALYSIS

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In order to improve the efficiency of coal utilisation and reduce the environmental footprint there is a need within the coal mining and utilisation industries to better characterise coal and coal utilisation products. Computer controlled scanning electron microscopy (CCSEM) has long been used in coal research and recent advances combining scanning electron microscopy with energy dispersive X-ray spectrometry and sophisticated image analysis software enables the automatic measurement of sample characteristics such as mineralogy, particle size distribution, particle morphology and mineral association.

This improved method of phase-specific analysis is a powerful tool for coal characterisation; it provides unique quantitative mineralogical, textural, and chemical data on a particle-by-particle basis, for both coal and mineral matter. Systems such as QEMSCAN and TESCAN automatically identify most common ash-forming minerals online (silicates, carbonates, oxides, sulfides, sulfates and phosphates), and then create digital particle images. These images contain information on particle shape, area and size, and modal composition, together with grain size estimates, phase associations, and chemical composition, all of which can be extracted using the accompanying image analysis software, and quantified on a particle-by-particle or size-by-size basis.

Examples will be presented of how this new instrumentation can be applied in areas such as coal preparation, characterisation of coal utilisation products such as fly ash, understanding of pulverised fuel boiler ash deposition issues, formation of gasifier slags, and environmental issues.

04EGB-03. STUDY OF MINERAL MATTER IN COAL FROM THE Upper PERMIAN BOWEN BASIN BY QEMSCAN AND OPTICAL MICROSCOPY

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The identification of the different minerals through optical microscopy in reflected light it is not always easy. Even if one can readily discern between carbonates and clays, the differentiation of individual minerals within these groups can be difficult. Modern techniques such as QEMSCAN (automated SEM-based system) allow the identification of the different mineral phases within a given sample through a pixel-to-pixel mineral chemistry recognition. Furthermore, the use of coal blocks, instead of crushed samples, allows the mapping of the actual mineral matter distribution and the original rock textures/microstructures.

In this study QEMSCAN associated with optical microscopy observation was used for mineral identification, quantification and distribution in 107 samples (3cm polished blocks) from the upper Permian Bowen Basin coal measures – Rangal Coal Measures (RCM), Fort Cooper Coal Measures (FCCM) and Moranbah Coal Measures (MCM).

In the samples used in this study, kaolinite appears as the predominant mineral in the RCM occurring as infill in cleats confined mostly to the collotelinite layers and in the cell lumens of the inertinite macerals. Carbonates, such as siderite and calcite also occur, with the former dispersed in the coal matrix representing syngenetic mineral phases formed during early stages of the coal formation, and the latter carbonate precipitation associated with cleats and fractures that cut both lithotypes (vitrain and durain bands). In the FCCM calcite and ankerite are the main mineral phases, as well as quartz. Both carbonate phases occur filling the cleat system and the cell lumens of the inertinite macerals, while quartz appears in mineral-rich layers associated with some clay minerals. In MCM the main mineral components are clay minerals, occurring as infilling cleats or in the open spaces of the maceral structures.

Other mineral phases occur in small proportions such as apatite, especially associated with the top seam from the RCM, pyrite occurring as euhedral crystals, titanium oxide (probably anastase) appearing in the cleat system cross-cutting kaolinite infillings, and more rarely barite and zircon, the former filling the cell lumens and the latter dispersed in the matrix.

The trends in the mineral composition of the coal measures reflect different mineralisation events in the Bowen Basin. According to detail studies of the surrounding strata in coal-bearing sequences in the Bowen Basin, the complex mineralisation was related to hydrothermal events occurring during a late Triassic extensional tectonic event in eastern Queensland that affected especially the northern part of the Bowen Basin. Moreover, the difference found in the mineralogy may be also a result of the fluid/rock ratios and fracture system that affect the permeability and fluid circulation.

04EGB-04. DETAILED PROFILING OF INORGANIC ELEMENTS IN COAL SEAMS USING CORE SCANNING XRF TECHNIQUES

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Detailed quantitative profiles showing the abundance of inorganic elements in coal seam drill cores have been measured using an automated energy-dispersive X-ray fluorescence (ED-XRF) core-scanning instrument. Such an approach has potential application for rapid determination of the fine-scale vertical distribution of mineral matter or ash-forming elements in a coal seam, identifying horizons at which particular elements may be concentrated, evaluating in detail the relationships between different inorganic elements, and maximising the data available to guide broader-scale sampling for more conventional analysis programs. In conjunction with X-radiography, carried out as part of the scanning process, the results may also assist in design of crushing and preparation facilities for optimum beneficiation of the coal seam.

Profiling was carried out on 60 mm diameter as-drilled core segments from the high-volatile bituminous Goonyella Middle seam in the northern Bowen Basin of Queensland, using an Itrax core scanner (Cox Analytical, Sweden). The scanning process included high-resolution optical imaging, X-radiography, and collection of ED-XRF spectra at 200 µm intervals along the axis of each core segment. Sodium was not included in the measurements due to its low atomic number, and magnesium was below the instrument's detection limit in the coal samples studied.

Calibration curves were prepared using pressed pellets of reference coals as standards, each independently analysed by conventional techniques; a Compton matrix correction model was also applied. The concentration of each element at each step in each profile, as a fraction of the coal, was then determined from the relevant peak areas using the resulting regression equations. The element concentrations were compiled to produce a set of quantitative chemical profiles for each core segment, which were plotted alongside the relevant X-radiograph and optical image to provide an integrated basis for assessing the variations in inorganic element characteristics through each core section, and to relate those variations to the abundance of visible mineral matter and the macroscopic modes of mineral occurrence.

The percentages of each element measured (except for sulfur) were also converted to oxides, to provide a better indication of the expected ash analysis characteristics. Crushing, ashing and chemical analysis of a scanned core segment by conventional techniques showed that the total percentages of the ash-forming oxides were consistent with the (conventional) ash percentage, and that the indicated chemistry from the scanner was consistent with directly-determined ash analysis data. An inverse relationship was observed between the total oxide percentage indicated by the scanner and the overall level of Compton backscatter, also measured by the instrument, providing a potential link to data gathered from down-hole density logs during coal exploration programs.

Such profiling allows assessment of chemical (and mineralogical) variations through the seam at a scale that cannot be duplicated by conventional ply-by-ply sampling and analysis programs, and is potentially useful for a range of research and industrial purposes. In addition to profiles of major ash-forming constituents, the technique also has potential for evaluation of trace element distribution in Australian and other coal seams.

04EGC – COAL SEAM GAS – INSIGHTS INTO A RAPIDLY EXPANDING RESOURCE AND INDUSTRY

04EGC-01. POPULATING THE CONTAINER – APPROACHES TO CHARACTERISING THE WALLOON SUB-GROUP AND THEIR COAL MEASURES IN THE SURAT BASIN

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Although the end target of static modelling of reservoirs is to understand the dynamic flow behaviour of different units and their interconnectivity, the stratigraphy and sedimentary facies models provide the framework within which to estimate and extrapolate the reservoir parameters. Stratigraphic boundaries are constructs that allow bounding surfaces within a model to be built, and geologists and engineers to communicate how and why different units have different properties and behaviours. Sedimentary facies provide a mechanism to predict the size and shape of specific elements within a unit, for example coals, floodplains and channels and a variety of sub elements therein, to be predicted. The myriad of available sub-elements or environments coupled with operator subjectivity and philosophy in choosing the bounding surfaces, their contacts and the interpretation of environments, compounded by probability of occurrence in modelling approaches, leads to variability and uncertainty in the outcome. These different components are tested in the Jurassic age Walloon Sub-group and their coal measures. Approximately 2000 open file wells and their geophysical wireline data were used to define stratigraphy using both a litho- and a sequence stratigraphic approach. In the majority of wells the major unit boundaries were similar (within metres). These unit boundaries provided constraining layers within which three dimensional grid or cellular models were created. Cell sizes were varied and compared to capture the thin-bedded nature of the coals and other lithofacies (e.g. 1000 m x 1000 m x 2 m; 250 m x 250 m x 1 m and other combinations). Properties of rock density and natural gamma were used to interpret and assign lithofacies to each cell, using a cut off value approach. The lithofacies were compared to manual interpretation of sedimentary facies from core, and to resulting wireline motifs for their recognition in electrofacies. Finally, a neural network approach (Facimage™) to automated recognition of coal lithofacies and clastic sedimentary facies, which included a minimum thickness and a trending function, was applied to the logs and compared to manual interpretation. The results in all three cases were comparable at the basic level of lithologies, and elements of coal mire, floodplain, and channel within a given core. The three different cases with their varying levels of complexity were then used to populate the geological grid model using statistics for continuous, categorical and object based approaches. The variability among multiple realisations of a given facies approach is as high as that between approaches. The probability that a given litho- or sedimentary facies will occur kilometres away from well control is poor and the resulting simulations did not necessarily predict the location of different facies, but do illustrate the vertical and lateral heterogeneity within the Walloon Sub-group, and the differences between over and underlying units. The more bounding surfaces used to guide the cell assignments, the more laterally connected were the different facies, except where object modelling was used to predefine connectivity. Variability in the juxtaposition of the different lithofacies, as interpreted and modelled, create different scales of simple to tortuous flow paths that are expected to reduce connectivity within the coal measures, and between over and underlying sandstone dominated units.

04EGC-02. ESTIMATION OF VOLUMETRIC FRACTION OF COAL IN THE STACK OF COAL SEAMS FROM SEISMIC ANISOTROPY PARAMETERS: FEASIBILITY STUDY

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Estimation of the relative volume of coal within a layer of host rock containing coal seams using seismic methods can have large impact on coal and coal seam gas exploration. However, coal seams are often thin compared to the vertical resolution of seismic data. As such it is challenging to estimate the volumetric fraction of coal seams from standard reflection seismic imaging. To address this issue, we propose a method of the volumetric fraction estimation based on an effective anisotropy of the layered structure.

Seismic anisotropy can be caused by layering (Backus 1962). Usually this effect is not strong due to the fact that the contrast of the elastic properties of the layers is relatively small. However, coal has elastic properties are usually very different from the surrounding rocks; compressional wave velocity and density are often significantly lower than the surrounding sediments.

Herein we present a feasibility study of using effective VTI anisotropy parameters for estimating the coal/coal seam fraction in a stack of coal seams and host rock. These parameters can be relatively easily derived from surface seismic data.

Strong velocity contrasts in coal seams environments can be described by effective media with very strong VTI anisotropy. The anisotropy parameters can be used to quantify the coal seam properties. The Thomsen anisotropy parameter ε of such layered structures can be simply related to the volumetric fraction of coal. If we know the P-wave and shear moduli of the coal and the host rock, then we can use a simple exact relation between the Thomsen anisotropy parameter ε and the volumetric fraction of the coal in the formation. This means that by measuring this parameter by seismic methods, one can directly estimate the resource quantities. To produce an accurate estimates of ε we need to use long offsets for the seismic methods. The strong impedance contrast between the layers in coal seam environments could cause significant seismic attenuation that could impede the anisotropy estimation from seismic data. However, only the high frequencies are expected to attenuate significantly, while the low frequencies that are relevant to the Backus averaging would not suffer from such scattering attenuation.

We illustrate applicability of the method using two examples from the Cooper Basin, South Australia.

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04EGC-03. DIFFERENTIAL WETTABILITY TO CO_2 FOR SUB-BITUMINOUS AND BITUMINOUS COALS: EFFECT ON CO_2 STORAGE AND MIGRATION IN COAL

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The objective of this study was to assess how differences in coal maceral composition and rank between sub-bituminous and medium–high volatile bituminous coals affect the surface interactions between CO_2 and coal in the presence of water.

Coal wettability is expressed through the magnitude of the contact angle of gas on coal surfaces. In this work we characterised wettability in terms of a maximum (Θ_{max}) and a minimum (Θ_{min}) value of contact angle at specific temperature and pressure conditions. The experimental hardware and data analyses methods, developed for this work, were based on a 'captive bubble' technique, whereby a gas bubble is captured beneath a coal sample in a pressurised water cell. As the water used in the experiment is distilled water the experimental method produces results analogous to a transient 'receding' contact angle measurement.

The two coal samples used for experiments were collected from the Illawarra Coal Measures of the Southern Coalfield of the Sydney Basin (high volatile bituminous), and from the Walloon Coal Measures of the Surat Basin (sub-bituminous). Purpose-designed discs were prepared from the coal samples for use in the contact angle system. A mosaic of images was compiled for each coal disc to identify the main organic matter components and assess surface heterogeneity. Maceral composition and vitrinite reflectance analyses were conducted specifically on the laminations with which CO_2 bubbles were in contact. The coals were studied for their surface interactions with CO_2 at gas–water pressures ranging from ~2 to 15 MPa, at a constant temperature of 35°C.

For both coals it can be observed that low gas–water pressures generally produce large contact angles between the gas–water interface and coal surface, whereas high gas pressures produce small contact angles. Thus, the gas wettability of the sub-bituminous and medium–high volatile bituminous coals studied is enhanced at higher pressures. In the case of the Walloon coal sample the maximum values of contact angle for the gas–water pressures between ~2 and 15 MPa are generally greater (156° at 2 MPa to 138° at 15.1 MPa) than for the Illawarra sample (143° at 2 MPa to 113° at 15.1 MPa). Similarly, the minimum values of contact angle for the Walloon coal are generally greater ranging from 110° at 2 MPa to 90° at 15.1 MPa, with Θ_{min} ranging from 90° at 2 MPa to 55° at 15.1 MPa for the Illawarra coal sample.

Overall the results show that for most gas–water pressures studied, the Walloon coal remains water-wet (Θ_{min} = >90°), and only becomes intermediate-wet (Θ_{min} = 90°) at gas–water pressures around 15 MPa, whereas the Illawarra coal becomes intermediate-wet (Θ_{min} = 90°) at gas–water pressures up to 4 MPa and gas-wet (Θ_{min} = <90°) at gas–water pressures >4 MPa. These preliminary findings have implications for the study of storage of CO_2 in that the high volatile bituminous coal which is preferentially CO_2-wet would allow the penetration of gas into the water-filled pore system and its adsorption onto the surfaces of the micropores, making it a more suitable CO_2 storage reservoir than the sub-bituminous coal.

04EGD – COAL SEAM GAS – INSIGHTS INTO A RAPIDLY EXPANDING RESOURCE AND INDUSTRY

04EGD-01. SENSITIVITY OF RESERVOIR PARAMETERS TO COAL TYPE AND RANK, EXAMPLES FROM PERMIAN AGE COAL, BOWEN BASIN, AUSTRALIA

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Coal seam gas (CSG) is economically important in Queensland, Australia and many coal seams contain methane and other gases that are used as a source of energy, domestically and internationally. Development and production efficiency of CSG is related to drilling and completion as well as the character of the coal itself. Gas molecules are stored in the coal matrix *via* adsorption within the micropores. Following a reduction in pressure, the molecules diffuse and flow through the matrix into a network of connected pores and/or fractures, where they are targeted for CSG extraction. The porosity, storage capacity and permeability of the coal seam are all influenced by the original plant matter (coal type) and the maturity of the coal (coal rank), with varying degrees. This study investigates the sensitivity of reservoir parameters, such as sorption capacity, porosity and permeability, to coal rank and type. Twenty five coal samples from nine mine sites extracting upper Permian age coal within the Bowen Basin were analysed to ascertain the sensitivity of reservoir parameters. Samples from each site were separated into three lithotypes – dull, banded and bright banded. Lithotype samples were further characterised by proximate and petrographic analysis of maceral, phyteral and mineral matter, by mercury and helium porosimetry, and by low pressure permeability analysis at 2 different block sizes (15 mm and 40 mm). The rank of the coal samples varied from 0.9 to 1.9% $R_{v,max}$. Dull coals were characterised by high percentage of inertinite contents (<40% m.m.f.) whereas bright-banded coals were characterised by high vitrinite (<75% vitrinite m.m.f.). Gas sorption capacities at a constant temperature increased with increasing rank, irrespective of coal type (within 1 standard deviation of both bright and dull coal average volume content). The outliers, within 2 s.d., were the coals analysed as heat affected. Dull coals ($R_{v,max}$ 0.9 to 1.9%, high inertinite content) had a median pore diameter of 50Å, whereas bright coals ($R_{v,max}$ 1.3 to 1.5%, high vitrinite content) had a median pore diameter of 46Å. A weak trend based on coal type was observed (within 2 s.d.) using mercury porosimetry. Low-pressure permeability at STP ranged from 0.1–75 mD for dull coals, whereas bright coals ranged from 0.3 to 260 mD. For a 15 mm cube, permeability was interpreted to be matrix permeability, showing an average ratio within dull coals of 1.1:1.0:0.6 ratio and bright coals showed an average ratio of 4:3:1 (face cleat: butt cleat: perpendicular to bedding). The 40 mm cubes showed were interpreted to be cleat permeability and showed and average ratio of 10:5:3.5 for dull coals and bright coals showed an average ratio of 3:2:1 (fc:bc:pb). From this, it was inferred that anisotropy between cleat and banding increased as vitrinite content increased, showing a strong coal type trend. The index that is created as a by-product of these analyses assists in future modelling or predictive analysis within similar Australian Permian aged coal seams and may be a useful tool when assessing new developments in different seams or coal measures.

04EGE – PETROLEUM RESERVOIR CHARACTERISATION AND MODELLING – TOWARDS BOOKING ACCURATE RESERVES

04EGE-01. NEXT GENERATION MODELLING OF RIFT BASINS AND CONTINENTAL MARGINS

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Sedimentary basins capture Earth's sea level, climate history, and the variation of the surface topography due to geodynamic, tectonic, and surface processes. They host a range of conventional and unconventional hydrocarbon resources of critical importance for the continued functioning of modern society. The key to moving exploration into deeper basins in less accessible regions is to understand the interactions between surface processes, tectonic processes and mantle convection. Indeed, continental interiors are severely affected by deep-mantle forces, including surface tilting and uplift/subsidence over pulsing mantle plumes, causing the creation or destruction of entire river systems and shallow seas. Hence, mantle flow, plate tectonics, and surface processes are linked through a complex web of thermal and mechanical feedback loops impossible to grasp through analogue modelling alone. If we are to model feedbacks between surface processes, lithospheric dynamics and mantle flow, we need to go beyond analogue and 2D numerical models to integrate all of the critical factors that play into basin development. An Australian-led consortium has recently started integrating these processes by coupling three modelling packages: *GPlates*, *Underworld* and *LECODE*. This enables simultaneous modelling of deep Earth and surface processes, spanning basin scales to individual sediment grains – the key to an integrated understanding of these factors. By tying basin models to geological and geophysical observations, potentially including basin stratigraphy, seismic, heat flow and thermochronology data, we will be able to link observed patterns of basin uplift and subsidence to either mantle dynamic, tectonic, or climate-driven processes. We have tested part of our workflow on a 3D model of a continental lithosphere in isostatic equilibrium on a static asthenosphere. The size of the model is 150 x 400 x 400 km with computational grid resolution of 2.34 x 2.34 x 2.34 km. Kinematic boundary conditions drive orthogonal extension with time-dependent velocity, with rheological, density and temperature properties appropriate for an average ~130 km thick lithosphere. We explore the parameter space *via* three alternative models. In the first run, no surface process is active. In the second run, surface processes are implemented in an analogue-like manner by filling low elevated regions standing below an imposed base level with sediments, while eroding higher regions above a threshold elevation. In the third experiment, surface processes are implemented in a self-consistent manner using *LECODE*. Only the third experiment is able to simulate the range of natural complexities seen in nature, including migration of depocentres, transition sedimentary sinks to sedimentary sources, and dynamic links between surface loading/unloading and faulting. This advance in basin modelling opens new opportunities for model-data assimilation, and uncertainty quantification, leading to a new generation of predictive 5D basin models (space, time and uncertainty). The future objective of our Basin GENESIS effort is to use this approach to understand the diversity of fundamental feedbacks between crustal deformation, mantle flow and sediment transport at the scale of sedimentary systems, and to transform this new body of knowledge into the first predictive exploration and targeting tool that genuinely integrates all aspects of basin genesis.

04EGE-02. COAL CONTRIBUTION TO OIL AND GAS ACCUMULATIONS IN THE BONAPARTE AND GIPPSLAND BASIN: NEW INSIGHTS FROM MOLECULAR AND BULK KINETIC DATA

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In the Bonaparte Basin, coals of the Middle Jurassic Plover Formation which were deposited in a fluvio-deltaic setting have excellent petroleum potential and HI values above 400 mg HC/g TOC, indicating their potential to efficiently expel liquid hydrocarbons. These coals show an enrichment in alkylphenols and aromatic hydrocarbons (benzene, toluene and xylene) relative to the n-alkanes/alkenes in their pyrolysates. These characteristics, combined with broad activation energy distribution (58 to 70 kcal/mol), suggest the occurrence of a lignocellulosic organic matter content and thus a pronounced terrigenous influence. The open system pyrolysis-gas chromatography (Py-GC) results reveal that they have the potential to generate two petroleum organofacies: gas-condensates and paraffinic–naphthenic–aromatic (PNA) oils with a high wax content. With the assumption of a constant geological heating rate of 3.3°C/Ma, the main phase of petroleum formation (at 70% transformation ratio) occurs over a broad temperature range of 160–180°C, indicating that bulk kinetic predictions are directly controlled by the molecular structure of the kerogens within these coals. Artificial maturation using closed pyrolysis at a heating rate of 0.7°C/min indicates that in the main oil window coals of the Plover Formation generate black oils with low gas:oil ratios (160 Sm^3/Sm^3), whereas at advanced levels of kerogen conversion (90%), light oils are produced. Oils on the Laminaria High, an area within the northern Bonaparte Basin, are interpreted to be expelled at a temperature range of 127−137°C. Thus these oils could not be derived from coals of the Plover Formation, as at these estimated thermal maturities the kerogen within these coals has not reached any significant conversion (less than 15% transformation). In contrast, kinetic model predictions show that the high wax PNA generating facies could produce some oils with low GORs, but in the Vulcan Sub-basin it is mainly gas and condensates that are derived from these coals.

In the Gippsland Basin, coals deposited within the delta plain facies throughout the Paleocene Halibut Subgroup have landplant-dominated organic matter with variable potential for both gas and liquid hydrocarbon generation. Based on the sample set used in this study, the Py-GC results indicate that these coals are heterogeneous, being capable of generating high wax PNA oils. Assuming a constant geological heating rate of 3.3°C/Ma, kinetic modelling predicts that the main phase of petroleum formation from coals of the Halibut Subgroup occurs at 178°C, indicating high kinetic stability. Where sampled, coals from the Halibut Subgroup have lower HI values than are required for efficient oil expulsion. This finding, coupled with their relatively low volume proportion with respect to shales, suggests that the coals may not have contributed significant volumes of hydrocarbons to the oil accumulations. However, gas can be generated and expelled from these coals by cracking of the retained hydrocarbons.

04EGE-03. FACIES ARCHITECTURE OF A DRYLAND RIVER CONVEX BAR, UMBUM CREEK, LAKE EYRE, CENTRAL AUSTRALIA

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Dryland rivers are complex depositional systems which are increasingly recognised as important petroleum reservoirs. Modern analogues that quantify facies architecture are essential data sets to aid in the development of reservoir models for comparable ancient subsurface deposits. The Umbum Creek is a sandy ephemeral river which drains into the western side of Lake Eyre, central Australia, and displays a complex morphology typical of arid-zone rivers. In its lower reaches the present day ephemeral fluvial system occupies a single relatively straight incised channel belt, with its tributaries eroding and incising into the adjacent gibber plains on the interfluves. Where the creek meets the playa shoreline, a substantial subaerial terminal splay complex has developed. Within the incised channel belt, two prominent convex bars, occurring about 5km upstream of the playa edge, have formed in response to a locally steeper fluvial gradient, where the fluvial profile is trying to equilibrate by meandering. Those 1x2 km large and approx. 5 m thick sedimentary features are overall characterised by a variety of fine- to coarse-grained facies, which are caused by fluctuations during flood events indicative for varying flow regime in dryland settings. The convex bars are constructed of a combination of lateral and downstream accreting bars, simple unit bars, chute channels with associated splays, vegetated shadow bars and deep scour pools. A chute channel, which is only activated during large-flood events, represents the lateral boundary of each bar towards the channel belt margin. The chute channel operates as an erosive channel system with fan morphology downstream, which initiates at the outside bend of the downstream prominent convex bar. Shadow bars dominate within the overflow where floodwaters incise into older fluvial fine-grain sediments. The northern interfluve locally supplies coarse-grained sediments to the lower reaches of the Umbum Creek and where the overflow terminates at the playa margin, muddy deposits intersperse with relict and aeolian sediments. Understanding the spatial occurrence and distribution of such convex bars within a dryland fluvial system in combination with a sound understanding of their facies architecture can provide new exploration strategies for petroleum reservoirs in similar setting.

INFRASTRUCTURE, SERVICE & COMMUNITY

04ISCA - GEOLOGICAL CHALLENGES ON MAJOR ENGINEERING /INFRASTRUCTURE PROJECTS

04ISCA-01. THE USE OF MULTIPLE HYPOTHESES AND GEOLOGICAL THINKING IN IDENTIFYING AND ADDRESSING GEOLOGICAL PROBLEMS ON ENGINEERING PROJECTS

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Charles Leggett noted in 1962 in his book "Geology and Engineering" that "the practice of civil engineering in the field is an art, requiring experience and sound judgement for the solution of every problem of ground conditions, no two of which are ever exactly alike".

Although this is still true today, engineering geology "the application of the science of geology to the art of civil engineering" (ibid) has moved on a long way since then, or has it?

I come across too many projects where a proper or well thought out pre-feasibility or even feasibility study has not been carried out, leading to major problems during design and/or construction which better planning and/or lateral thinking could have avoided or minimised.

Peter Fookes, particularly in his First Glossop Lecture in 1997 "Geology for Engineers: the Geological Model, Prediction and Performance" and his joint follow-up paper "Total Geological History: A Model Approach to the Anticipation, Observation and Understanding of Site Conditions", presented in 2000 at the International Conference on Geotechnical and Geological Engineering, elegantly presents the concept that the engineering geology of a site is a product of its geological history, including past and present climatic conditions and geomorphological processes. This includes:

- the genesis of the bedrock and any subsequent alteration by tectonic and other forces capable of folding, faulting or physically disturbing the bedrock;
- diagenesis, hydrothermal alteration, metamorphism and volcanism that can alter or modify the original rock or add to it; and
- subaerial weathering and other surface or near surface influences, including groundwater, fluvial, marine, eolian and glacial processes; erosion and deposition and the formation of superficial processes.

Understanding of these processes and their likely effect on engineering structures requires:

- a sound, broad-based geological knowledge, including some geophysics, geochemistry, rock mechanics and soil mechanics;
- a good understanding of geomorphological (physical geological) processes and process rates;
- a working knowledge of civil, structural, mining and construction engineering, and
- some familiarity with contractual law as applied to engineering.

The first two bodies of knowledge are used to develop a three-dimensional geological model of the ground on or in which the engineering project is to be constructed. To improve on the accuracy of this model requires investigation, which in my experience, if based on the concept of Multiple Hypothesis, is likely to be more economical in cost and time and is likely to lead to a more accurate ground model that is relevant to the project.

The Multiple Hypothesis (or scientific) approach requires the development of all possible ground models that could fit the known data at any particular point in time of the investigation. The investigation then should be devised to cost effectively test these hypotheses, accepting or rejecting them and probably devising new hypothesis, until only, hopefully, one remains standing, The Geological Model.

This paper develops this old but often forgotten concept, looks at the current range of investigation tools at our disposal, most traditional, some more-novel and is illustrated by many case history vignettes from different geological and geomorphological settings.

04ISCB – ROCK ART IN AUSTRALIA

04ISCB-01. ROCK SURFACE PROCESSES AND MINERALISED COATINGS ASSOCIATED WITH ROCK ART IN NORTHERN AUSTRALIA

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Northern Australia contains some of the world's largest rock art assemblages displaying unparalleled stylistic diversity. A succession of markedly different rock art themes and styles have already been placed within robust relative dating schema. Relatively little is known about the absolute ages of the earlier rock art, however. There is widespread evidence for human occupation from after 50 000 years ago and it has been argued that art would be part of the colonising repertoire and used to mark emergent territories and group identity. Critical questions now concern the age and condition of the earliest visible art and how different styles might reflect human responses to environmental, climatic and social changes during the Quaternary.

Rock paintings are commonly preserved on widespread Proterozoic orthoquartzites, such as the King Leopold Sandstone in the Kimberley and the Kombolgie Formation in Arnhem Land. Locally, rock art is associated with caves, ravines or vertical rock faces sheltered by shallow overhangs, and characterised by local relief of up to tens of metres. Surfaces that form the substrate for rock paintings are typically formed by spallation of large rock flakes or detachment of slabs from overhanging rock ceilings. Relatively little is yet understood about these local geomorphic processes, but it is clear that new surfaces have continued to form throughout the period over which art has been produced. Understanding the rates and timing of surface formation could potentially indicate an upper limit on the age of the art.

Complex mineralised crusts and surface coatings are found adhering to the rock faces, frequently surrounding and overlying rock art, and potentially providing a minimum age for the art. In the tropical monsoonal climate of northern Australia these coatings are ccommonly found between between areas of rainwater runoff and more sheltered areas where paintings are preserved. The coatings are often layered vertically and vary from about 1–10 mm in thickness. They may be banded laterally over 10–30 cm suggesting migration of constituent materials across the surface. The coatings may also wholly or partly obscure underlying paintings, and can bleach or otherwise degrade pigments in the art.

Several studies have identified some of the more common minerals present within such crusts, but they often include highly complex assemblages of mineral and organic materials and relatively little is yet understood about their origin and formation. Common minerals present include sulfates, oxalates, phosphates, nitrates, and amorphous silica, amongst others. A variety of organic constituents have also been identified suggesting microbial activity and possible materials of plant and animal origin. Uranium is commonly present, occasionally at high concentrations, although the nature of its occurrence is not yet clear. The potential of some of these materials for U-series and AMS radiocarbon dating is currently being investigated.

Understanding the processes responsible for the development of these rock surfaces and their mineralised coatings can provide important insights into the geomorphic process operating and also provide age brackets for the rock art. The lessons learned can contribute to high quality conservation and management outcomes for these significant cultural landscapes.

04ISCC – DEVELOPING GEOLOGICAL MODELS FOR ENGINEERING PROJECTS

04ISCC-01. DEVELOPING GEOLOGICAL MODELS FOR ENGINEERING PROJECTS

Tim Sullivan

Pells Sullivan Meynink and UNSW

Geology and mining have always been a part of the industry and living landscape of Australia. One of the only things that have changed is the scale, becoming much larger. More recently urban and regional sprawl have increased and this will continue. At the same time the civil infrastructure to service these local regional and national demands has become larger, longer and more technically complex. The demand for maximisation of available resources only adds to the challenges, because almost invariably the more technically challenging and difficult areas for exploitation are those remaining. In many instances the design and inflexibility of natural, civil and private infrastructure, do not mesh well with large-scale mining, which is based in large part on rapid and major changes to the environment. This lecture presents a series of case studies that illustrate the possible adverse outcomes and the breadth and range of issues that need to be addressed. The essential role of geology is highlighted in explaining and understanding the risks. The importance of geology as a fundamental input to local and regional planning is emphasised.

04ISCD – ROCK ART IN AUSTRALIA

04ISCD-01. KIMBERLEY ROCK ART PAINTS – ARCHEOLOGICAL IMPLICATIONS OF GEOCHEMISTRY AND MINERALOGY

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Landscape is innately a part of Aboriginal Australian culture. This is expressed in the socialisation of geological surfaces such as rock shelters, caves and boulders *via* the production, and maintenance, of rock art. The chemical and mineralogical signatures of archeological pigments not only reflect their diagenesis, but also their cultural and post depositional contexts. Every choice made by the artist(s) in this process leaves a structured archeological trace. Accessing these surviving material traces is complex, requiring innovative methods in order to minimise impact to this priceless cultural heritage. As part of a recent multi-faceted archeological investigation we have characterised the geochemistry and mineralogy of Kimberley rock art paints in remote northwest Western Australia. Using a combination of non-invasive and minimally destructive analytics including Portable X-Ray Fluorescence spectrometry, conventional and Synchrotron X-Ray Diffraction, Micro Computed Tomography and Scanning Electron Microscopy, we have collected elemental, structural and morphological data regarding the procurement, processing, production and post-depositional environment of rock art. Our analyses show that the geological history of Kimberley rock art is even more complex than previously indicated. Here we present geoarcheological evidence for change and continuity of cultural traditions through time in *Wanjina* and *Gwion* rock art.

04ISCD-02. PETROGLYPH MONITORING ON THE BURRUP PENINSULA – PART 1

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The Burrup Peninsula is located 1300 km north of Perth near Karratha in the Pilbara region of Western Australia. The peninsula is of unique cultural and archeological significance as it contains Australia’s largest and most important collection of indigenous petroglyphs. Petroglyphs are rock engravings created by removing part of a rock surface *via* picking, carving and abrading. Alongside the petroglyphs, the Burrup Peninsula has several large industrial complexes including iron ore processing, liquefied natural gas production, salt and fertiliser production. It is also one of Australia’s largest ports. As some of the petroglyphs adjoin these 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 were likely to affect the petroglyphs.

In 2003 the current study was commissioned by the BRAMMC to monitor colour change of the petroglyphs over time. The study was based on the monitoring of seven sites. Two control sites were located on the northern Burrup area, with little exposure to industrial pollutants, and five test sites were located further south on the lower Burrup Peninsula, closer to the industrial areas. For the last 10 years (2004 to 2013) petroglyphs at these seven specially selected sites (chosen under the guidance of indigenous elders) were monitored using spectrophotometric techniques to obtain information relating to colour changes.

Three spots on each engraving and three spots on each background rock surface were measured *in-situ* using a portable spectrophotometer, with the colour of the rock surfaces expressed as a point in three-dimensional L*a*b* colour space (L* – degree of lightness, a* – degree of red/green, b* – degree of yellow/blue), identifying a tristimulus value (L*a*b*) for each sample point, which was then used to calculate the colour difference (ΔE) between engravings and background. The colour difference was evaluated through measuring the tristimulus values of points over time, and calculating ΔE to evaluate the colour difference with time. The colour difference between an engraving and a rock surface was evaluated to determine whether ΔE was decreasing, which would be indicative of fading and/or degradation of the petroglyph. The 2004 spectral study was used as the baseline dataset to monitor potential variation during the last 10 years.

The comparison of the colour measurements collected and processed for both the Northern (control sites) and Southern test sites has shown no consistent trend in an increasing or decreasing direction. For the last 10 years no measurable colour difference change was detected, indicating that the petroglyphs in the vicinity of the industrial activity on the Burrup Peninsula have not, at this stage, been adversely affected.

04ISCE – ROCK ART IN AUSTRALIA

04ISCE-01. THE WEATHERING HISTORY OF THE PETROGLYPHS OF THE MURUJUGA (BURRUP) PENINSULA IN WESTERN AUSTRALIA

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The Yaburara people called the Burrup Island Murujuga meaning "hip-bone sticking out". The man-made Burrup Peninsula is around 30 km long and 6 km wide and is located 1300 km from Perth, Western Australia. The Murujuga Peninsula is home to one of the most important collection of indigenous petroglyphs in the world. The petroglyphs have been carved in two rock types, namely granophyre and gabbro, dated at around 2.7 billion years. These rocks have been subjected to weathering and display a core of fresh rock surrounded by a cm-thick "leached" zone in turn covered by a mm-thick, iron oxide rich skin. The petroglyphs were engraved in the rocks by removing the top skin to expose the leached zone providing a strong contrast between the "engraving" and the "background".

Alongside the petroglyphs, the Murujuga Peninsula has several large industrial complexes including iron ore, liquefied natural gas production, salt and fertiliser production near one of Australia's largest ports at Dampier. There has been very public concern expressed that the petroglyphs could be damaged by airborne emissions from the various industries and 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 were likely to affect the petroglyphs. The BRAMMC commissioned a number of studies to monitor the petroglyphs including 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 in the northern Murujuga area and the other five located further south on the lower Murujuga Peninsula, closer to the industrial areas. For the past 11 years (2004 to 2014), petroglyphs at seven specially selected sites (chosen under the guidance of indigenous elders) in the Burrup Peninsula were monitored using colour and reflectance spectroscopy measurements. However, these studies only deal with surface measurements and although they are perfectly adequate for monitoring, a more detailed study of the weathering of these rocks has been undertaken.

Common minerals of the fresh rocks include chlorite, epidote, K-feldspar and plagioclase, muscovite, quartz and magnetite, with the addition of amphiboles and clinopyroxene in the gabbro. In the leached zone, weathering of the primary minerals has lead to the formation of secondary minerals such as goethite, hematite, kaolinite and secondary apatite formed from bird droppings. The skin covering the rocks are essentially made of hematite and kaolinite.

This study provides an interesting insight on the interaction between rock, man and bird.

04ISCF – GEOSCIENCE EDUCATION: THE EVOLVING ROLE OF GEOSCIENCE OUTREACH AND EDUCATION

04ISCF-01. THE MARS LAB – A CONTEXT FOR EARTH SCIENCES EDUCATION

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The 30-year decline in undertaking senior science includes a decline in students taking up Earth sciences. Located in Sydney's Powerhouse Museum, the Mars Lab is a 140 square metre scientifically accurate replica of the Martian surface on which three experimental Mars Rovers are used for research as well as a national high school education project. Students are engaged as teams to use one of a selection of educational materials and digital tools to plan a scientific mission to investigate the rocks and geological features in the Mars Yard in an effort to find evidence that Mars may have once been a habitable environment. They then connect to the Mars Lab, *via* the web from their classroom (on laptops, PCs or tablets) to carry out their mission by controlling one of the three rovers across the Mars Yard to capture photographic images and instrument data for post-mission analysis. This paper presents the development, implementation across multiple schools nationally and the results and challenges of the use of these new digital tools and educational materials including one known as, Project Mars, which employs Project Based Learning.

04ISCF-02. LANDSCAPES AROUND CANBERRA – A FOCUS FOR GEOSCIENCE EDUCATION

<u>Douglas Finlayson</u>

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Canberra is often described as "a city built in the landscape". The design for Australia's capital city was won by Walter Burley Griffin and his wife Marion Griffin, and when describing the city landscapes to teachers it is often a surprise to them to learn that the landscapes are shaped by geological and weathering processes. The sweeping views of the Brindabella Mountain skyline from the summit of Mount Ainslie, the tower on Black Mountain and the iconic flagpole on top of the Australian Parliament building are all essentially images that reflect the significant geology of the region.

The introduction of the Earth sciences into the Australia-wide school/college curriculum has focussed attention on preparing material that the teaching professionals can apply in the classroom. Around Canberra, material for school and college teachers can be easily sourced locally. There is also a wealth of material that can be sourced regionally, nationally and internationally. However, geheritage sites in the local areas that students recognise make the learning experience much more relevant.

The GSA (ACT Division) 2008 publication *"A Geological Guide to the Canberra Region and Namadgi National Park"* provides a lay-person's description of regional geology. The publication has led to requests for teacher workshops and student excursions. A regional collection of rock samples resulted in the *"Birrigai Rock Cycle Pathway"* being constructed at the ACT Government Outdoor Education Centre near Tidbinbilla. A library of forty "*Geoheritage Sites in the Canberra Region"* is now available on the web for use on school excursions. Some sites are within local communities; others are all-day excursions to places like Captains Flat, Wee Jasper and Lake George.

Major geological heritage sites like the State Circle Unconformity near Parliament House are offered for use nationally as one of the case studies for the Teacher Earth Science Education Program (TESEP) as part of the Earth and Environmental Studies Text Book for the national curriculum. The Earth Science Teachers Association in WA has published an outstanding 520 page resource for teachers everywhere.

Internationally, the UK Earth Science Teachers Association and Keele University created "Earth Learning Ideas" in 2008. The program now offers over 170 classroom applications relevant to the Australian national curriculum. It makes available Earth science classroom ideas, at minimal cost and resources, for teachers of Earth science throughout the school-level science curriculum. Many applications are available on request from the GSA (ACT Division) as PDF files.

The use of local Earth science teaching material brings home to educators and students that there is a teaching resource on their doorstep. There is no need to think of Earth science as something that "happens" in distant places and in far-off lands. Earthquakes and landscape changes are happening all the time around Canberra. The local resources can be used to gain a better understanding of geological processes and how Australians derive much of their prosperity from the continent's geological legacy.

04ISCF-03. IMPROVING STUDENT ENGAGEMENT IN THE EARTH SCIENCES USING MINECRAFT

<u>Steven McClean</u>

Pittwater House Schools

One of the great problems in getting high school Science students to perform worthwhile Earth Science research is that of engaging the students. All too often, high school Science students consider the study of the Earth Sciences as being boring and of little interest usually because their only experience of the Earth Sciences has been a 'rock on a desk'. One method that has shown some success in increasing the level of engagement in the students has been in the use of the online gaming platform, Minecraft. Minecraft allows for the creation of different biomes (ecological regions with specific characteristics) that can be tailored to suit the type of Earth Science research that the teacher would like the students to undertake. With a little consultation, other subject areas such as Mathematics and English can become involved, leading to significant cross-curricular advantages.

04ISCG– GEOSCIENCE EDUCATION: THE EVOLVING ROLE OF GEOSCIENCE OUTREACH AND EDUCATION

04ISCG-01. THE INAUGURAL AUSTRALIAN EARTH AND ENVIRONMENTAL SCIENCE OLYMPIAD: AN AUSTRALIAN SCIENCE INNOVATIONS INITIATIVE

Greg McNamara, Lillian Lesueur & Bronte Nicholls

Australian Science Innovations

An Australia-wide search to find talented secondary students to represent Australia at the 2015 International Earth Science Olympiads in Russia is underway through the inaugural Australian Earth and Environmental Science Olympiad Competition.

Joining the well-established Olympiad competitions in biology, chemistry and physics, the Australian Earth and Environmental Science Olympiad will select and train talented secondary students in preparation to compete at the International Earth Science Olympiads.

Year 10 and 11 students are invited to test their knowledge of geology, geophysics, meteorology, oceanography, astronomy, and environmental sciences by first sitting a national exam. Those who perform well in the exam will be invited to attend an intensive summer school where their theory and practical skills will be developed further. Finally, a four-member team will be selected to compete at the International Earth Science Olympiad in Russia.

The international competition consists of theory and practical exams plus the International Team Field Investigation where teams of students from different countries work together to solve real life environmental problems.

In this presentation we will outline the basis of Australian Science Innovation's adoption of an Australian Earth and Environmental Science Olympiad program, the value of the program to gifted and talented students across all disciplines and highlight the successful involvement of Australian students in the International Earth Science Olympiad to date.

This Inspiring Australia initiative is supported by the Australian Government through the Department of Industry partnership with Australian Science Innovations. As the Peak Council of geoscientists in Australia, the Australian Geoscience Council is proud to also support the inaugural Australian Earth and Environmental Science Olympiad.

Teachers must register students in the Australian Science Olympiad Competition before 16 July 2014.

04ISCG-02. IMMERSIVE DIGITAL VISUALISATION OF GEOLOGICAL EXPOSURES – A VISION FOR A DIGITAL ATLAS OF AUSTRALIAN GEOLOGY

Michael Roach

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Australia's geology is diverse, with seminal localities widely dispersed across the continent. It is very difficult, within the logistic, safety and budgetary constraints of secondary and tertiary education programs, to directly expose Earth science students to a fully comprehensive range of field experiences. Fortunately new digital methods now enable students to experience remote localities in intuitive, interactive, immersive digital environments. This presentation will provide an overview of the techniques used to create these new resources, show some examples of interactive digital models, and present a vision for a national collaborative project to create a digital 'atlas' of Australian geology.

Recent major advances in the fields of digital imaging, photogrammetry, and Unmanned Aerial Vehicles (UAVs), now allow rapid and very inexpensive creation of photo-realistic three-dimensional digital models, full spherical panoramas and 'deep zoom' imagery of geological outcrops. Photo-realistic three-dimensional models derived from terrestrial or UAV photography can be viewed from any orientation and can be annotated to highlight important geological features. Full spherical panoramas can be linked to provide interactive 'walk through' geological tours of large geological exposures. 'Deep zoom' or gigapixel imagery captures the large-scale and small-scale features of an outcrop in a single image structure that allows seamless multi-scale viewing. These new resources provide much more informative, engaging and immersive virtual experiences for students than conventional static photography.

A library of new public-domain digital geological resources is currently being developed at The University of Tasmania with the initial focus on field sites that illustrate structural geology and rock deformation. This collection of resources will hopefully provide a prototype for a digital 'atlas' of Australian geology that will ultimately store images and 3D models of important and instructive geological exposures from across the continent, together with associated metadata and explanatory notes. Data collection for an 'atlas' covering the entire continent cannot be undertaken solely by any one organisation or institution, it really needs to be undertaken as a collaborative initiative involving the entire Australian Earth science community. Protocols have been developed to help guide digital data acquisition and It is proposed that a digital data portal should be established through which any geoscientist can submit appropriate imagery and associated metadata. These images would be processed to generate high-resolution 3D models and other digital resources that would then be made freely available *via* a web interface. A digital 'atlas' of Australian geology has obvious applications for tertiary and secondary Earth science education but also has significant potential as an outreach mechanism to highlight the diverse and spectacular nature of Australia's geology to the broader community.

04ISCG-03. GEOSCIENCE EDUCATION FOR A CHANGING WORLD: THE ESWA EXAMPLE

Joanne Watkins, Julia Ferguson & Jim Ross

Earth Science Western Australia, Perth, Australia

Earth Science Western Australia (ESWA) was conceived in 2003 out of widespread concern about very low numbers of geology students in the State's senior secondary schools. The average of only 40 students in four schools was inconsistent with the strategic needs of a minerals and energy-rich state.

Development of a new senior school curriculum in WA in 2004–5 included the introduction of Earth and Environmental Science (EES) as a senior school science subject from 2007. However, schools wishing to teach EES would not receive the additional resources essential to effective teaching of its geoscience component in the classroom and field. Furthermore, few teachers would have the requisite geoscience skills and experience. External support would be needed from 2006 onwards and providing this support became the focus of ESWA.

The appeal of the new course, plus ESWA's comprehensive support, has resulted in a sevenfold increase in schools offering EES and a twentyfold increase in student enrolments. In 2007 ESWA began extending its support to teachers and students in lower secondary and primary schools, by providing resources and professional development into the Earth and Beyond Science strand.

ESWA's experience in WA was important in the successful national campaign to have EES included as the fourth senior science subject in the new Australian Curriculum. As a result, Earth Science is also being taught nationally from K–10 as part of the Earth and Space Science subject.

This outcome provides the Australian geoscience community with an unprecedented national scale opportunity, similar to that recognised by ESWA in 2005. It is an opportunity to embed Earth Science into our education system, to thereby increase community awareness, and to demonstrate that EES is an exceptional contextual vehicle for teaching other sciences. To optimise this opportunity a more concerted national effort is required from the Australian geoscience community, with the professional organisations leading the way.

ESWA has operated for more than 8 years through the generous support and engagement of its many donors and the enthusiasm of its Board and Executive. Its successful record reflects a practical focus: supporting the needs of teachers and students; resources keyed to the curriculum; strong field support; strategies based on good educational research; implementation by well qualified staff; wide ranging collaboration (including TESEP); and appropriate evaluation of the outcomes. With time it is evident that ESWA has also influenced tertiary geoscience enrolments in WA. Since 2012 ESWA has been developing resources keyed to the Australian Curriculum for years 7, 8 and 9, under the Woodside Australian Science Project, including nationally available digital resources. (http://www.earthsciencewa.com.au/)

ESWA also provides cross-curricular hands-on resources and activities that incorporate Earth science-based learning experiences into other sciences. Recent STEM-based research in WA indicates the relevance of the ESWA model to addressing low levels of participation in the other senior sciences.

We at ESWA, view this conference as a timely opportunity to freely share our strategies, statistics, materials and enthusiasm with those with similar concerns in other states.

04ISCG-04. PETROGLYPH MONITORING ON THE BURRUP PENINSULA – PART 2

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The petroglyphs of the Burrup Peninsula are recognised as being amongst the most numerous and ancient in the world. Over recent decades there has been concern expressed that the petroglyphs could be affected by airborne emissions from local industry and there is keen interest in evaluating petroglyph surfaces in a non-subjective and repeatable manner.

This study reports on the multivariate analysis of systematic *in-situ* spectral reflectance measurements taken annually over eight years. The data were examined in terms of their spectral relationships; similarity and differences with respect to their location on the image (engraving or background) the site of the measurement and the year.

Multivariate statistical analyses revealed that the background and engraved parts of petroglyph images are generally mineralogically different, but are not exclusively so. Subtle but distinct differences exist between different rock surface sites, however year-to-year differences were not observed. The use of data reduction techniques such as Principal Components Analysis has proven to be extremely effective for examining and visualising large temporal and spatially distinct data sets as collected in this study.

RESOURCES

04REA – GEOMICROBIOLOGY, THE NEXUS BETWEEN GEOENGINEERING AND BIOTECHNOLOGY

04REa-01. FROM LITTLE THINGS BIG THINGS GROW – WHAT ABOUT GOLD NUGGETS?

Frank Reith[1,2], Jeremiah Shuster[3], Carla M Zammit[3] & Gordon Southam[3]

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The biosphere catalyses a variety of biogeochemical redox reactions that result in the transformation of Au. In particular, the reduction/oxidation of S-compounds appears to drive Au cycling in many environments. Weathering of electrum produces ‘bacteriomorphic’ Au, a controversial form of ‘biogenic’ Au forming as a result of dissolution and accretion processes. Weathering of Au-bearing metal sulfides produces chemically mobile Au(I)–thiosulfate-, and in saline environments, Au(III)–hydroxo-chloride complexes. Conversely, microbial destabilisation of these soluble Au(I/III)-complexes is coupled to the formation of secondary Au, *i.e.*, Au biomineralisation, and therefore completes the cycling of Au in near-surface environments.

However, the biogeochemical transformations of Au do not stop here. Already, Freise (1931) highlighted the importance of biodegradation of plant materials for the formation of macroscopic aggregates of secondary Au. Using a combination of laboratory and field studies, we have demonstrated that microbial Fe- and S-cycling directly and indirectly contribute to the destabilisation of Au(I/III)-complexes and the subsequent reduction to metallic secondary Au. Synchrotron-based spectroscopy analyses (µXRF, µXANES and µEXAFS) allowed us to map the distribution and speciation of Au within individual *Cupriavidus metallidurans* cells. This demonstrated the importance of organic S-compounds for the destabilisation/reduction of Au(I/III)-complexes. Secondary Au begins as colloidal nano-particles that aggregate into micro-crystalline octahedral Au crystals. The continuum of dissolution and re-precipitation then resulted in the formation of laboratory ‘grown’ Au grains (1–3 mm in diameter), which were morphologically and compositionally similar to natural Au grains. These systems represent an increase in size of up to seven orders of magnitude compared to the ‘original’ colloidal material. A Au nugget (15 mm in diameter) collected from an eluvial placer deposit near Alexandra (New Zealand) contained well-rounded quartz grains embedded in a matrix of secondary Au. This suggests that large (>3 mm)Au nuggets, previously believed to be the result of detrital processes, can form *via* accretion in surface environments.

These results are particularly interesting for Au processing and metallurgy, because large quantities of Au (in some case >20 wt%) are lost. This costs companies money and shortens the life of mines. However, current advances in our understanding of biogeochemical Au grain formation suggest that sustainable Au processing is possible through low-cost biogeochemical approaches that optimise Au recovery. In order to test this, we have established an experimental bio-processing facility at the Prophet Gold Mine, Kilkivan, Queensland. In the process ultrafine Au will be bio-transformed to granular Au, and the granular Au can then be recovered conventional processing facility. If successful, the method will provide a cost-effective and environmentally sustainable bio-processing solution for the recovery of fine-grained gold from low-grade ores and tailings materials.

Reference

Freise F W 1931. The transportation of gold by organic underground solutions. *Economic Geology* **26**, 421–431.

04REa-02. CHARACTERISATION OF THE MICROBIAL COMMUNITIES IN TWO BOWEN BASIN COAL MINES, QUEENSLAND, AUSTRALIA

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In the future, biogenic methane production from abandoned coal mines in the Bowen Basin may become a new, alternative source of natural gas in Queensland. To determine if this is feasible, two Bowen Basin mines were sampled to investigate the microbial communities involved in consumption of bituminous coal and methane production. The use of 16S rRNA gene amplicon sequencing and microbial culturing showed the presence of both aerobic and anaerobic communities in different areas of the mines. In general, aerobic waters had a higher cell density and greater biomass than anaerobic waters, including one instance where a millimetre thick biofilm was growing on the coal mine wall. These aerobic waters contained many species that were closely related to aerobic methylotrophic bacteria. However, methanogenic archaea were also observed and methane production was detected in anaerobic cultures grown on coal in the laboratory. This suggests that while methanotrophy exists in active mines, a methane-producing community could quickly colonise an abandoned mine once it became anaerobic after closing.

This hypothesis was confirmed by the presence of relatively simple methanogenic community in the collapsed goaf of a mine located in the Goonyella Middle coal seam. The two most common bacteria, composing approximately 65% of the microbial community, had the greatest similarity to *Acinetobacter* spp. and *Dechloromonas* spp. Members of the *Acinetobacter* and *Dechloromonas* genera are common environmental microorganisms and some species that are known hydrocarbon degraders. The third most common species in the water was a methanogen, which had 16S rRNA gene sequence divergent from described methanogens species. In the laboratory, this microbial community grew well in an anaerobic medium where bituminous coal was the sole source of organic carbon. The dominant coal-consuming bacterium in the cultures was observed to have a strong attachment to coal particles, despite the absence of coal particles in the pumped waters. Evidence of biogenic methane production was also observed in the German Creek coal seam mine. Methane from a degassing coal seam sampled in April 2013 had a $\delta^{13}C$ value between –71 and –69‰ and a δD value between –221 and –235‰, which falls within the biogenic hydrogen-reduction field on a Whiticar plot. However, to date only acetoclastic or methylotrophic and not hydrogen-reduction methanogenesis has been observed in enrichment cultures from the tested mine waters. Despite the relatively high rank of Bowen Basin coal, microbial communities collected from mines show potential to produce methane from waste coal, provided the mine site conditions are properly managed.

04REB – GEOMICROBIOLOGY, THE NEXUS BETWEEN GEOENGINEERING AND BIOTECHNOLOGY

04REb-01. BIODEGRADATION OF THIOCYANATE BY BURKHOLDERIA AT NEUTRAL PH

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Thiocyanate (SCN^-) is a common contaminant in effluent from gold mining and it is highly toxic to aquatic organisms and humans (Boening & Chew 1999; Gould *et al.* 2012). Thiocyanate contamination limits the amount of water available for industrial use, and poses a significant threat to living organisms in the surrounding environment. There is therefore an urgent need to treat this contamination in the wastewater so that it can be safely re-used or discharged (e.g., into wetlands). Most gold processing plants currently generate large quantities of SCN^- contamination in the effluent from ore processing. These companies must contain SCN^- within tailings storage facilities to prevent surface or groundwater contamination. This practice is costly and poses a great risk if mine tailings failure occurs. Biological treatment has been proven as the most cost effective and environmentally friendly strategy that can convert SCN^{-} into nontoxic compounds (Gould *et al.* 2012). However, little research has been conducted with respect to the potential for *in-situ* bioremediation.

A new bacterial strain with the capacity to degrade SCN^{-} has been recently isolated from contaminated soils at a gold mine tailings facility. The isolated bacterium was identified as a novel strain of *Burkholderia phytofirmans* (ST01hv) using 16S rRNA gene sequencing. The isolate oxidised sulfur in SCN^{-} (as the sole nitrogen source) and used acetate as the sole carbon source to produce sulfate. In addition, the novel strain appears to have the capacity to assimilate sulfate. The isolation of ST01hv represents an opportunity for a new bioremediation technique using a native soil bacterium to clean up thiocyanate contamination in wastewaters from Australian gold mines.

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04REC – GEOLOGICAL MAPPING: ITS POWER AND ITS FUTURE

04REC-01. THE DIGITAL ERA IN GEOLOGY: HOW TO MAKE THE MOST OF IT – FROM FIELD WORK TO DATABASES, TO FINDING NEW MINERAL DEPOSITS

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The two great historical leaps in technology: the *ca* 12 000 BC Agricultural Revolution and *ca* 1800 AD Industrial Revolution, resulted in huge global gains in efficiency and productivity. The Digital Revolution, the change from analogue to digital technology (also termed the Information Age), is in its infancy yet is considered the third greatest technological leap in history. The question is, how can we best harness the benefits in geology?

Geology is a spatial science that lends itself readily to the digitisation of observations and measurements, yet we have only just begun to build our information systems, let alone apply this data to applications such as dynamic plate reconstructions or predicting the location of undiscovered mineral deposits.

From trial and error experience mainly gained in geological surveys, we provide a practical guide to making the most from digital geology, and suggest pathways for the future. The process is here divided into the following stages: acquisition, storage, delivery and value adding. Examples include:

Acquisition – during field work, digital mapping provides greater spatial accuracy but computer technology is still causing issues. Laboratory measurements are more readily captured but data overload is an issue for some techniques.

Storage – for databases, single point of truth and common look-ups are key. All structured data stored must be relevant to end-users, and quality-in equals quality-out.

Delivery – online data delivery is now standard. Best practice involves daily replication from production database to delivery site. The key to a good delivery service is in the ease of discovery.

Value adding– applying digital data to solve geological problems requires best-available data from a single point of truth database. The flexibility of software to handle frequent data updates and re-run data inversions and forward modelling for complex 3D/4D models, will become a standard process.

04REC-02. THE CONTRIBUTION OF "MANUAL" AND "DIGITAL" GEOLOGICAL MAPPING STRATEGIES IN MINE-SCALE STRUCTURAL ANALYSIS: AN EXAMPLE FROM HILL END, NSW

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It is useful to review the steps taken during mine structural mapping programmes and to evaluate the outcomes with respect to the techniques and approaches applied. Which steps are most suited to a “manual” or “digital” approach and how can both approaches combine effectively?

Recent mining allowed underground access to un-mined mineralised vein systems for the first time in +100 years. A good body of work exists on the geology of the slate-belt hosted Hill End goldfield but, until recently, no studies could explain the sporadic and localised nature of the high-grade gold mineralisation. In particular, no structural work had been completed during active mining until the present study. Critically, developing and mining along any of up to +10 regularly spaced bedding parallel veins is no guarantee of profitability as zones containing economic grades are difficult to locate.

The initial evaluation stage consisted of a trial structural analysis using a combination of “manual” underground wall and roof mapping strategies in pre-existing drives together with drill core analysis. This was successful in developing an initial structural history for the mine but only highlighted the along-strike and vertical complexity of gold-bearing bedding parallel quartz veins. A number of potential factors such as: lithological variation, parasitic folding, boudinage, thrusting and late-stage faulting were highlighted as factors that could terminate zones of mineable gold grade but there were no clear candidates for the control of high-grade shoots.

Level access was established into the Reward Mine area at Hill End and production started. “Manual” structural analysis and mapping continued in these new areas to clarify and refine the relative chronology of deformation and vein forming events. Significantly, problems with vein correlations between levels that affected stope-design lead to the identification of major faults that were subsequently interpreted as the main control on ore-shoot development. At this stage “digital” data became an important interpretive tool. Gold-grade data collected from face advances every 1 m in rises and from every 2 m in levels could be compared with a range of structural data sets developed in the initial evaluation and subsequent clarification stages of the project. Only at this stage was it possible to isolate and map structures that correlated with the detailed “digital” gold grade data. The intersection between a late, steeply west-dipping reverse fault zone with a major east-dipping bedding parallel laminated quartz vein was found to form a moderate southerly plunging high grade gold shoot contained within the fractured vein. At this point, when “manual” and “digital” mapping strategies have been evaluated and tested, a fully “digital” approach to mapping and data collection could be attempted.

04REC-03. TOWARDS AUTOMATIC GEOLOGICAL MAP LEGENDS: GSWA'S EXPLANATORY NOTES REPORTING SYSTEM

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A geological map legend is an essential part of illustrating the age, lithology, stratigraphy and structural relationships of rock units in a given area. Geological maps, both digital and hardcopy, increasingly rely on database extractions for the correct positioning of rock types observed in the field, the plotting of structural symbols, and the application of colour design to distinguish different units. In contrast, composing map legends is still a largely ‘manual’ drafting process based on the author’s current understanding of the regional geology.

GSWA’s Explanatory Notes System (ENS) and its reporting functions incorporate business rules that facilitate the sorting of rock units in a chronostratigraphic and spatial sequence, and thus assist geologists, cartographers, and editors in the generation and assessment of geological map legends. The sorting of geological units in ENS is based on 5 broad components:

Lithostratigraphic units are linked in parent–child relationships that allow their stratigraphic sorting from geologically youngest to oldest units within a set of relational database tables. This creates discrete stratigraphic ‘trees’, each representing a separate stratigraphic succession with the highest ranking unit at the ‘top of the list’ (TOL in ENS). So, for example, the Bangemall Supergroup is the TOL unit for the stratigraphic tree that includes the Edmund, Collier, Scorpion, Salvation and Uaroo Groups and their component sub-groups, formations, and members.

Overview Reports for any randomly selected lithostratigraphic unit enforce strict logic rules to extract a geologically sorted list from the relational database tables above. The extracted list reflects the order in which the selected unit and associated children should appear on a map legend, with youngest at the top and oldest at the bottom.

In a separate ENS module, TOL lithostratigraphic units and their associated discrete stratigraphic trees can be sorted relative to each other under a single tectonic unit.

Tectonic units are also linked to each other in parent–child relationships through a set of relational database tables, but with the fundamental difference that only a single tree exists for the whole of Western Australia, i.e. all tectonic units are geologically sorted within a single tectonic 'sequence' for the State. A Tectonic Overview Report can be generated for any level within this sequence – for the STATE, this report links all Western Australia tectonic units in a single tectonic framework.

The Hierarchy Report in ENS combines the tectonic sequence for the State (point 4) with the sorting of TOL trees under their designated tectonic unit (point 3) to generate a state-wide 'geological column'.

The ENS hierarchy report contains all the information necessary for the generation of the graphic depiction typical of a traditional hardcopy map legend and for originating the lookup tables that substitute legends in digital maps.

04RED – GEOLOGICAL MAPPING: ITS POWER AND ITS FUTURE

04RED-01. THE IMPORTANCE OF REGOLITH MAPPING AND REGOLITH SCIENCE FOR UNDERSTANDING SOUTH AUSTRALIA'S GEOLOGY FROM COVER TO BEDROCK – THE WAY FORWARD

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A major challenge for mineral exploration in over 80% of Australia is exploring efficiently and effectively through extensive and thick regolith. In those areas of thick and contiguous cover, understanding regolith composition and distribution is typically the only surficial guide to the composition of the underlying bedrock. Provision of regolith data, integrated with geological mapping, geophysics, geochemical and plant biogeochemical sampling and regional drilling programs provides important geological frameworks both within and through the cover. This can include identification of transported *vs in-situ* regolith, depth to the regolith–bedrock interface, and identification of dispersion pathways for target and pathfinder elements and their spatial relationship to regolith materials and even the recommendation of suitable exploration techniques for different regolith settings. The Geological Survey of South Australia (GSSA) is committed to have regolith mapping and regolith geoscience as an integral part of their work program to address and assist in the challenges for discovering deeper mineral targets, but also for providing a framework for geochemical sampling programs. A first step towards this was the completion of the South Australian State regolith map in 2012, which not only included a state-wide consistent dataset for regolith materials and landforms but also data layers for various types of induration including e.g. calcrete and ferruginous duricrust, and lag, which are important sample media for exploration. Following on from this was the need for integrating regolith mapping and regolith geoscience into the Survey's mapping program. An example of this integrative mapping approach is the Eastern Musgrave Province mapping project. The Musgrave Province is one of the least understood and underexplored Proterozoic terranes in Australia despite being in a key position between the three Paleoproterozoic cratonic blocks that form proto-Australia. It is potentially highly prospective, particularly for Ni–Cu–PGE magmatic sulfide deposits and related 'laterites' associated with Giles Complex intrusives. Within this mapping project the focus is not only on bedrock and structural mapping but also includes detailed mapping of regolith material and landforms and 3D weathering profiles, dating of regolith units, and a regional comprehensive biogeochemical survey. A new regolith categorisation approach has been developed and integrated into the GSSA Field Observation database in order to capture and record consistent and high quality regolith data during field mapping. Field mapping and data capture is undertaken digitally by utilising a tablet with ArcGIS software that is directly linked with the GSSA Field Observation database. This also allows the use of a wide range of data layers like hyper- and multispectral imagery, high resolution DEMs and radiometric data for direct use during field mapping. Biogeochemical surveys have been proven to be cost and time efficient, hence GSSA has undertaken an approximately 2x5 km spatial survey over a 1:100 000 mapsheet using mulga (Acacia aneura) phyllodes as the sample medium. GSSA envisages the integration of these complimentary regolith-related datasets into regional mapping programs as the way forward in unravelling the cover challenge.

04RED-02. TECTONIC GEOMORPHOLOGY MAPPING AND ANALYSIS OF THE LOWER DARLING VALLEY AND NORTHERN MURRAY BASIN, N.S.W.: NEW INSIGHTS INTO HYDROLOGICAL AND PALAEO-HYDROLOGICAL PROCESSES, WITH IMPLICATIONS FOR EXPLORATION SAMPLING STRATEGIES

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Recent investigations of the Lower Darling Valley (LDV) and broader northern Murray Basin, show there is evidence of extensive Neogene-to-Recent tectonics. Deformation is revealed by high resolution airborne electromagnetics (AEM), and is manifested as discrete faults, tilting and warping of unconsolidated Murray Geological Basin sediments, including the Pleistocene Blanchetown Clay. Many of the faults offsetting the Blanchetown Clay have a surface morphotectonic expression, revealed by high resolution LiDAR data.

LDV tectonic geomorphic mapping and analysis have revealed that the present-day courses of the Darling River and its Talyawalka Creek anabranch are largely structurally controlled. Several of the lakes in the Menindee Lakes System (MLS) and Anabranch Lakes are also localised and modified by tectonics, with crossing shorelines at Lake Mindona and evidence for lake-floor tilting and inversion in other Anabranch lakes. Similar features are also observed in the Willandra Lakes, east of the LDV. The Darling River has straight-line segments and box-like patterns controlled by intersecting faults mapped in LiDAR, AEM, airborne magnetic and regional gravity datasets. DEM analysis also shows that the Darling River is still adjusting its grade in response to localised uplift and tilting associated with displacement where crossed by the Talyawalka Fault System (TFS), south of Menindee. The TFS has a surface trace of >160km, and an apparent (modified) fault scarp >7m.

The LDV Quaternary fluvial sequence consists of scroll-plain tracts of different ages incised into higher, older and more featureless floodplains, which were also originally deposited by lateral-migration fluvial phases. Optically-stimulated luminescence (OSL) and radiocarbon dating of periods of scroll-plain activity, reveals a complex history of river avulsion through the Late Quaternary. The youngest, now inactive, scroll-plain phase associated with the modern Darling River, was active in the period 7-2 ka. A previous anabranch scroll-plain phase was active around 22-17 ka, while older less distinct scroll-plain tracts are associated with the anabranch system (~30ka) and the Darling River tract (~50-45 ka). The oldest dates of 85 ka and >150 ka come from lateral-migration sediments, that lack visible scroll-plain traces and lie beneath the higher floodplain. Scroll-plain activity and river avulsion do not appear to correspond with major shifts in the climate record, with local evidence suggesting that avulsion is related to discrete faulting and associated tilting. Many of the older palaeoriver tracts are also associated with palaeolakes, with evidence for 'tectonic stranding' of these landscape elements. In the LDV and broader Murray Basin landscapes, it is likely that the palaeorivers were associated with enhanced palaeorecharge episodes. Some of these features contain relatively low salinity groundwater, including the Larloona Palaeochannel, which is linked to palaeorecharge associated with a 22-17 ka scroll-plain tract of the Talyawalka Creek.

In summary, tectonic geomorphic mapping and analysis provide important new insights into present day hydrological and palaeohydrological processes. Tectonic geomorphology maps can also assist exploration strategies by providing key constraints on the hydromorphic dispersion of metals (in soils and groundwater), while the mapping of faults at surface provides potential sampling points to help assess mineral and hydrocarbon potential at depth.

04RED-03. REGIONAL AEM SURVEYS BENEFIT MINERAL EXPLORATION, GEOLOGICAL MAPPING AND GROUNDWATER RESOURCE MANAGEMENT

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Geoscience Australia (GA) conducted three regional airborne electromagnetic (AEM) surveys as part of the 2006–2011 Onshore Energy Security Program over the Paterson (Western Australia 2007–08), Pine Creek–Kombolgie (Northern Territory 2009) and Frome (South Australia 2010) regions. The surveys were designed to provide reliable, fit-for-purpose pre-competitive AEM data for mapping critical features of uranium mineral systems. The data have since been found suitable for mapping a range of other mineral systems (gold, silver, copper, lead, zinc), under-cover geological mapping and groundwater resource estimation. The contractor-delivered data were reprocessed at GA using the GA Layered Earth Inversion (GA-LEI) to create new interpretation products. These products are GIS-ready and are freely available from the GA website (http://www.ga.gov.au/minerals/projects/current-projects/airborne-electromagnetics.html). The surveys were flown in collaboration with industry and government partners who gained by paying reduced line-kilometre costs with no mobilisation expenses, and also from the management and AEM interpretation expertise of GA.

Each of the AEM surveys has now stimulated enough economic activity to offset the original survey costs to the Commonwealth Government, and results are showing impacts as the data are used by industry and government. In the Paterson area, the data have been used to discover copper–uranium mineralisation at the Yeneena prospect and copper–lead–zinc massive sulfide mineralisation at the Beadell prospect, to identify uranium-bearing unconformities near Kintyre, to explore for calcrete-hosted uranium mineral systems in paleovalleys, to search for groundwater resources necessary to develop the Kintyre uranium deposit and most recently to assess salt lakes for potash resources. In the Pine Creek region, the data have been used to define uranium targets associated with unconformities and were instrumental in discovering the Thunderball uranium prospect, as well as mapping seawater intrusion into coastal aquifers. In the Lake Frome region, data have been used to remap and reassess the sandstone-hosted uranium-bearing paleovalley systems in the southern Lake Frome area and north of the Flinders Ranges, influence new tenement grants near Marree, discover further copper resources at Farina and provide depth of cover information.

In each case, the data have been used by companies to assess or reassess tenements, reducing exploration risk by providing exploration targets and valuable depth and cover thickness information. The success of each of the three surveys has also initiated further rounds of industry AEM surveying at higher resolution to infill the broad-spaced GA flight lines; some of these surveys have been supported by State or Territory Government exploration incentive schemes. The success of the Paterson AEM Survey has also stimulated the Government of Western Australia to take on similar surveys, e.g. the recent Capricorn Orogen AEM Survey and a planned groundwater-focussed regional AEM survey for the Canning Basin.

Geoscience Australia is entering into a new round of regional AEM surveying in support of the UNCOVER initiative. The first new survey will be in the Southern Thomson Orogen region, over the Eulo Ridge; this survey is designed to map cover thickness and under-cover geology, providing new information for assessing the geology and prospectivity of this under-explored region.

04RED-04. EVALUATION OF DIGITAL FIELD MAPPING TOOLS – THE FUTURE IS HERE

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The approach to field study that a geologist takes has remained largely unchanged over the past century – working from a printed base map at a set scale and annotating observations of outcrop data and measurement results. These methods are advantageous in their ease of use, low cost, and versatility in a variety of field environments. However, digital methods for data collection and field mapping are becoming more common as computer hardware and software components become more advanced, but how do they measure up to traditional field mapping techniques? How do they affect the data collection and 3D interpretation process? Are they worth the initial investment in hardware, software, and education? We explore these questions by describing student field mapping projects and field mapping for research purposes that have guided the development of FieldMove Clino and FieldMove, digital geologic data collection and mapping software applications.

We find that digital mapping tools improve the 3D spatial interpretation process by facilitating more analysis and less data management than traditional techniques, especially in the "field office" during the evenings. When using traditional paper mapping techniques, significant time is spent on data organisation, transcription from paper to digital formats, and backup of collected field data, both during and after completion of the field season. Data organisation and transcription may also be repeated when converting paper maps and field notes to digital formats, which is hugely inefficient and prone to errors. In the digital mapping workflow, data organisation largely occurs in the field upon data collection, transcription from paper to digital format is unnecessary, and data backup can be as simple as copying digital files to external hard drives. Thus, we find that digital mapping allows more time in the evenings for problem solving, targeting areas of uncertainty, and formulating effective field plans.

A common hindrance to successful digital geologic mapping is a lack of advance preparation before leaving for the field. In addition to collation of digital base maps, elevation models, and existing geologic maps, the most important aspect of preparation is practice using the software and hardware tools. As with any compass, orienteering, and basic mapping skill, advance practice ensures that the mapping device is not the focus of the user's attention, leaving the field mapper to focus on 3D spatial analysis of rock units. We find that these issues are relatively easily overcome with advance planning and training, as well as an appreciation for the potential benefits of digital field mapping.

04REE – TECTONICS AND METALLOGENY IN THE LATE ARCHAEAN

04REE-01. FORMATION OF HORIZONTALLY LAYERED ARCHEAN CRUST: EXAMPLES FROM THE PILBARA, KAAPVAAL, AND YILGARN CRATONS

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The growth of continental crust through the Phanerozoic and Proterozoic is documented as having grown principally through lateral accretion at continental margins, either as a function of arc magmatism and/or the accretion of exotic terranes.

In the Archean, lateral growth of continental crust has been well documented for some terranes (e.g. West Pilbara Superterrane), or even whole cratons (e.g. Superior Craton), and is widely inferred to have been the sole mechanism for crustal growth over this early period of Earth history. Yet, just as modern Earth has continental crust that has formed over hotspots, or mantle plumes, so the Archean has terranes for which a formation through lateral growth is unsatisfactory.

In this presentation, I outline three areas of Archean crust for which lateral growth models do not apply and that appear to have formed through vertical magmatic accretion and internal differentiation as a result of one or more pulses of upwelling mantle: these include the East Pilbara Terrane (Pilbara Craton), the eastern Kaapvaal Craton, and the Yilgarn Craton. The key elements in favour of vertical crustal growth models for these Archean terrains are: widespread eruption of mafic–intermediate–felsic volcanic successions; craton-wide blooms of granitic magmatism; progressively evolving granitic compositions; and structural and metamorphic evidence for partial convective overturn.

Crustal growth episodes commence with input of mantle melts, as thick greenstone sequences of komatiite–basalt, erupted onto older (now largely cryptic) basement. As the volume of mantle-derived melts increases, the heat imparted to the crust increases such that it starts to melt and mingle with progressively fractionating magma chambers to produce conformably overlying and/or interbedded andesite–dacite–rhyolite successions and coeval mafic clotty-textured hybrid granitic magmas. Widespread crustal melting impedes the upwards transfer of mantle-derived melts, which then underplate and thicken the crust, even as the upper crust extends and undergoes partial convective overturn and the development of syn-tectonic clastic sedimentary basins.

Vertical crustal growth in these terranes recommences after periods of a few to tens of millions of years, dependant on aspects yet to be fully determined, but which may call on rates of delamination of the lower crust and/or subcontinental lithospheric mantle, renewed mantle upwelling, and/or thermal erosion of the SCLM. Addition of new eruptive successions on top, combined with delamination from below, cause previously upper crustal rocks to be buried to the mid crust, and mid crustal rocks to be buried to the deep crust, where they then melt and contribute to “new” magmas derived from recycled crust, across wide areas of developing continental lithosphere.

The crustal growth mechanism outlined here should be viewed as complimentary to, not exclusive of, crustal growth through Archean plate tectonics, and to reflect the effects of more vigorous mantle upwelling on a hotter Earth dominated by smaller plates.

04REE-02. ARCHEAN ANDESITES IN THE EAST YILGARN LARGE IGNEOUS PROVINCE, AUSTRALIA: THE CASE FOR THEIR ORIGIN BY PLUME/CRUST INTERACTION

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The timing of onset of modern plate tectonics on Earth is one of the fundamental unsolved problems in geology: how similar were the tectonic processes on the early Earth, when the mantle was hotter and the crust more ductile, to those operating today? A key line of evidence for Archean (pre-2.7 Ga) plate tectonics rests on the presence of andesites, intermediate lavas that are the signature rock type of modern subduction zones.

The 2.7 Ga Eastern Goldfields Superterrane of the Yilgarn Craton (herein East Yilgarn Craton) in Western Australia is a richly mineral-endowed crustal element that has been a prime focus of debate between proponents of an uniformitarian, plate-tectonic driven interpretation, and advocates of an alternative model where the entire assemblage of igneous rocks is derived ultimately from mantle plume activity. Andesites are a key component of the volcanic stratigraphy, and potentially provide critical clues to the evolution of this piece of Archean lithosphere.

Whereas East Yilgarn Craton andesites have incompatible trace element characteristics similar to those of modern island arc andesites, they are distinguished by unusually high Ni, Cr and MgO contents. Numerical modelling of fractionation of plume-related tholeiitic basalts, coupled with contamination by contemporaneous partial melts of pre-existing continental crust, provides a good fit to this feature, along with all of the essential major and trace element characteristics of the East Yilgarn Craton andesites. A small but growing body of isotopic data (Sm–Nd and Lu–Hf) are consistent with derivation of andesite from an essentially primitive, near chondritic end-member basalt, and a TTG–like dacite with CHUR-like to slightly depleted isotopic characteristics.

Thus, a rock type previously taken as a key line of evidence for plate tectonic processes in the East Yilgarn Craton can be explained just as well by a plume-driven mechanism, which is more consistent with the overwhelmingly plume-derived character of basalts and komatiites across the entire craton. This explains a paradox, noted in many pre-2.7 Ga volcanic rock sequences around the world, that apparently subduction-related rocks are interleaved with voluminous basaltic magmatism derived from 1000 km-scale plume-head arrival events. The problem is moot if Archean andesites are products of plume, not subduction zone, magmatism. We interpret the andesites within a framework of a craton-scale, plume driven Large Igneous Province whose rock type distribution was controlled by the geometry of pre-existing ancient blocks of continental lithosphere..

04REE-03. ZIRCON MULTI-ISOTOPIC MAPPING – A POTENTIALLY ROBUST PATHFINDER TO LARGE-SCALE TARGETING FOR GOLD MINERAL SYSTEMS

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Multi-isotopic maps have been demonstrated by previous studies to be a powerful tool for imaging lithospheric blocks of different age. Such maps are based on *in-situ* zircon U–Pb and Lu–Hf isotopic analyses that are combined with whole-rock Sm–Nd data. As the ancient deep lithospheric boundaries sometimes cannot be seen in modern seismic images, the isotopic mapping serves as a form of 'paleogeophysics' for imaging paleocraton margins through time. It has been shown that there is a strong spatial correlation between lithospheric boundaries and the concentration of a variety of mineral deposit types. The interpretation is that these isotopic boundaries mark lithosphere-scale structures that control magma and fluid flux, and thus the location of large mineral systems through time. However, the only available case study in the Archean is the Yilgarn of WA, and even that is only focused on the centre of the craton. Therefore, it is critical to test this hypothesis in other parts of the world. A comparative study was conducted in the Wabigoon Subprovince in the western Superior Craton of Canada. Numerous gold occurrences and prospects are present throughout the Wabigoon Subprovince. However, the most economic gold mineralisation, i.e. gold mines, clusters mainly in the Eastern Wabigoon and Marmion gold camps. New zircon Hf isotopic mapping of magmatic rocks was undertaken in this study identifying distinct isotopic domains. The boundaries of these isotopic domains are interpreted to be lithospheric boundaries between different terrane, and the results fit well with the distribution of gold mines. For example, the boundary between Winnipeg River terrane and Eastern Wabigoon terrane is trending NE based on new zircon Hf isotopic mapping, which is consistent with the gold trend in Eastern Wabigoon terrane. This coincidence supports the hypothesis that the terrane boundaries yield important controls on the location of significant gold mineralisation. Another important observation is that gold mines are rare within ancient evolved domains (e.g. Winnipeg River terrane), but instead cluster within juvenile domains (e.g. the Eastern Wabigoon terrane), adjacent to domain boundaries (e.g. Hammond Reef, 10 Moz Au). This spatial relationship of gold with the boundaries of more juvenile domains is similar to that observed in Yilgarn Craton of Western Australia. Although the nature of these isotopic domain boundaries remain unclear, it is interpreted based on relationships to surface geology and potential field geophysics that they are the location of vertically accretive translithospheric structures multiply reactivated through time. Thus, such isotopic mapping is a powerful technique to image whole lithosphere architecture, and may be key mappable criteria for the location of major gold camps.

DYNAMIC PLANET

04DPA – PRECAMBRIAN GEOCHRONOLOGY

04DPA-01. ALEC TRENDALL: AN APPRECIATION

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Alec Trendall's career spanned over 60 years during which he made significant contributions to our understanding of the geology of South Georgia, Uganda and Western Australia. A man of many talents he had a broad interest in geology, spoke Russian fluently, was an accomplished player of ancient keyboard instruments and late in life took to farming on a small-holding with various fruit trees and goats.

He was born in the UK, in 1928, and spent part of his childhood in India before returning to the UK in 1937 to complete his secondary education and going on to obtain his BSc at Imperial College London and a PhD at the University of Liverpool under his supervisor Robert Shackleton. In 1951 he joined Duncan Carse's expeditions to South Georgia. On the 1951–52 expedition, he fell down a bergschrund and severely dislocated his knee and returned to England for specialist treatment. During his recuperation he was offered a lectureship at Keele University, and married Kathleen Waldon, a nurse who had played a major part in his rehabilitation. However, South Georgia continued to call and he joined the 1953–54 expedition sailing south two months after his marriage.

On his return from South Georgia Alec joined the Geological Survey of Uganda in 1954 as a field geologist spending most of his time in the bush accompanied by his wife, their growing family of three children and a clavichord.

With Uganda independence looming Alec accepted a position with the Geological Survey of Western Australia (GSWA) where he was successively petrologist, Deputy Director and Director. In moving to Perth in 1962 he had little idea that the banded iron-formations (BIFs) of the Hamersley Group were to become a consuming interest for the rest of his geological career. In pursuing his investigations Alec made several trips abroad to study similar deposits in South Africa, North America, Europe, India and Brazil, and received world-wide recognition for his work on BIFs.

Alec realised that work on the Precambrian rocks of Western Australia depended on accurate geochronological data. In 1968 he and John De Laeter established a joint program whereby GSWA supplied the samples and Curtin University did the analyses using, initially, the Rb–Sr technique, with other techniques being added over the years.

In 1984 Alec discovered stromatolitic carbonate rocks on the east bank of the Shaw River in the Pilbara. The initial discovery site, the 'Trendall locality', is one of the most significant early life locations so far discovered.

After retirement in 1990 he continued his geological work, particularly in geochronology and he and Kath moved to Springhaven a property near Denmark on the south coast. Alec returned to South Georgia to commemorate Duncan Carse's achievements, which he recorded in his book *Putting South Georgia on the Map.*

Alec was first and foremost a field geologist with the philosophy: 'Do not accept what I tell you or others tell you; go into the field and see what the rocks themselves tell you'.

04DPA-02. GROWING ANCIENT AUSTRALIA: HAFNIUM AND NEODYMIUM ISOTOPE CONSTRAINTS FROM THE YILGARN AND PILBARA CRATONS

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Australia's ancient geological nucleus has long been a key battleground in the ongoing debate about the rates and volumes of continental crustal growth on Earth through time. Accurate and precise geochronology is fundamental to this, not only for constraining the absolute age of geological events, but also for providing a robust framework for interpretation of the radiogenic isotope tracer data that underpin much of the crustal growth debate. Here, we unravel the ancient growth history of the Australian continent through a combination of U–Pb ages and hafnium (^{176}Lu–^{176}Hf) isotope data from zircons, and neodymium (^{147}Sm–^{143}Nd) isotope data from the corresponding bulk rocks, targeting both felsic and mafic compositions. This approach emphasises isotopic data from well-characterised igneous rocks, rather than relying on detrital zircons whose geological context is lost, and seeks to link the crustal and mantle evolutionary records. Two key areas are examined, these being (1) the Narryer Terrane (>3.73–2.65 Ga) of the northwestern Yilgarn Craton, incorporating the Jack Hills and Mt Narryer supracrustal sequences that host Hadean (>4 Ga) detrital zircons, and (2) the Pilbara Craton (>3.52–2.83 Ga), an archetypal Archean granite–greenstone terrane comprising dome-like granitic complexes flanked by metavolcanic and sedimentary rocks. Gneisses and migmatites of the Narryer Terrane surround the Jack Hills belt and potentially harbor fragments of the >4 Ga rocks from which the scarce Hadean detrital zircons are derived. New zircon U–Pb, Hf and whole-rock Nd isotope data from the Narryer gneisses suggest pulses of juvenile crust generation at *ca* 3.76 Ga and 3.49–3.35 Ga, with extensive granulite facies reworking at *ca* 3.3 Ga and into the late Archean. There is limited isotopic evidence for participation of >3.8 Ga crustal components in these thermal episodes, perhaps implying that any surviving Hadean substrate was volumetrically trivial. Likewise, a comprehensive Hf–Nd isotopic study of felsic igneous rocks of the Pilbara Craton, from both the granitic complexes and volcanic units in the greenstone belts, suggests that growth of the craton commenced at *ca* 3.65 Ga, refuting recent claims for a Hadean continental basement. Granitic/felsic volcanic rocks emplaced in pulses from 3.52 Ga to at least 3.12 Ga appear to have been sourced from precursors with short crustal residence times, and thus represent juvenile continental additions, rather than having formed by remelting much older rocks. Importantly, Hf–Nd isotope systematics reveal that the oldest primitive basalts and komatiites in the Pilbara Craton separated from mildly superchondritic mantle, not from mantle that was strongly depleted by prior voluminous crust extraction. The Pilbara Craton either developed remote from the isotopic influence of the putative Hadean continental masses, and/or the stabilised volumes of the earliest continents have been overestimated. The latter would be consistent with the extreme global paucity of >3.9 Ga rocks and minerals, and the dominantly chondritic Hf isotope composition of the oldest felsic rocks in the Earth's most ancient and best-preserved Archean cratons.

04DPB – PRECAMBRIAN GEOCHRONOLOGY

04DPB-01. RAPID MESOPROTEROZOIC COOLING AND TRANSPRESSIONAL EXHUMATION IN THE WESTERN ALBANY-FRASER OROGEN, WESTERN AUSTRALIA

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The exhumation of granulite-facies terranes in Proterozoic orogens is typically a slow, post-orogenic process driven by mechanisms such as extensional collapse and erosion. This model contrasts with the record of fast syn-orogenic cooling and exhumation we uncover for the Mesoproterozoic Albany-Fraser Orogen of southwestern Australia. ^{40}Ar/^{39}Ar thermochronology of hornblende, biotite and muscovite grains from a 360 km transect across the western Albany-Fraser Orogen is used to study the cooling and exhumation history of the amphibolite to granulite-facies orogenic root. To the north, muscovites from the Northern Foreland record cooling at *ca* 1159 Ma. In the central and southern domains of the orogen, the Biranup and Nornalup Zones, hornblende yields *ca* 1169 Ma cooling ages, and biotite yields *ca* 1172–1144 Ma cooling ages. The new cooling ages imply that the three domains were exhumed rapidly after peak metamorphism at *ca* 1180 Ma, attained a similar structural level (8.5–11.5 km) by *ca* 1159 Ma, and have experienced a uniform exhumation history since that time.

To fully propagate uncertainty and minimise error correlations, we conducted a Monte Carlo simulation to constrain mineral closure temperatures and post-metamorphic cooling rates. Simulation of cooling from hornblende to biotite closure temperatures in the Nornalup and Biranup Zones yields median cooling rates of 32.7 ± 0.4°C/Ma and 21.7 ± 0.2°C/Ma respectively. These fast cooling rates require an exhumation mechanism consistent with rapid cooling and exhumation in an active tectonic setting undergoing peak metamorphism. The transpressional tectonic activity commonly associated with deformation in the Albany-Fraser Orogeny may have been an active driver of this fast exhumation. This is distinctly different from exhumation models for granulite-facies domains in other Mesoproterozoic orogens, which typically experience slow 1–5°C/Ma cooling driven by isostatic mechanisms such as post-orogenic extension and erosion. The observed differences reflect exhumation during different stages of the orogenic cycle: the Albany-Fraser Orogen records fast syn- to late-orogenic exhumation, rather than slow post-orogenic exhumation.

04DPB-02. FORMATION AND ALTERATION HISTORY OF DETRITAL CHROMITES FROM JACK HILLS SEDIMENTS, WESTERN AUSTRALIA

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The Re–Os isotope systematics and HSE abundances are reported for detrital chromites from the Proterozoic Jack Hills metasedimentary belt in Western Australia, also known to host detrital zircons with ages as old as 4.4 Ga. We also present the U–Pb isotopic data for monazite inclusions in the chromites. Besides zircon, chromite is typically the only other `heavy' mineral present in the sediments.

Detrital grains of chromite occur as euhedral, octahedral, and rounded spherical grains, suggesting both proximal and distal populations. Three fractions of chromite grains studied in this work included: (1) euhedral and octahedral chromite grains (proximal origin), (2) rounded chromites (distal origin), and (3) a mixture of the populations (1) and (2).

All chromite fractions show extensive alteration which affected the major-element abundances *via* reducing the MgO content to 1.0–1.6 wt%, but increasing the ZnO (1.0–1.7 wt%), MnO (0.9–1.3 wt%), and FeO (27–34 wt%) abundances, and removing Fe^{3+} from the spinel structure. It is most probable that the original contents of Al (Al_2O_3 = 17–24 wt%), and Cr (Cr_2O_3 = 38–49 wt%) also increased at the expense of Fe^{3+}.

The chromites contain rare inclusions of laurite, monazite and galena, as well as melt inclusions. The latter point to a volcanic origin for the precursor rocks that hosted the chromite. At present, all melt inclusions are represented by secondary alteration minerals, and therefore not suitable for further studies.

The monazite inclusions in chromites have been analysed *in-situ* for U–Pb isotopic compositions using SHRIMP. They have low U and high common Pb; the mean $^{207}Pb/^{206}Pb$ age (n = 6) is 2650 ± 180 Ma, with the best analysis giving 2676 ± 50 Ma. This age corresponds to the younger generation of monazites (2.8–2.55 Ga) identified in Jack Hill sediments (Iizuka *et al.* 2010). This age likely corresponds to the timing of the hydrothermal alteration event.

One laurite inclusion was analysed *in-situ* for Re–Os contents and Os isotopic composition. The model Re–Os ages obtained are 3.24 ± 0.23 and 3.25 ± 0.23 Ga (T_{RD} and T_{MA}, respectively). Similar or slightly older ages (3.2–3.5 Ga) were obtained in previous studies (Valley *et al.* 2005) for chromite separates from Jack Hill sediments.

Analyses of bulk chromite fractions yielded $^{187}Re/^{188}Os$ of 0.0265 to 0.0373 and $^{187}Os/^{188}Os$ values of 0.10998 to 0.11415 for fractions 2 and 3. Chromite from the fraction 1 has a resolvably higher $^{187}Os/^{188}Os$ (0.18133) and might contain some material introduced from the hydrothermal event. The model Re–Os age of 2.66 Ga is similar to that of monazite, but significantly younger than that of laurite, reflecting the effects of hydrothermal alteration.

The PGE contents of chromite separates from different fractions are quite similar, with enrichment in Os–Ir–Ru (132 ppb) relative to Pt–Pd (17 ppb). The fractionation of Os–Ir–Ru relative to Pt–Pd is consistent with the compatible and incompatible behaviour of these elements, respectively, in natural (Puchtel & Humayun 2001; Stone & Crocket 2003) and synthetic systems (Brennan *et al.* 2012), and with derivation from ultramafic rocks.

Our study confirms the Paleo- to Mezoarchean age of chromites hosted in Jack Hills sediments. However, no evidence of older chromites corresponding to the oldest zircons population (*ca* 4.4 Ga) has been found. This may indicate either lower resistance of chromites to alteration or much lower abundance of ultramafic rocks in that particular segment of continental crust compared to the felsic rocks. The alteration event that affected the chromites and introduced monazites was dated at 2.6–2.7 Ga. This age is consistent with the major hydrothermal mineralisation event in the Yilgarn Craton of Western Australia.

04DPB-03. AGE CONSTRAINTS FROM THE ROCKY CAPE GROUP: PUTTING TASMANIA ON THE MESOPROTEROZOIC MAP

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The oldest known rocks in Tasmania occur in the Proterozoic Rocky Cape Group, a ~10 km thick quartzarenite–siltstone–pelite-dominated succession, which was previously constrained to have been deposited between 1450 Ma and 750 Ma. New detrital zircon and authigenic monazite ages dated *via* U–Pb Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) sampled from sub-greenschist facies sandstones and siltstones throughout the Rocky Cape Group allow us to: (1) vastly improve on depositional age constraints, including constraining the age of the 'string of beads' fossil *Horodyskia*-bearing strata; (2) make regional basin-scale correlations; and (3) speculate on the tectonic correlations between proto-Australia and Laurentia at *ca* 1.45 Ga.

Detrital zircon and authigenic monazite grains ages analysis yield a deposition window between *ca* 1450 Ma (youngest zircon populations) and *ca* 1330 Ma (oldest authigenic monazite population) for the ~9 km thick lower–middle units (Pedder River Siltstone, Lagoon River Quartzite, Balfour Sub-group, which hosts *Horodyskia*, Detention Sub-group). The upper units (~1 km) include the Irby Siltstone, which is younger than *ca* 1310 Ma; this unit is likely separated from both the lower–middle units and the overlying < *ca* 1010 Ma Jacob Quartzite by disconformities. Authigenic monazite age distributions are complex, with multiple age domains within most samples. The common Pb corrected $^{206}U/^{238}Pb$ ages, defined by oldest grains in each sample, identify three statistically significant groups: (1) *ca* 1330 Ma (Lagoon River Quartzite and Pedder River Siltstone), (2) *ca* 1260 Ma (Cowrie Siltstone and Balfour Sub-group), and (3) 1085 ± 9 Ma (Detention Sub-group). We suggest monazite was precipitated during episodic fluid flow events at these three stages. The original source for REE-bearing fluids could be detrital monazite, which is rarely preserved, and/or organic matter from the interbedded carbonaceous shales.

The lower–middle Rocky Cape Group has a shared provenance with the higher-grade metasediments (Surprise Bay and Fraser formations) of nearby King Island; the newly derived depositional ages also overlap and support the correlation of these rock associations. On the basis of current datasets, there are no obvious correlations that can be made with Mesoproterozoic basins preserved in mainland Australia. Instead, an overlap in the timing of deposition, similarities in detrital zircon signatures and analogous depositional environment suggests the *ca* 1.45–1.37 Ga upper Belt-Purcell Supergroup (Missoula and Lemhi groups) of western North America constitutes a plausible correlation with the Tasmanian Mesoproterozoic succession. If the (unexposed) Paleoproterozoic basement of Tasmania correlates with the Transantarctic Mountains region of East Antarctica as previously proposed, we suggest that the overlying Mesoproterozoic sequences were deposited during rifting of the supercontinent Nuna, between proto-Australia (including the Mawson craton of Antarctica) and Laurentia as predicted by the most recent paleogeographic reconstructions. Both the Tasmanian and western Laurentian packages were affected by episodic post-depositional fluid flow events between *ca* 1.35–1.05 Ga, possible thermotectonic imprints of the subsequent assembly of Rodinia.

04DPB-04. U–PB SYSTEMATICS OF ZIRCON FROM THE ACRAMAN IMPACT STRUCTURE

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The Acraman event of South Australia created one of the largest impact structures on Earth, and its distal ejecta provide an important marker horizon in the Neoproterozoic stratigraphy of Australia. We conducted a petrographic characterisation and U–Pb SHRIMP study of zircon grains from impact melt rock sampled at the central eroded Acraman impact structure. Microtextural variations of zircons reveal varying effects of the Acraman event ranging from seemingly pristine, magmatic textures *via* shocked grains with planar deformation features and planar fractures to wholly granular, neocrystallised zircons. Baddeleyite-bearing granular zircons indicate shock pressures in excess of ~65–70 GPa, which are considerably higher than previous shock pressure estimates. U–Pb systematics of untreated zircon grains demonstrate a range of isotopic resetting commensurate with the degree of shock; weakly shocked crystalline grains yielded ages on concordia around *ca* 1.6 Ga reflecting the inherited magmatic age of the Gawler Range Volcanics. Only the entirely granular zircon population was fully reset by the impact event, but this population has experienced significant Pb loss. The granularisation of zircons at temperatures exceeding ~1100°C may have promoted the escape of radiogenic Pb *via* diffusion and α-recoil, as suggested by grain size-dependent diffusion and recoil modelling. Pb loss in the highly shocked to granular zircon population appears to have been roughly contemporaneous with hydrothermal alteration events, as supported by 450–500 Ma U–Pb isochron ages and $^{40}Ar/^{39}Ar$ age resetting of feldspars from the melt rock and the shocked Yardea Dacite. The isotopic age constraints on the Acraman impact event remain inferential, largely based on the stratigraphic occurrence of the Acraman-Bunyeroo ejecta layer.

04DPC – PLATE KINEMATICS AND DYNAMICS

04DPC-01. ARE SUBDUCTION ZONES INHERENTLY WEAK?

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An outstanding question in geodynamics is how weak are plate boundaries when compared to their interiors? Particularly, how weak are subduction zone interfaces? Because subduction is believed to be the major driver of plate tectonics, this question is of fundamental importance for geodynamics. Several lines of evidence suggest that subduction zones are weak and that the unique availability of water on Earth plays a key role. We have evaluated the strength of subduction zone interfaces using two approaches: i) an empirical relationship between shear stress at the interface and subduction velocity, deduced from laboratory experiments of subduction; and ii) a parametric study of natural subduction zones that provides new insights on subduction zone interface strength. Our results suggest that subduction is only mechanically feasible when shear stresses along the plate interface are relatively low (<33 MPa). To account for this global requirement, we propose that there is a feedback mechanism between subduction velocity, water release rate from the subducting plate and serpentinisation and weakening of the forearc mantle that may explain how relatively low shear stresses are maintained at subduction interfaces globally.

04DPC-02. QUANTIFYING THE ENERGY DISSIPATION OF OVERRIDING PLATE DEFORMATION IN THREE-DIMENSIONAL SUBDUCTION MODELS

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Analogue and numerical models of subduction have been proposed to quantify the amount of the slab's total potential energy that is used to drive mantle flow and to assess how much of this energy is used to bend the subducting plate. Furthermore, the force and the energy required to deform the overriding plate are generally thought to come from the negative buoyancy and the potential energy of the subducted slab, respectively. Such deformation might involve extension, leading to the formation of backarc basins, or shortening, which may result in the formation of Cordilleran mountains. However, how much of the slab's potential energy is consumed in the deformation of the overriding plate has never been investigated. In this work, we present dynamic three-dimensional laboratory models of progressive subduction with an overriding plate to quantify the force (F_{OPD}) that drives overriding plate deformation and the involved energy dissipation rate (Φ_{OPD}) during such deformation, and we compare them with the negative buoyancy (F_{BU}) and the total potential energy release rate (Φ_{BU}) of the subducted slab, respectively. Considering there is an uncertainty in the effective viscosity ratio between the subducting plate and sub-lithospheric upper mantle (η_{SP}/η_{UM}), and a variability in overriding plate thickness (T_{OP}), we investigate models in which we vary η_{SP}/η_{UM} from 157 to 560 and T_{OP} from 1.0 cm to 2.5 cm, scaling to 50–125 km in nature. In our models of narrow subduction zones (15 cm in experiment, scaling to 750 km in nature) the overriding plate always experiences overall extension during trench retreat. Overall, F_{OPD}/F_{BU} has average values of 0.5–2.5%, with a maximum of 5.0% and Φ_{OPD}/Φ_{BU} has average values of 0.10–0.30%, with a maximum of 0.70%, which indicate that only a small portion of the negative buoyancy of the subducted slab is used to deform the overriding plate and an even smaller percentage of the slab's potential energy is consumed during overriding plate deformation. In addition, our results show that 2–30% of the overriding plate energy dissipation is dissipated in the forearc region and 14–42% in the region of maximum backarc extension. Finally, our calculated force to deform overriding plate is of comparable magnitude as the ridge push force in nature.

04DPC-03. EARLY CENOZOIC AUSTRALIAN PLATE MOTION CHANGES LINKED TO NEW GUINEA SUBDUCTION ZONE

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New Guinea is the second-largest island in the world and sits at the junction of several major tectonic plates, including the Australian, Pacific, Sunda, Caroline and Philippine plates. The island is considered the archetype example of arc–continent collisions, with one active arc–continent collision in the northeast and one or more arc–continent collisions since the Late Cretaceous. Understanding New Guinea's geological evolution is vital as it links Southeast Asia with the Southwest Pacific. The complexity of the region has fuelled controversy on the timing, extent and number of collision events in New Guinea. Here we present a tectonic reconstruction of the region, constrained by regional geology, global absolute plate motions and mantle seismic tomography, demonstrating the existence of one collision event in the earliest Eocene characterised by widespread obduction. This event is related to the final stage of northward subduction of oceanic lithosphere located north of New Guinea from the latest Cretaceous until the early Eocene along a ~4000 km wide subduction zone (here named the New Guinea–Pocklington subduction zone). Geological data indicate collision and obduction in the early Eocene along the northern New Guinea margin as well as termination of spreading in the Coral Sea, implying subduction termination and slab detachment in the early Eocene. This coincides with a rapid drop in northward Australian plate motion at *ca* 50 Ma to ~0 cm/yr, interpreted as resulting from loss in slab pull. Using a global P-wave seismic tomography model we identify a ~4000 km long high-velocity anomaly, interpreted as slab material of the fossil New Guinea–Pocklington subduction zone. The geometry of this slab anomaly is coincident with the geometry of the New Guinea–Pocklington Trough fossil subduction zone, and it is located at a position predicted by our absolute plate motion reconstruction.

04DPC-04. RECONSTRUCTING ANCIENT OCEAN BASINS AND EVOLVING PLATE BOUNDARY CONFIGURATIONS – A KEY TO UNDERSTANDING SOLID EARTH EVOLUTION

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The large-scale pattern and time-dependence of mantle convection mainly depends on the history of subduction. Therefore the location, geometry and velocities of subduction zones and age of subducted lithosphere constitute primary constraints for solid Earth evolution. We reconstruct paleo-oceans by creating “synthetic plates”, the locations and geometries of which are established on the basis of preserved ocean crust (magnetic lineations and fracture zones), geological data – particularly volcanic arcs and ophiolites preserved on overriding plates – and the rules of plate tectonics. Pre-Cenozoic ocean basin and plate boundary reconstructions are subject to increasing uncertainties back through time, which we explore by testing alternative end-member scenarios. Based on this approach we have constructed and combined a global relative/absolute plate motion model, a set of evolving plate boundaries and the evolution of the age of the ocean floor since the Jurassic, which we use as time-dependent surface boundary conditions for mantle convection models. These models reveal many surprises, including previous misinterpretations of the origin of particular slab volumes (fast seismic anomalies) in the mantle, as well as tomographically imaged slabs, which we cannot yet account for. We evaluate tomographic and geodynamic evidence for now subducted Tethyan ocean floor and back-arc basins between Greater India and Eurasia to test competing plate tectonic scenarios. Our results strongly support scenarios of NeoTethyan intra-oceanic subduction prior to the suturing of Greater India with Eurasia, resulting in multi-phase arc–continent and then a continent–continent collision. Mantle flow models reproduce the lateral and vertical mantle structure that is interpreted from seismic tomographic models, and allow us to account for the origin and evolution of Tethyan slabs in the mantle. In the southwest Pacific we compare end-member kinematic models to determine whether subduction occurred to the east of the Lord Howe Rise during the Cretaceous to Eocene; a time when plate boundary activity between the Lord Howe Rise and Pacific plate is strongly debated. We compare a model of back-arc basin opening and closure, with a model of tectonic quiescence in which the Lord Howe Rise was part of the Pacific plate. In the circum-Arctic we show that remnants of oceans including the South Anuyi and Mongol-Okhotsk oceans and northern Panthalassa can now be found under Greenland, Siberia and North America and we suggest an alternative interpretation of the location and affinities of the Farallon and Mongol-Okhotsk slabs. Our models illustrate Australia's late Cenozoic northeastward motion towards a downwelling related to the sinking eastern Gondwanaland slabs in the lower mantle. A surface expression of this plate–mantle interaction is the well-documented progressive late Cenozoic anomalous subsidence of the northwest and western shelf of Australia, up to 1000 km away from the nearest plate

boundary. Future extensions of this approach will include reconstructions of pre-Pangean plate motions, boundaries and ocean basins, and the incorporation of plate deformation to move towards a unified conceptual and methodological framework for understanding how continents and ocean basins interact with the connected non-linear evolution of the plates and the deep Earth.

04DPD – ARCHEAN & PROTEROZOIC GONDWANA

04DPD-01. WHEN DID THE WAC WHACK THE NAC? DOCKING OF THE WEST AND NORTH AUSTRALIAN CRATONS

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Current models for the Proterozoic assembly of Australia incorporate docking of the West Australian Craton (WAC) with the North Australian Craton (NAC) at *ca* 1800–1765 Ma. This timing is based on the interpretation that: (1) that the high-P Yapungku Orogeny in the Rudall Complex of northwestern Australia occurred at this time; and (2) that this event was a result of WAC/NAC collision. However, field observations and geochronological data from the Rudall Complex suggest that the docking might have occurred post-1765 Ma.

The timing of high-P (to 1.2 Gpa) metamorphism during the Yapungku Orogeny is currently poorly constrained, but has been interpreted to be coeval with voluminous 1800–1765 Ma felsic magmatism in the Rudall Complex. These intrusive rocks are overprinted by a high-grade foliation (regional S_2) that is considered to have formed during peak-Yapungku metamorphism. Current interpretations of the minimum age of the Yapungku Orogeny are based on an age obtained from an aplite dyke considered to post-date deformation, with the younger limit of the 1778 ± 16 Ma age being used to assign a *ca* 1765 Ma younger limit for tectonism. However, field examination of the aplite dykes shows that they are in fact variably overprinted by S_2, indicating that the *ca* 1765 Ma ages obtained from the aplites and their granitic host rocks provide only a maximum age for deformation, leaving open the possibility that the Yapungku Orogeny occurred later than previously thought.

A further constraint on the timing of WAC/NAC docking is provided by zircon U–Pb ages obtained from mafic and felsic intrusive rocks of the Krackatinny Supersuite in the eastern Rudall Complex. This suite has calc-alkaline geochemical characteristics, with a moderately evolved Sm–Nd isotopic signature consistent with incorporation of a pre-existing crustal component. Zircon U–Pb dating of the Krackatinny Supersuite shows that it was emplaced between 1590 and 1550 Ma, significantly older than a *ca* 1330–1290 Ma age previously assigned to these rocks based on ages obtained from leucocratic intrusive rocks that occur in the same area. If the calc-alkaline igneous rocks of the Krackatinny Supersuite reflect continental arc magmatism at 1590–1550 Ma, this implies that an ocean basin existed to the northeast of the WAC at that time, and that final amalgamation of the WAC and NAC did not occur until 1550 Ma or later. This interpretation suggests that the Krackatinny Supersuite is related to coeval arc magmatism in the Musgrave Inlier, defining a relatively linear zone of convergence between the NAC and the West and South Australian cratons during this period.

In this scenario, it is possible that 1800–1765 Ma magmatism in the Rudall Complex was emplaced during extension near the margin of the WAC, rather than in a collisional setting. This is consistent with the presence of metasedimentary rocks within the Rudall Complex that are dominated by 1800–1765 Ma detrital zircons. These metasedimentary rocks are overprinted by S_2, and imply that a phase of exhumation and deposition occurred prior to the Yapungku Orogeny, further supporting the notion that WAC/NAC amalgamation occurred after 1765 Ma. Very limited data obtained from metamorphic zircon dating is suggestive of events at *ca* 1640 Ma, *ca* 1580 Ma and *ca* 1335 Ma, but further work is required to directly constrain the timing of collision.

04DPD-02. A MESOARCHEAN TERRANE BOUNDARY IN THE SOUTHERN PILBARA CRATON?

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The geology of the Pilbara region represents a unique insight into the Earth's environment and global tectonic processes during the Paleoarchean to Paleoproterozoic. The Archean Pilbara Craton underlies 250 000 km^2 of the Pilbara region. However, outcrop is largely restricted to the north, and the craton is dominantly covered by Neoarchean to Paleoproterozoic volcano-sedimentary sequences to the south. An exception is the Rocklea Dome, which presents a rare opportunity to understand the dynamic history of the southern Pilbara Craton.

Previously mapped only at regional scale, an interpretation of regional aeromagnetics suggested that the Rocklea Dome represents part of the Paleoarchean East Pilbara Terrane (Hickman *et al.* 2010). However, recent geological mapping of the dome has revealed a far more complex geological history than that presented in past literature. Such findings include suites of distinctive rock associations on either side of a high strain zone that are here interpreted to represent distinct geotectonic terranes. In the north, a greenschist facies volcanosedimentary package incorporates basal sandstone, felsic volcanics, and overlying mafic and ultra-mafic volcanics and chert. The base of the package is intruded by a porphyritic granodiorite. The Southern Domain includes gneissic granite that contains rafts of older, folded grey tonalitic gneiss. A number of large greenstone panels that outcrop across the dome consist of greenschist-facies tholeiitic and komatiitic metabasalts in the east, and amphibolite, amphibolite schist and amphibolite gneiss in the west. Preserved pillows indicate younging towards the east and southeast. A widespread unit of foliated mafic metamonzogranite and a post-tectonic granite intrude the greenstone panels.

The southern domain demonstrates a far more complex structural history than the north, incorporating a total of six deformation events. The Northern Domain has all bedding striking east–west, with dip consistently toward the north and a single, bedding-subparallel foliation. Both domains are intruded by sheets of leucogranite that are strongly deformed within the high strain ductile mylonite zone that exhibits a dextral porphyryclastic–porphyryblastic mylonitic texture and strong subhorizontal stretching lineations.

We present a four-dimensional model for the geological history of the Rocklea Dome incorporating stratigraphy, structure and geochemistry. Dating of key units is in progress. This model defines the tectonic history of the region allowing comparison to extensively researched cratonic rocks of the northern Pilbara Craton.

Reference

Hickman A H, Smithies R H & Tyler I M 2010. Evolution of active plate margins: West Pilbara Superterrane, De Grey Superbasin, and the Fortescue and Hamersley Basins – a field guide. *Record 2012/3*, 1–74.

04DPD-03. SEDIMENTATION SYNCHRONOUS WITH *ca* 1590 MA FELSIC AND MAFIC VOLCANISM IN THE GAWLER RANGE VOLCANICS AT ROOPENA, NE EYRE PENINSULA, SOUTH AUSTRALIA

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A sequence of sediments occurring near Roopena, 40 km SW of Port Augusta on the NE Eyre Peninsula, the Fresh Well Formation (new name, to be defined; FWF), provides evidence of sedimentation synchronous with the lower GRV (*ca* 1590 Ma), supporting genetic models that propose local extension in the central Gawler Craton at this time. The formation extends over an area 4 km N–S by 3 km E–W and is up to 225 m thick, and consists of a flat-lying sequence of argillaceous and tuffaceous sandstone, siltstone and laminated glauconitic and dolomitic shale and mudstone with lesser pebble conglomerate and lithic sandstone deposited in a lacustrine/shallow marine environment. It contains peperitic textures and tuff beds and is interlayered with lava flows of the Roopena Volcanics (RV) of the lower GRV.

Deposition of the lower part of the formation appears to have been controlled by a paleo-topography created by folding and faulting of the underlying Paleoproterozoic basement. The earliest sediments were deposited only along the E margin of the basin adjacent to a N–S-trending fault. The lower part of the sequence comprises a basal conglomerate composed of clasts derived from Gawler Craton basement, as well as sandstone, siltstone and shale facies, and occupied paleo-lows. It locally contains peperitic textures consisting of felsic volcanic and mudstone fragments, associated with the synchronous 'Angle Dam porphyry' of the lower GRV.

The lower FWF is overlain by a single flow of the RV similarly restricted to the E margin of the basin, which is characterised by an amygdaloidal or brecciated top and a highly altered base. The basalt is extremely variable in thickness (6–40 m) and appears to have pooled in topographic lows.

Following the extrusion of the lower flow of the RV sedimentation of the FWF recommenced, progressively extending further W into the basin. The upper part of the FWF comprises a sequence of shale, siltstone, sandstone and conglomerate rich in felsic volcanic detritus and contains three water-lain tuffs. These tuffs (T1, T2, T3) serve as time marker horizons, which enable the identification of differential sediment accumulation within the basin. T1 and T2 were deposited only along the E margin of the basin. Some variation exists in the distance between the top of the basalt flow and the base of T1 and the top of T1 and base of T2, indicating that some relief still existed on the basin floor, or that accommodation space was created in some parts of the basin at this time. By the time of T3 deposition, the FWF had extended to the far W of the basin. The distance between the top of T2 and base of T3 is generally constant except for in the S, where accommodation space was created at this time.

The upper FWF is overlain by up to 12 additional flows of the RV totalling ≤250 m in preserved thickness. No further sedimentation is recorded in the basin, suggesting that the remaining accommodation space was completely filled by the basalt flows.

04DPD-04. BASIN FORMATION BY OROGENIC COLLAPSE: ZIRCON U–PB–HF ISOTOPE EVIDENCE FROM THE KIMBERLEY AND SPEEWAH GROUPS, NORTHERN AUSTRALIA

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Changes in the provenance of sedimentary successions through time can provide valuable information on the nature and timing of tectonic processes related to basin formation and on possible sediment source regions. The Paleoproterozoic Speewah Group and unconformably overlying Kimberley Group, northern Western Australia, are sandstone-dominated fluvial and shallow marine sedimentary successions, also containing siltstone, mudstone, claystone, mafic volcanic rocks, and rare carbonates. Both groups are intruded by sills and dykes of the *ca* 1797 Ma tholeiitic Hart Dolerite. Deposition of the Speewah and Kimberley Groups occurred during and immediately after the 1835–1810 Ma Halls Creek Orogeny, which is thought to mark collision between the North Australian and Kimberley Cratons. However the tectonic drivers for basin formation and associated mafic volcanism have been unclear. In order to better understand these drivers, we present new U–Pb SHRIMP age and Lu–Hf LA-MC-ICPMS isotope data for detrital zircons from the Speewah and Kimberley Groups. The results show a marked change in provenance at the base of the Kimberley Group. The Speewah Group is dominated by Paleoproterozoic 1880–1850 Ma detrital zircons with unradiogenic Hf (εHf_t = –8 to +1), whereas the onset of deposition of the Kimberley Group sees a dramatic increase in the proportion of mainly Neoarchean detrital zircons (*ca* 2525–2480 Ma) with radiogenic Hf (εHf_t = +0.5 to +7). We propose that the Speewah Group was derived largely from highlands of 1865–1850 Ma Paperbark Supersuite granites during the Halls Creek Orogeny. We also propose that the increase in Neoarchean detritus in the Kimberley Group reflects post-orogenic extensional collapse at *ca* 1800 Ma. Orogenic collapse resulted in uplift and erosion of currently unexposed, or subsequently rifted, Neoarchean basement of the Kimberley Craton. A Neoarchean source from within (rather than exotic to) the Kimberley Craton is also supported by the isotopic character of the Paperbark Supersuite, which is consistent with magmatic reworking of a Neoarchean source. Paleocurrent directions in the Kimberley Group, correlation of age and isotopic character of potential source rocks, and a recent paleomagnetic tectonic reconstruction are consistent with a possible sediment source region in the Dharwar Craton, which may have been contiguous with the Kimberley Craton at *ca* 1800 Ma.

LIVING EARTH

04LEA – ADVANCES IN GEOCHRONOLOGY - SHEDDING NEW LIGHT ON EARTH SURFACE PROCESSES AND THE QUATERNARY ENVIRONMENT

04LEA-01. RELIABLE EARTH-SURFACE TEMPERATURES

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It is highly desirable to have a reliable palaeotemperature recorder that can be applied to a variety of Earth-surface and marine carbonate materials, such as soil carbonates, lake carbonates, speleothem, bones, corals, foraminifers, and diagenetic carbonates, among others. Conventional δ18O measurements do not satisfy this requirement. The interpretation of conventional δ18O values of carbonate minerals including fossils, in the general case, is made difficult, and is occasionally confounded, because both the temperature and δ18O 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 (13C, 18O) bond with or near each other rather than with the sea of light isotopes in which they swim" (Eiler, 2006). The proportions of 13C -18O bonds in carbonate minerals (i.e. mass 47 in CO2, extracted from CaCO3 with phosphoric acid) are sensitive to their growth temperatures, independent of bulk isotopic composition.

The methodology requires the simultaneous measurement of all six masses of CO2 (44, 45, 46, 47, 48, 49). Ultra high-sensitivity gas-source mass spectrometry is required, measuring D47 (i.e. CO2 of mass 47/mass 44) to +/- 0.01 per mil and δ18O to 0.001 per mil. Hydrocarbon and chlorine contaminants (e.g. 12C35Cl), even at the ppb level, are fatal to the analysis. Accordingly, CO2 masses 48 and 49 are also measured, and CO2 'clean-up' by gas chromatography is mandatory. Long analysis times (2 to 8 h) are required to gain the necessary precision to declare a carbonate growth temperature of +/- 1.5 to 2 deg Celsius. The long 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 47CO2) 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 CO2 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, siderite, dolomite, molluscs, brachiopods, some foraminifers, fish otoliths, and some corals, and should be applicable to any carbonate minerals that were formed in the 0-200°C temperature range. Moreover, simultaneous determinations of 47CO2 and δ18O for carbonates will constrain the δ18O value (to +/- 0.5 per mil) of the water from which they precipitate. Furthermore, initial empirical measurements (Ghosh et al., 2006b) suggest that the 47CO2 values of carbonates remain unchanged despite later heating to 150-200 deg C even over geological time scales.

The clumped-isotope technique will provide and is providing quantitative estimates of ocean temperatures and sea water δ18O values for much of geological time; terrestrial ground temperatures for the Cenozoic and earlier; hydrologic budgets (temperature and precipitation/ evaporation balance) for inland water-bodies and semi-enclosed water-bodies and details of fluid processes during diagenesis and low-temperature ore deposition. One surprising result is that data from some dinosaur bones indicate their warm-bloodedness. Speleothem and shallow-water corals display D47 disequilibrium and are not readily useable, in isolation, and may need supplementation by an additional independent analytical technique to realise their full potential.

04LEB – RECENT ADVANCES IN THE EVOLUTION OF LIFE THROUGH THE ARCHEAN

04LEB-01. SMELLY OLD LAKES: FACIES DEPENDENCE OF EXTREMELY-DEPLETED NEOARCHEAN $^{13}C_{ORG}$ VALUES

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Highly-depleted $^{13}C_{org}$ values are reported from numerous Neoarchean formations, including those within the Transvaal Supergroup in South Africa, the Fortescue Group in Western Australia and the Steeprock Group in Canada. The acetyl-CoA pathway employed by methanogenic Archaea is capable of extreme ^{13}C fractionations and is generally thought to be responsible for these values, leading to the proposal of a global age of methanotrophy in the Neoarchean (Hayes *19*94). However, *extremely*-depleted values are largely restricted to a single succession: the Fortescue Group, which was deposited on the Pilbara Craton between *ca* 2.8 and 2.6 Ga. I will summarise what is known about depositional environments of the Fortescue Group and discuss ways in which the atypical, continental depositional setting of the group may be affecting our understanding of the timing, intensity and significance of the Neoarchean $\delta^{13}C_{org}$ anomaly.

04LEC – GENERAL CONTRIBUTION

04LEC-01. A THRIVING PROTEROZOIC BIOSPHERE AT THE RISE OF ATMOSPHERIC OXYGEN: EVIDENCE FROM THE *ca* 2.3 Ga TUREE CREEK GROUP, WESTERN AUSTRALIA

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The Paleoproterozoic Turee Creek Group of Western Australia was deposited at 2.45–2.2 Ga, across the critical interval when levels of atmospheric oxygen first began to rise, the atmosphere cooled, and glaciogenic deposits were first widely preserved in the rock record. It is unique in representing a continuous depositional record across the Great Oxidation Event and being well preserved at low metamorphic grade. Near the top of the group (immediately post GOE), a 600 m thick unit of dolomite preserves both shallow water stromatolitic facies and deep water dolarenites and dololutites, as well as a thin units of shale and ferruginous rocks. Deeper water units contain layers and nodules of black chert, emplaced after rock deposition and the formation of dolomite concretions but prior to diagenetic compaction.

Shallow water dolomites contain thick sequences of interbedded columnar, domical, and stratiform stromatolites, in addition to thick sections (30 m) with thrombolytic-textured microbialite. An unusual stromatolite form has a “Christmas-tree” like appearance with horizontal, slightly upward-curving branches that somewhat resemble the branching patterns of *Jacutophyton*. A unit of mm-scale bedded jasper and quartz on the flanks of a large (30 m) teepee structure contains vertically-oriented filamentous microstructures resembling *Frutexites*.

In the deeper water part of the succession, black cherts contain a variety of kerogenous microfossils. Black chert from dololutite contains predominantly filamentous microbes and relatively rare, non-filamentous, microfossils that together comprise a mesh of interlaced microbial filaments that clump and wrap around elliptical domains of clear silica. The most abundant microfossils in these samples are broad, septate filaments having elongate cells (~5 µm wide and ~8 µm long); medium- (~2.5 µm-wide) and narrow- (~1.5 µm-wide) diameter filaments composed of bead-like cells; and very narrow filaments, <1.0 µm in breadth. The broadest of these exhibit well-preserved transverse cell walls. Distinctive features of the Turee Creek filaments compared with fossilised shallow-water stromatolitic assemblages are their exceptional length (many hundreds to over a thousand microns in length), and their interlaced web-like fabric, which has not previously been reported from the geological record. This assemblage is interpreted as a sulfuretum.

Cherts from more ferruginous layers contain a distinct assemblage consisting of rare filaments, more common, spherical bodies, and very fine filamentous forms (20 µm long x 1 µm wide) in weakly radiating bundles. Spherical bodies are 50–100 µm in diameter and characterised by inner body with a honeycomb texture of kerogen surrounding clear (cell?) domains, all of which is surrounded by a spherical rind of very fine-grained silica containing thin strands of kerogen with branching outer tips that emanate out from the inner kerogenous body. The outer rind of fine silica suggests the presence of a very thin, outer wall to the structures.

Many of the microfossils and structures described here are similar to forms from younger Proterozoic rocks, but are older by at least 400 Ma and indicate that the Proterozoic biosphere – including possibly, eukaryotic life – was established soon after the GOE.

04LED – GENERAL CONTRIBUTION

04LED-01. THE NATURE AND GEOLOGICAL SETTING OF THE RED CRUST – A WIDESPREAD LOWER CAMBRIAN (SERIES 2) FERRIMICROBIALITE HORIZON, WEST-CENTRAL FLINDERS RANGES, SOUTH AUSTRALIA

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The Red Crust consists of up to six, one to ten centimetre thick dark red ferrimicrobialite layers interbedded with bioclastic limestones at the top of the Wilkawillina Limestone (Cambrian Series 2) or its stratigraphic equivalents. It is present in the Arrowie Basin in the central and northern Flinders Ranges and the Stansbury Basin on Yorke Peninsula.

The Red Crust is made up of several different types of ferrimicrobialites; digitate, domal and laminar ferrimicrostromatolites, filamentous and coccoidal ferrimicrobialites, and Frutexites. Calcimicrobialites are locally abundant.

Ferrimicrobial activity is evident several metres below the main laminated Red Crust horizon. Within grainstone substrates, ferri-oncoids, intergrain Leptothrix and other ferrimicrobialite growths and ferrimicrobialite microborings are common. Where the Red crust overlies archaeocyath reef-tract, ferrimicrobialites are intergrown with archaeocyath extrathecal tissue (stereoplasm) up to several metres below the main Red Crust itself.

Within the Red Crust, archaeocyaths and other sponges, including the calcareous sponge Gravestockia grow upon, and are overgrown by complex ferrimicrobial layers.

The Red Crust was previously interpreted to be a fossil soil or calcrete formed on a surface of subaerial exposure and a regionally important disconformity and sequence boundary. However,the Red Crust itself definitely formed in a marine environment as shown by the calcareous sponges and archaeocyaths growing within it, and the ubiquitous presence of bioclastic and microbial material of marine provenance. There is no microfacies evidence, or karstic features, within the substrate to indicate subaerial exposure.

The deep red colour of the Red Crust is due to hematite, which is always intimately associated with microbialites. Limestone hosting the Red Crust contains <0.1% iron while the Red Crust itself contains up to 15% iron. The intimate association of iron with the microbialites in this marine environment indicates that the concentration was due to microbial activity extracting these ions from sea-water. Either unusually intense microbial activity concentrated these ions from the normal low background levels, or iron was derived from an incursion of marine waters enriched in soluble ferrous ions. The wide areal, and limited stratigraphic, extent of the Red Crust shows that this was a regional scale event but quite short lived. The Red Crust formed as a 'blanket' covering much of the sea floor, and was not present on surfaces of emergence. It is interpreted to be an isochronous horizon.

The lower Cambrian Red Crust is similar to iron and manganese rich crusts with ferrimicrostromatolites and Frutexites described from the Tethyan Jurassic, which are interpreted to be condensed, deep-water sediments with the metals derived from hydrothermal or volcanic activity. The Red Crust of the Arrowie Basin formed mainly in marine environments.

The Red Crust is of considerable paleontological and paleoecological interest as a texturally well preserved, extensive, ferri-and calcimicrobial horizon with associated archaeocyath and other sponge faunas. The Red Crust may be the result of a wide spread lower Cambrian excursion of anoxic Fe^{2+} enriched deep marine waters onto a carbonate shelf environment.

04LED-02. SEVERE SELENIUM DEPLETION IN THE OCEANS IN THE PHANEROZOIC AS A PLAUSIBLE FACTOR IN THREE MAJOR MASS EXTINCTION EVENTS

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Many trace elements (TEs) are essential for life. Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) techniques can measure such elements with accuracy down to single parts per billion in pyrite from marine black shale samples. This new dataset of TEs throughout the past 3 billion years reveals trends in TEs in the oceans. Se is an essential TE for all animal life as it is utilised in the formation of anti-oxidising enzymes and selenoproteins, with aquatic organisms generally having larger and more Se-dependent selenoproteomes. Known environmental and tolerance levels of the TE selenium (Se) for extant organisms can be utilised to infer how periods of severe Se depletion offer a potential causal factor in certain mass extinction events. Our data shows that extreme Se and other vital TE deficiency in the oceans fell below estimated thresholds for life in modern oceans, and these periods of TE deficiency preceded three major mass extinction events at the end Ordovician, end Devonian and end Triassic. Oceanic anoxia has been invoked for these events as a cause for marine extinctions, but TE depletion begins before peak oxygen lows based on current O_2curves, and persist longer. The end Devonian extinctions comprise 4 subsequent events (Taghanic, Frasne, Kellwasser, Hagenberg events) over 15 million years (385–359 Ma) in which rapid decline of Se, Co, Mb, Zn and Cu in the oceans formed a ‘perfect storm’ of severe TE depletions. Such depletions of essential TEs would have stressed much of the marine biota and represent an important but hitherto underexplored correlate of major mass extinctions in the marine realm. Fluctuations in other trace elements do not correlate as closely with these extinction events, nor is there any abnormal TE trend associated with end Permian or end Cretaceous extinctions. We suggest these major extinction-related cycles were broken either by large increases of oxygen from seafloor exhalation and nutrient increases, or by major increases in plant biomass.

04LED-03. SIMILARITIES BETWEEN SEVERAL MAJOR EXTINCTIONS AND PRESERVATION OF LIFE: BIOMOLECULES TO GEOMOLECULES: AN INTERDISCIPLINARY APPROACH

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Photic zone euxinia (PZE) conditions in ancient seas have been proven important for elucidating biogeochemical changes that occur during three of the five mass extinctions of the Phanerozoic– Permian/Triassic (Grice *et al.* 2005 *Science* **307**, 706–709), Triassic/Jurassic (Jaraula *et al.* 2013 *Geology* **41**, 955–958) and the late Givetian–early Frasnian (Devonian) events (Tulipani *et al.* 2014 *Gondwana Research* submitted) including conditions associated with unique fossil preservation (Melendez *et al.* 2013 *Geology* **41**, 123–126). The series of events preceding the Triassic/Jurassic event, during, and post extinction is remarkably similar to those reported for the Permian/Triassic extinction, the largest extinction event of the Phanerozoic.

For the late Givetian–early Frasnian event, the first forests evolved and reef-building communities and associated fauna in tropical, marine settings were largely affected (Grice *et al.* 2009 *Geochimica et Cosmochimica Acta* **73**, 6531–6543) a novel biomarker proxy for freshwater incursions in marine paleoenvironments has been established. Evidence of a persistently stratified water-column (freshwater lens overlying more saline hypolimnion), with prevailing anoxia and PZE were established on the margins of the reef slope (Canning Basin, WA).

Also from the Canning Basin, WA – the exceptional preservation of a suite of biomarkers in a Devonian invertebrate fossil within a carbonate concretion supports rapid encasement of the crustacean (identified by % of C_{27} steroids) enhanced by sulfate reducing bacteria under PZE conditions. PZE plays a critical role in fossil (including soft tissue) and biomarker preservation. In the same sample the oldest occurrence of intact sterols are identified and have been preserved for *ca* 380 Ma (Melendez *et al.* 2013 *Nature Scientific Reports* **3**, 2768). The exceptional preservation of the biomass is attributed to microbially induced carbonate encapsulation, preventing full decomposition and transformation thus extending sterol occurrences in the geosphere by 250 Ma. A suite of *ca* 50 diagenetic transformation products of sterols was also reported, showing the unique coexistence of biomolecules and geomolecules in the same sample previously assumed unfeasible. The coexistence of steroids in a diagenetic continuum range from stenols to triaromatic steroids all attributed to microbially mediated eogenetic processes. Under exceptional conditions concretions preserve biomolecules at extraordinary levels, providing a new research opportunity to study the distributions of biomolecules in deep time and improving our understanding of the evolution of life where fossils are rarely preserved.

Three critical questions will be addressed during this keynote presentation. 1. When and how on Earth was life nearly entirely wiped-out? 2. How similar were 3 of the 5 mass extinctions on Earth? 3. How did exceptional preservation of biological material occur?

04LEE – GENERAL CONTRIBUTION

04LEE-01. AN ANTIPODEAN PALAEOSPONDYLUS?

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Palaeospondylus gunni Traquair is a small-jawed vertebrate, known exclusively from thousands of articulated specimens collected from the Middle Devonian of northern Scotland. The taxon has intrigued and beguiled fossil fish workers since its first description in 1890, being first described as an agnathan, and subsequently as a member of almost every jawed fish group known, including larval forms of the other gnathostomes found in the same deposits. The problems with determining the relationships of *P. gunni* are caused by the small size of specimens (usually less than 3 cm long), and the near-impossibility of preparing them in order to identify separate elements of the skeleton, other than by serial thin sectioning. Using that technique, the histological structure of the skeleton was recently revealed to be a novel mineralised tissue formed of a calcium phosphate scaffold that encased individual cartilage cells, which were not mineralised and thus not themselves preserved.

A small Emsian–Eifelian limestone outcrop of the Cravens Peak Beds, northwestern Queensland, has yielded rich and well preserved assemblages of microremains from vertebrates including osteichthyans, acanthodians, chondrichthyans and placoderms. Amongst these assemblages are small elements formed of the same novel tissue that forms the endoskeleton of *P. gunni*, which as far as known is otherwise totally unrepresented in the fossil record. These small, isolated elements, which have shapes comparable to the skeletal elements determinable in *P. gunni*, are readily examined by scanning electron microscopy, and now by microCT scanning and 3D printing, which show their uncompressed shape, articulation surfaces, and canals penetrating the elements. Based on the new information revealed by these techniques, we can more realistically compare the elements with skeletal structures in other jawed vertebrates to perhaps definitively determine the affinities of *Palaeospondylus*.

04LEE-02. THE UTILITY OF SURVIVOR TAXA FOR MICROVERTEBRATE BIOSTRATIGRAPHY AND CHEMOSTRATIGRPAHY IN DEVONIAN AND CARBONIFEROUS SECTIONS, CANNING BASIN WESTERN AUSTRALIA

Kate Trinajstic[1], Brett Roelofs[1], Milo Barham[1], Ted Playton[2] & Susan Turner[3]

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There were two major extinction events during the Late Devonian. The first at the Frasnian/Famennian boundary is classed as a mass extinction and is estimated to have resulted in the loss of 60% of all taxa. This event had little effect on the vertebrate fauna whereas the second extinction event, at the end Famennian, greatly affected the vertebrates with all placoderms (armoured jawed fishes) and thelodonts (jawless fishes) becoming extinct at this time. Gondwana had up to this point provided a refuge for the thelodonts as they were extinct in the northern hemisphere by the end of the Givetian. However, it has been difficult to locate the precise position of major extinction events within the Canning Basin as the facies lack the distinct and associated lithological changes common in the Northern Hemisphere. Conodont and goniatite biostratigraphy has been traditionally used to locate the boundaries; however, the lack of age diagnostic fossils in backreef and restricted facies makes dating these facies problematic. Recent studies have indicated that microvertebrates (fish teeth and scales) are age diagnostic in restricted facies. One particular value of microvertebrates is that they also occur with conodonts in more open marine conditions and so can be correlated to the standard zonations. For this study sampling for conodonts and microvertebrates was carried out within measured sections at Horse Spring, Casey Falls and South Oscar Range with additional spot samples collected from the upper Famennian and lower Carboniferous Fairfield Group. The microvertebrate fauna recovered included scales from a Turiniid thelodont (jawless fish), recorded from the *crepida* to upper *marginifera* conodont zones, and representing the youngest recorded presence for this taxon. Prior to this work the youngest record of thelodonts was from lower Frasnian sediments in the Carnarvon Basin, Western Australia and then later Frasnian sediments from the Canning Basin. These discoveries have extended the known range of thelodonts from the Silurian to the end Famennian. In addition, a diverse chondrichthyans (shark) fauna has been recovered with many species showing temporal affinities to taxa in the Middle East and North Africa. The utility of microvertebrates as environmental proxies was also evaluated. Analyses reveal consistent $\delta^{18}O$ values for chondrichthyan taxa from different environments. This study indicates that microvertebrates can be utilised in biostratigraphy and chemostratigraphy to correlate between basin, fore-reef and platform facies in the Canning Basin, Western Australia and their occurrence in Western Australia provides new data for biostratigraphic correlation across Gondwana.

04LEF – THE AUSTRALIAN NEOGENE: PRELUDE TO THE PRESENT

04LEF-01. EARLY PLIOCENE ARIDITY AND NEOGENE LANDSCAPE EVOLUTION RECORDED BY A FLUVIAL SEDIMENT SYSTEM (CAMPASPE FORMATION) NORTH QUEENSLAND

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Campaspe Formation, a fluviatile sand-dominated unit, is extensively developed in the Charters Towers region of north Queensland where it covers an area of 11 000 km^2 overlying Paleozoic basement and erosional remnants of

Paleogene Southern Cross Formation. In the northern part of its distribution it is interlayered with, and overlain by, flows of Nulla Basalt. It is dated as early Pliocene, based on the 3.8 Ma age of the Myrilumbing Flow interlayered with its upper part as consistent with thin ferricrete developed at its surface. The formation defines the Campaspe Surface at an elevation of 200–440 m in the present landscape, falling gently from upland to the west towards the current channel of the Burdekin River. This surface is a relict alluvial plain, which mirrors the contemporary drainage. Although lightly incised by westerly-flowing tributaries of the Burdekin River it has survived, essentially intact, from the early Pliocene. Geometry of the formation is established from some 2000 mineral exploration drill holes and seismic profiling. It has an average thickness of some 60 m, reaching a maximum of over 200 m. It blankets a pre-existing, low relief landscape in which a basement ridge divides it into two sub-basins that conform to the present drainage.

The formation consists of poorly sorted sandstone with minor conglomerate and siltstone and contains paleosol horizons with associated calcrete. Matrix supported sandstone is represented in the succession, indicating deposition from hyperconcentrated flows. Sandstones generally show poorly defined planar layering but beds with cross lamination also occur. They are characterised by pore-filling silt and mud such that the unit produces essentially no groundwater. Facies attributes are consistent with deposition by ephemeral, dry climate stream-flow inefficient in cross-drainage discharge, inducing aggradation and resulting in a substantial sediment body perched in the landscape. Framework grain compositions show the formation to be mineralogically mature, representing erosional debris that has been through intense weathering in an earlier climatic regime. That earlier cycle is reflected by duricrust developed in the fluviatile–lacustrine Southern Cross Formation of Paleogene age. Duricrust surfaces are now upstanding in the landscape, representing erosional remnants from inverted relief developed in a mid-Cenozoic, pluvial, landscape cycle.

Pliocene aridity has been recognised for southern and central Australia but has not previously been documented for the northern part of the continent. A climate regime substantially more arid than that of the present can now be assigned to Australia in general. Erosion associated with aridity induces landscapes of subdued relief. Early Pliocene aridity leading to dry climate conditions of the present is likely to have exerted a profound influence on the physiography of the Australian continent. Its influence as an environmental backdrop shaping evolution of the Australian fauna and flora has yet to be fully evaluated.

04LEF-02. A FLUVIAL APPROACH TO CONSTRAINING NEOGENE SURFACE UPLIFT IN SOUTH WESTERN AUSTRALIA

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Embedded within Australia’s topography is a fluvial network that is sensitive to variations in horizontal and vertical motions. The notion that a river acts as a ‘tape recorder’ for vertical perturbations suggests that changes in spatial and temporal characteristics of surface uplift can be deduced through the analysis of longitudinal river profiles. The relative tectonic quiescence of the Australian continent during the Cenozoic makes it an excellent natural laboratory to study recent large-scale variations in surface uplift, often linked with mantle convective processes. Here, we analyse 20 longitudinal river profiles around the Australian continent. Concave upward profiles in northeast Australia indicate an absence of recent surface uplift. In contrast, the major knickzones within longitudinal profiles of rivers in southwest Australia suggest recent surface uplift. Given the lack of recent large-scale tectonic activity in that region, this uplift requires an explanation. Applying an inverse algorithm to river profiles of south Western Australia reveals that this surface uplift started in the Eocene and culminated in the mid–late Neogene. The surface uplift rates deduced from this river profile analysis generally agree with independent geological observations including preserved shallow-marine sediment outcrops across the Eucla Basin and south Western Australia. We show that the interplay between global sea level and long-wavelength dynamic topography associated with south Western Australia’s plate motion path over the remnants of an ancient Pacific slab is a plausible mechanism driving this surface uplift.

04LEG – GENERAL CONTRIBUTION

04LEG-01. MIOCENE BASALT, TECTONICS, AND EVOLUTION OF MURRUMBIDGEE RIVER DRAINAGE OF THE BURRINJUCK-JUGIONG AREA, SOUTHERN NSW HIGHLANDS

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The north flowing tract of the Murrumbidgee River west of Canberra follows the faulted boundary between the Canberra-Yass Plain, at about 600 m a.s.l., and a gently north sloping dissected highland to the west, up to 600 m higher. Thirty five km northwest of Canberra the river bends westward, towards the Cenozoic Murray Basin, in a valley deeply incised into the highland. It has been dammed in a narrow granite gorge at Burrinjuck near the western margin of the highland. Five km west-northwest of the dam the river bends north for 10 km, then west-northwest for 20 km and south for 15 km before bending again to the west. It formerly flowed more directly west-northwest and west from Burrinjuck. Its paleovalley contains up to 150 m of lower Miocene basalt, overlying and interbedded in places with quartz-rich sand, silt, and very well rounded quartz-rich pebble gravel. Bedrock of the paleovalley is Silurian dacitic volcanics and granodiorite. Much of this is deeply weathered. The basalt flowed down former southern tributaries, temporarily damming the river and causing the northerly diversion. It would also have temporarily dammed Jugiong Creek, a major downstream northern tributary. The paleovalley slopes westward, at a gradient steeper than the present river, from an elevation of about 580 m near Burrinjuck. This is around 300 m higher than the present deeply incised river.

The lower Miocene landscape had local erosional relief of around 100 to 300 m, about half the present relief. This implies rejuvenation of drainage by a substantial late Cenozoic tilting and uplift of the highlands relative to the Murray Basin to the west.

A small basalt outcrop has recently been discovered 5.5 km north of Wee Jasper at 400 m a.s.l. in the valley of the Goodradigbee River, a southern tributary of the Murrumbidgee upstream from the granite gorge and the lower Miocene basalt outcrops. This implies a later episode of basaltic volcanism when erosional relief was closer to the present relief.

04LEG-02. CEMENTED IN TIME: FORMATION OF THE 20 000 YEAR OLD WILLANDRA FOSSIL TRACKWAY

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The Willandra Lakes system of southwestern NSW is situated within the Murray Basin, and consists of 19 interconnected relict lake basins. In general, the lake sediments within the Willandra Lakes system consist of well-sorted quartz sands (with typical lacustrine shelly fauna), associated with deeper water clays and sandy clays. In 2003, the region was found to host the largest known *in-situ* tract of Pleistocene human footprints in the world, with the site located on the shoreline of a small, relict lake basin between Lakes Garnpung and Leaghur. Optically Stimulated Luminescence dating revealed that the sediments were deposited between 19 000 and 20 000 years ago. The area is of great cultural value to the local Aboriginal communities (the traditional tribal groups Paakantyi, Mutthi Mutthi and Ngiyampaa), as well as to both the national and international scientific communities. Detailed mineralogical (quantitative XRD), geochemical (XRF, ICP-MS, stable isotopes) and textural (petrography, SEM) analyses of the sediments were undertaken to help determine their origin and provide a basis for their future conservation.

The footprints themselves are impressed into a hardpan unit, surrounded by low sand dunes. Approximately 820 m^2 of the hardpan has been excavated and explored. The footprint-bearing sediments are composed of a series of thin laminae totalling 150 mm thick, accumulated over repeated cycles of wetting and drying. These sediments are largely composed of pelloids and intraclasts of authigenic clay-sized particles (<2–8 µm) of ferroan magnesite (or hydromagnesite/palygorskite), eolian-derived fractured quartz grains and minor (<10 wt%) kaolinite/illite. There is a large lateral and vertical variation in the modal mineralogy; the NE corner contains 90.5 wt% ferroan magnesite (and minor smithsonite) while the SW and W parts contain 49 wt% ferroan magnesite. The other sediments are largely composed of eolian quartz (up to 85 wt%), kaolinite, illite, rutile, albite, microcline, hematite, goethite and rare dolomite. In terms of stable isotopes, the ferroan magnesite carbonate has a $\delta^{13}C$ of –2.5‰ while the hydromagnesite has $\delta^{13}C$ of 0.4‰.

The magnesite, hydromagnesite and palygorskite appear to have been derived through precipitation within the lake. Although direct precipitation of these phases is rare under surficial conditions, it can occur if there is a high Mg/Ca, only possible if extensive early precipitation of calcite cements occurred before the waters entered into the lake. As the lake dried-out, there was an increase in salinity resulting in a decrease in the activity of water in solution, thereby increasing the hydrated Mg^{2+} leading to magnesite precipitation.

04LEg-03. PALYNO-ASSEMBLAGES INDICATIVE OF SCLEROPHYLLOUS AND XEROMORPHIC PLANT COMMUNITIES IN THE LATE EOCENE OF SOUTHERN WESTERN AUSTRALIA

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Palynological age dating and the reconstruction of past vegetation for the early Cenozoic (Paleogene) of Western Australia (WA) rely on the extrapolation of biostratigraphic zones established for southeastern Australian basins. These studies indicate that *Nothofagus*-dominated mesothermic forests were prominent in these areas. Several studies have highlighted problems with this method as very different pollen-spore assemblages are being recovered from WA sediments. Of most significance is the recognition of high percentages of species that potentially indicate a greater sclerophyllous and xeromorphic component to the late Eocene vegetation of southern WA.

Late Eocene sediments from the Mulga Rocks deposits, southern Officer Basin (Great Victoria Desert, Western Australia) contain pollen and spore assemblages comprised of an unusually high percentage of affiliates of Myrtaceae (e.g. eucalypts, melaleucas). Also prominent are fossil proteaceous species suggestive of heath, woodland and/or dry sclerophyll forests. Of the most importance are those aligned with the tribe Conospermeae (*Petrophile* Knight) and the Grevilleoideaea genus *Xylomelum* Sm. This contrasts with previous assumptions that the *Nothofagus* (a cool, temperate rainforest species) dominated mesothermal rainforests interpreted for southern eastern Australia extended across the entire southern half of the continent in the late Eocene.

04LEg-04. RARE EARTH ELEMENT, Sr/Ca, AND Mg/Ca RATIOS IN LARGER BENTHIC FORAMINIFERS FROM HERON REEF, GREAT BARRIER REEF

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The trace element geochemistry of planktic foraminifers provides a very important source of paleoceanographic and paleoclimatic data. Larger benthic foraminifers (LBFs) have been the subject of much less geochemical characterisation primarily because they occur in relatively thin and discontinuous shallow carbonate facies, rather than in thick deep sea successions. Regardless, LBFs are major sediment producers in shallow low latitude settings and provide important biostratigraphic and paleoecological data back into the late Paleozoic. We analysed four common LBFs from modern reef flat sand on Heron Reef, Great Barrier Reef, for rare earth element (REE), Y, Sr and Mg concentrations using inductively coupled plasma-mass spectrometry. Taxa analysed include: the miliolid *Marginopora vertebralis* (high-Mg calcite [HMC] with porcelaneous microstructure), and rotalids *Calcarina hispida* and *Baculogypsina sphaerulata* (HMC with lamellar hyaline microstructure) and *Amphistegina lessonii* (low Mg calcite [LMC] with lamellar hyaline microstructure). Samples were sorted into well preserved, moderately preserved and poorly preserved classes prior to analysis. Samples were found to be free of terrigenous contamination. The best preserved *A. lessonii* have mean Mg/Ca = 36.3 mmol/mol (SD = 2.6) and Sr/Ca = 1.7 mmol/mol (SD = 0.04) for pink samples and Mg/Ca = 30.1 mmol/mol (SD = 3.4) and Sr/Ca = 1.6 mmol/mol (SD = 0.08) for white samples. Best preserved *C. hispida* (combined pink and white) and *B. sphaerulata* have mean Mg/Ca = 119.9 mmol/mol (SD = 2.8) and 120.5 mmol/mol (SD = 2.2), respectively, whereas the best preserved *M. vertebralis* have mean Mg/Ca = 126.1 mmol/mol (SD = 6.8) and Sr/Ca = 2.1 mmol/mol (SD = 0.3). The three rotalids have similar total REE concentrations with mean ΣREE being 131.5 ppb for *C. hispida*, 143.0 for *B. sphaerulata*, and 142.0 ppb for *A. lessonii*, in each case with systematically increasing REE concentration in more poorly preserved tests. The miliolid *M. vertebralis* has more than one order of magnitude higher REE concentrations with mean ΣREE = 2543.0 ppb. Shale normalised REE+Y patterns of *C. hispida, B. spaerulata* and *A. lessonii* are very similar and are characterised by: light REE (LREE) depletion (range Nd_{SN}/Yb_{SN} = 0.23–0.37); negative Ce anomalies [range $(Ce/Ce^*)_{SN}$ = 0.75–0.87]; positive La anomalies [range $(La/La^*)_{SN}$ = 1.39–1.84]; superchondritic Y/Ho ratios (range = 43.8–51.9); and slight positive Gd anomalies [range $(Gd/Gd^*)_{SN}$ = 1.08–1.26]. Hence, they appear to have incorporated REEs proportionally from shallow seawater. Shale normalised REE+Y patterns of *M. vertebralis* differ having: significantly less LREE depletion (range Nd_{SN}/Yb_{SN} = 0.54–0.77); consistent negative Ce anomalies [range $(Ce/Ce^*)_{SN}$ = 0.84–0.86]; positive La anomalies [range $(La/La^*)_{SN}$ = 1.33–1.43]; superchondritic Y/Ho ratios (range = 48.5–51.6); and slight positive Gd anomalies [range $(Gd/Gd^*)_{SN}$ = 1.12–1.18]. Hence, whereas the rotalid genera with hyaline tests may serve as proxies for seawater REE distributions, the porcelaneous miliolid does not. Hence, foraminifers with hyaline tests, such as the Cenozoic nummulitids, may provide more reliable proxies for seawater REE distributions than porcelaneous forms, regardless of Mg content (i.e., HMC *vs* LMC).

POSTERS

MONDAY 7 JULY

ENVIRONMENT

01EV-P02. 'AGE', RECHARGE RATES AND CONNECTIVITY OF GROUNDWATER IN DEEPER AQUIFERS OF THE SYDNEY BASIN.

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The Permo-Triassic Sydney Basin covers almost 50 000 km^2 and extends from the outer continental shelf inland to the Great Diving Range, from Newcastle in the north to Batemans Bay in the south. Major lithological units broadly include the Permian Coal Measures, the Permo-Triassic Narrabeen Group, the Triassic Hawkesbury Sandstone and the Wianamatta Shale. The Hawkesbury Sandstone is generally made of very thick heavily compacted quartz sands, with minor discontinuous shale units. Its aquifer system is a complex, dual porosity, deep fractured system with three aquifers typically recognised. The shallow and intermediate aquifers contribute to spring and base stream flows as well as groundwater dependent ecosystems, and the deep regional aquifer system. It is this deeper system that is investigated in this study.

Groundwater from the Sydney Basin, and in particular Hawkesbury Sandstone aquifers, forms part of emergency supply strategies for coping with future severe droughts, with >5 million people living in the region, in addition to large industrial development. Despite the significance of these resources there are still large gaps in our knowledge of these aquifers including aspects such as age recharge and mixing rates. Filling these knowledge gaps has become even more critical in order to understand impacts of existing and planned coal and coal seam gas (CSG) mining of the underlying Illawarra Coal Measures. Community concerns over risks associated with CSG extraction have reached fever pitch in recent years, and there is public demand for research into these aquifers. Understanding of these systems has been complicated by the poor quality of existing data – commonly relying solely on driller bore-logs, reporting only being carried out for specific mine or extraction activities, and therefore conducted over localised zones, and the lack of communication between companies and agencies with data. Additionally, large variations in hydraulic properties have been noted over localised areas.

This study sampled bores along a loosely east–west transect across urban Sydney, targeting the deeper Hawkesbury Sandstone and Narrabeen group aquifers. Very high salinities are recorded by several samples, interpreted to relate to the influence of the overlying Wianamatta Group and Cumberland Basin sediments in those locations. Equally however, this signal may record the impact of interaction with coal seams. Results also show inconsistencies between tritium and radiocarbon groundwater 'ages' in multiple locations, suggesting that extensive mixing occurs between aquifers. A relationship between bicarbonate, depth and $\delta^{13}C$ isotopic ratios highlights the influence of methanogenesis for deeper samples and either interaction with localised organic matter or deeper inputs derived from the coal measures. These findings have implications for potential coals seam gas extraction in the region, demonstrating that impacts could be significant in areas of high fracturing and connectivity. This supports previous assessments of groundwater vulnerability and the need for further detailed research.

01EV-P03. UNDERSTANDING RIVER – GROUNDWATER INTERACTIONS IN A KARST SYSTEM, WELLINGTON, NSW

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Wellington, central western New South Wales, Australia, has limestone formations, which are a part of the Lower Devonian Garra Formation. Since the area was folded and fractured in the Mid-Devonian and early Carboniferous, there is a high potential for connectivity between the river, the alluvium and the karst aquifer through faults, fractures and conduits. The Wellington Caves provides a unique, direct access to the karstic groundwater systems, which are considered representative of limestones in New South Wales. In some parts of the limestone, large karstic caves and passages have formed. Overlying the Garra Formation are alluvial sediments, which are associated with the Bell River. For four years, we have monitored river water levels and groundwater levels. The latter have been measured in boreholes in the alluvium and limestone, and in cave chambers in Cathedral Cave and in Anticline Cave where the groundwater is intercepted.

Our comparison of the monitoring data provides a unique insight into the connectivity between the surface water, and the alluvial and karst systems. It is also important for the understanding of the importance of river recharge for groundwater resources in the region. Recharge to the alluvial aquifer and karst system is demonstrated to be from the Bell River, which is a losing river along this reach. Our alluvial and karst groundwater monitoring sites show synchronous timing in the rise of water level in both alluvial and karst groundwater systems to high discharge events in the river. When there is no flow in the Bell River, groundwater levels in the alluvial and karst systems decrease rapidly, as observed in the recent 2013–2014 drought in the region.

Water chemistry results show that the karst groundwater system has a typical carbonate geochemical signature, in contrast to the alluvial groundwater and the Bell River water. The synchronicity of water level response between river and groundwater systems, in combination with the constant karst water chemistry, demonstrates that a hydraulic or piston effect occurs during periods of river flooding. The increases in groundwater levels in the karst and alluvial systems provide proof for a direct hydraulic connection, but river water does not reach and recharge the caves. This is particularly evident from our monitoring data through the major December 2010 floods. Ongoing research using hydrogeochemical modelling will provide constraints on the precise nature of connectivity in this system. The results of these assessments provide unique information on the sustainable planning and management of water resources in the study area.

01EV-P04. GEOPHYSICAL IMAGING OF GREAT ARTESIAN BASIN MOUND SPRINGS

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Artesian mound springs occur along the southwestern edge of the Great Artesian Basin (GAB), in northern South Australia, but their deep structure and relationship to faulting is not well understood. This paper presents a range of electrical geophysical surveys conducted over three mound spring systems (Beresford and Warburton Springs, the Bubbler Spring complex, and Freeling Springs) to define depth and flow paths from the GAB aquifers to the surface.

Techniques used include electrokinetic self potentials (SP), audiomagnetotellurics (MT), and time-domain electromagnetics (TEM). Self potentials, which are naturally occurring voltages that occur directly from the subsurface fluid flow, show a pattern of larger voltages at spring vents and seeps. Spatial correlation suggests that these responses are caused by narrow, upwards flow paths beneath the springs. Similar responses also occur underneath 'extinct' springs, suggesting that shallow subsurface discharge of aquifer waters is still occurring. Little evidence was found for significant downward infiltration from spring tails.

Modelling of TEM and MT data shows that the confining Bulldog Shale, which is generally very conductive, contains slightly more resistive areas underneath springs and spring complexes at a depth range of tens to hundreds of metres. These more resistive zones can be related to a combination of carbonate precipitation in subsurface pores and less saline aquifer water migrating upwards through fault systems. Magnetotelluric anisotropic-modelling shows that fault zones exist under many of the mound springs, particularly at Beresford and Warburton Springs and the Bubbler Spring complex, with data consistent with models containing parallel vertical fault planes striking NW–SE. The models contain fault zones in the aquifer and immediately underlying basement, suggesting that fluids may be sourced from the aquifer and deeper layers. However, the fault zone is not sensed effectively in the Bulldog Shale aquitard, due to the very slight resistivity contrast.

We conclude that a combination of electrical geophysical methods can play a significant role in mapping complex groundwater dynamics in sedimentary environments.

01EV-P05. ASSESSMENT OF THE HYDRAULIC CONNECTION BETWEEN GROUNDWATER AND SURFACE WATER USING LONG-TERM AQUIFER PUMPING TESTS

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Understanding groundwater–surface water connectivity is an integral part of assessing groundwater impacts associated with mining and coal seam gas developments. This paper outlines part of a study that investigated the hydraulic connection between groundwater and surface water as well as between different aquifers to assess the potential impacts associated with proposed mining activities at a site in New South Wales.

Two long-term (21-day) pumping tests were carried out adjacent to streams to assess the hydraulic connections between the stream, the associated alluvium, and the underlying Permo-Triassic water bearing zones. In each of the two locations, test pumping was carried out at production bores located within 100 m of the streams and screened across water bearing zones within the Permo-Triassic rocks. Piezometric levels were monitored using nested piezometers screened in several hydrogeological units, including the alluvium and underlying coal measures.

Both long-term pumping tests resulted in drawdown in the order of 10–20 cm toward the end of the tests. Moderate rainfall recharge to the aquifers during both tests complicated interpretation of the test data. A local-scale numerical model was used to verify the 3D hydraulic parameters in each of the units, in particular, the parameters that control leakage from the alluvium to the Permian aquifers when they are depressurised. The modelled best fit K_h and K_v for the alluvium were estimated in the order of 1 m/d and 0.001 m/day respectively. These results imply very low leakage rates and a horizontal to vertical permeability ratio in the order of 10^3 or more.

These findings were consistent with other lines of evidence, including strong vertical hydraulic gradients, distinct isotopic compositions and radiocarbon ages, and suggest that induced leakage rates due to depressurisation of the coal measures would be very low and probably less than the long-term rate of recharge to the alluvial systems *via* rainfall and floods.

01EV-P07. CONSTRAINING HYDROCHEMICAL PATHWAYS IN A SMALL INTERNALLY DRAINING BASIN (LAKE GEORGE BASIN, NSW) USING ISOTOPES OF THE WATER MOLECULE

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Lake George, located in the Southern Tablelands of New South Wales, is a shallow, intermittent lake with highly variable salinity and water levels. The lake is the focus of drainage for a small internally draining basin containing 6 subcatchments. Previous studies indicate that the lake's water level (and salt content) is primarily affected by the short- and long-term variations in precipitation, runoff and evaporation. Contributions from the regional groundwater are likely to be low because of the thick (~40 m) clay unit that underlies the modern extent of the lake. As a result, the lake's hydrograph, which is one of the oldest in the world, has recorded droughts and wet periods of southeastern Australia over the last 200 years.

This project aims to provide much needed information regarding the sustainability of the Bungendore town water supply, which is composed entirely of groundwater from the Bungendore Alluvium, as well as identify potential risks to water quality in the basin. This project also forms one part of a much larger project to investigate the landscape and human evolution of the Lake George Basin, which aims to investigate climatic, vegetation, geomorphological and human change in the basin in recent geological time (<4 million years before present).

Water chemistry and physical data are being used to determine hydrochemical pathways and groundwater recharge rates. Monthly composite precipitation samples are being collected at three sites: north of the lake (Winderadeen homestead), south of the lake (Bungendore post office), and the eastern shore (Rocky Point). Lake water, creek water and groundwater samples are also collected from surface water, existing monitoring bores, and domestic supply bores. Deuterium, oxygen-18 and tritium compositions, as well as major and minor element concentrations are measured using established analytical methods.

Deuterium and oxygen-18 compositions indicate that groundwater is primarily recharged by winter and spring rainfall. In addition, creek water maintains a groundwater type isotopic composition year-round despite variable precipitation compositions, which suggests that the creeks of the basin are fed by aquifers and through flow rather than fresh precipitation. This is also supported by tritium activity observations of creek water (3.27 TU), which are lower than the tritium concentration of local precipitation (4.01–5.41 TU). A local evaporation line has also been determined for Lake George during the period July 2013 (after high rainfall) to November (when the lake dried out due high evaporation rates), which has a significantly shallower slope (5.2) than the preliminary local meteoric water line of the basin (7.0). During this period the lake water isotopic composition increased from values similar to winter/spring rainfall (δ^2H = –21.9 ‰ VSMOW; $\delta^{18}O$ = –4.33 ‰ VSMOW) to values greater than seawater composition (δ^2H = 37.1 ‰ VSMOW; $\delta^{18}O$ = 6.76 ‰ VSMOW). Finally, large discrepancies between chloride and stable isotope mass balances and observed isotopic and chloride concentrations of lake water indicate that either a large amount of mixing occurs with underlying saline porewater, or that current estimations of lake bathymetry do not produce accurate lake volume estimates at low water levels

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01EV-P08. MULTI-ISOTOPE ANALYSIS COUPLED TO RADIOCARBON MEASUREMENTS

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2012 saw the completion of an automated graphite preparation system for AMS radiocarbon measurement at the Research School of Earth Sciences, ANU. The system consists of an Elemental Analyser (EA) and carbonate preparation device coupled to a Sercon 20-20 stable isotope ratio mass spectrometer (IRMS) and an in-house built automatic graphite preparation line. Organic samples are combusted in the EA, gases are purified and ~10% of the gas goes to a high precision measurement of $\delta^{15}N$ and $\delta^{13}C$; the rest of the CO_2 gas is trapped from the helium stream cryogenically. The helium is pumped away using turbo pumps and the trapped CO_2 is automatically transferred to an individual graphite reaction vessel for conversion to graphite using hydrogen and a temperature of 570°C. Carbonate samples are reacted in 5.9 ml glass septa vials under a helium atmosphere, CO_2 is purified and 10% of the CO_2 enters the IRMS for a high precision $\delta^{13}C$ and $\delta^{18}O$ or $\delta^{15}N$ measurement. With this system we process 20 samples a day and we can obtain (depending on the starting material) stable isotope ratios on the exact material that we obtain a radiocarbon measurement on using our Accelerator Mass Spectrometer. Specific scientific examples of the utility of these additional measurements will be shown. Specifically this has proved extremely useful for bone and coral.

01EV-P09. HOW WEATHER AND CLIMATE INFLUENCES SPELEOTHEM GROWTH AND PALEO-CLIMATE ISOTOPIC RECORDS

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Speleothem growth band variations in chemical and isotopic composition are used to infer paleo-climatic conditions. Interpretation of speleothem paleoclimatic records may be improved by matching analysed subsamples to the represented elapsed time and prevailing weather or climatic conditions. Analysed subsamples may represent a month for rapid growth speleothems or many years for slow speleothem growth. Speleothem growth may also be seasonally biased affecting the paleo-climate record. To better understand the temporal fine scale of speleothem growth patterns we have principally used CO_2 concentration in cave air. As $CaCO_3$ is precipitated to accrete a new speleothem layer, CO_2 is released into the atmosphere. However, CO_2 may also come from other sources. To discriminate between different sources a real-time isotopic CO_2 analyser, located near the entrance to Chifley Cave, is used. Cave air is sequentially sampled for 10mins from 4 internal and 2 external locations and analysed for H_2O, CH_4, CO_2, and $\delta^{13}C_{CO2}$. The 3 principal sources of CO_2 are external air, speleothem growth and soil-air. The proportion of each CO_2 source contributing to the total cave air CO_2 is calculated for each sampled Chifley Cave location. CO_2 exhaled from passing tour groups is often recorded as a minor rapid increase before subsiding to the previous background levels over 10–15 mins. Cave air CO_2 shows a seasonal (summer maximum) and often a diurnal cycle, from a minimum late morning to a maximum in the late evening caused by ventilation of external low CO_2 air. Differences between the external temperature and the near constant cave air temperature causes a buoyancy contrast which drives bidirectional cave air ventilation. On hot days cool cave air (11°C) sinks into the Grand Arch and is replenished by sucking external air from the Plughole cave opening. The slightly lower cave atmospheric pressure on hot days also causes soil-air rich in CO_2 to seep into Chifley Cave, notably at the bottom of Katies Bower. On cold winter days relatively buoyant warm cave air escapes *via* the Plughole 70 m above and through minor fissures reversing the summer pattern. A detailed description (10 min sampling for 2 years) of the speleothem growth pattern in response to external temperature variation is presented.

01EV-P11. SCOPE TO PREDICT SOIL PROPERTIES AT FIELD SCALE FROM SMALL SAMPLES USING PROXIMALLY SENSED γ-RAY SPECTROMETER AND EM INDUCTION DATA

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Spatial predictions of soil properties are needed for various purposes. However, the costs associated with soil sampling and laboratory analysis are substantial. One way to improve efficiencies is to combine measurement of soil properties with collection of cheaper-to-measure ancillary data. There are two possible approaches. The first is the formation of classes from ancillary data. A second is the use of a simple predictive linear model of the target soil property on the ancillary variables. Here, results are presented and compared where proximally sensed gamma-ray (γ-ray) spectrometry and electromagnetic induction (EMI) data are used to predict the variation in topsoil properties (e.g. clay content and pH). In the first instance, the proximal data is numerically clustered using a fuzzy k-means (FKM) clustering algorithm to identify contiguous classes. The resultant digital soil maps (i.e. k = 2–10 classes) are consistent with a soil series map generated using traditional soil profile description, classification and mapping methods at a highly variable site near the township of Shelford, Nottinghamshire UK. In terms of prediction, the calculated expected value of mean squared prediction error (i.e. $\sigma^2_{p,C}$) indicated that values of k = 7 and 8 were ideal for predicting clay and pH. Secondly, a linear mixed model (LMM) is fitted in which the proximal data are fixed effects but the residuals are treated as a combination of a spatially correlated random effect and an independent and identically distributed error. In terms of prediction, the expected value of the mean squared prediction error from a regression ($\sigma^2_{p,R}$) suggested that the regression models were able to predict clay content better than FKM clustering. The reverse was true with respect to pH, however. We conclude that both methods have merit. In the case of the clustering the approach is able to account for soil properties, which have non-linearity with the ancillary data (i.e. pH), whereas the LMM approach is best when there is a strong linear relationship (i.e. clay).

01EV-P12. USE OF FIELD-PORTABLE XRF ANALYSIS OF VEGETATION FOR EXPLORATION AND ENVIRONMENTAL GEOCHEMISTRY

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Real-time field analysis of geochemical samples, with limited sample preparation requirements, provides a major advantage in both exploration and environmental geochemical studies. While the quality of the data varies between elements, even semi-quantitative results can assist in screening of samples prior to undertaking laboratory-based analysis. Vegetation is a sampling media that offers potential to map variations in regolith, groundwater and bedrock metal distributions related to the effects of mine site contamination or natural dispersion from mineralisation. Vegetation has also proven an effective alternative to surface regolith sampling in areas with transported cover.

Two orientation studies have been conducted on the application of field-portable XRF directly on vegetation in the field. The first was conducted on two species of wattle – black wattle (*Acacia mearnsii*) and silver wattle (*A. dealbata*) – in the Woodlawn Minesite and surrounding region. The second was conducted on saltbush (*Atriplex vesicaria*) and casuarina over deeply weathered quartz–albite gneiss-hosted pyritiferous cobalt mineralisation southwest of Broken Hill.

At Woodlawn, high levels of contamination for a number of elements related to the deposit itself (Cu, Pb, Zn, Ag) occur in the bark in a zone extending up to 1 km away from the tailing ponds. There is a close correlation between trace elements in the leaves and twigs, but weaker correlation between those organs and bark, in both ore and host rock-related elements. Trace elements are typically more elevated on the side of the trees facing the tailings ponds than away from it and there are correlations between trace and major elements, indicating the main source of metals in the bark to be derived from dust. At Broken Hill, a discontinuous zone with elevated Co and other mineralisation-related metals in plant organs occurs above (weathered) mineralised horizons. Along drainages there is elevated Mn and Zn but this does not appear to be related to the effects of mineralisation.

Laboratory test indicate the penetration distance for X-rays from the field-portable XRF to be in the order of 3 mm for compressed leaves or bark. There is a close correlation for most elements between the fpXRF and laboratory-based XRF or ICPMS analysis.

01EV-P13. SURFACE SOIL SURVEY IN AN ARCHEOLOGICAL CONTEXT: THE KAZANLAK GEOSCIENCE PROJECT, BULGARIA

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While the interdisciplinary field of geoarcheology now often involves petrological surveys at archeological sites, the Kazanlak Geoscience Project aimed to go back to the geomorphology-based beginnings of the field to demonstrate how a simple soil survey could be beneficial to an archeological project. During the 2011 autumn season of the Tundzha Regional Archaeology Project (TRAP), a small geoscience team conducted such a soil survey across the Kazanlak valley in central Bulgaria. Sample sites were randomly selected using stratified systematic random sampling (SSRS), and 155 soil samples were collected. The soil was tested for organic matter content, carbonate content, texture and coarse fraction, with the results analysed and interpolated in a GIS to determine spatial patterns in each of these soil properties within the study area. The data were then used in combination with topographic and land cover datasets to produce a quantitative model of soil erosion potential for the region, which predicted erosion rates of up to 895 t/ha/yr or 70 mm/yr. These findings have various potential applications, such as past landscape reconstructions or in determining spatial relationships between soil properties, landscape stability and surface distribution of archeological artefacts.

01EV-P14. METHODS FOR ADDRESSING NONSTATIONARITY IN CLIMATE SCIENCE, SURFACE HYDROLOGY, AND GEOPHYSICS

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Geostatistical simulation methods are a natural tool to model spatially correlated processes. Geostatistical analysis consists of building a spatial model from the data, and then to use this model for stochastic interpolation. While interpolating large areas, often modellers face difficulties in characterising the inherent non-stationary features. The multiple-point geostatistics (MPS) approach has been developed to go beyond the limitations of two-point variogram based methods, and allow obtaining more realistic representations by deriving the necessary statistics from training images. Still the issue of nonstationarity has to be dealt with in an appropriate manner. From our recent studies on this topic, we present here three different examples in which capturing nonstationarity are crucial. Each study needed a unique way to capture the nonstationarity in spatial features. (i) In hydrological applications the land surface has a variety of features such as topography, water bodies, vegetation, dry land, coastal areas etc. To downscale the outputs of global climate models (GCMs) from coarse resolution to fine resolution the land features will have large influence on the magnitude of variables like latent heat flux, soil moisture, surface temperature etc. The nonstationarity in spatial features can be considered in MPS simulation by imposing locational information such as latitude and longitude and also the type of vegetation cover at those locations. (ii) In fluvial hydraulics the river bed contains sand dunes of different size and shapes which moves along the direction of the flow. In addition, there are many man-made features that are narrow such as pipes, groynes and piers whose positions are fixed. We included latitude, longitude and the distance of points from the left boundary. (iii) Our third example comes from the 3D facies modelling in a fan-delta reservoir in which the width and spread of the channel changes spatially. The nonstationarity is modelled by providing an interpolated map of rotation angles and affinity ratios obtained from the analogue.

01EV-P15. THERMAL EXPANSION OF DEUTERATED MONOCLINIC NATROJAROSITE: A COMBINED TIME-OF-FLIGHT NEUTRON AND SYNCHROTRON POWDER DIFFRACTION STUDY.

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Jarosite and related minerals are of great interest to a range of mineral processing and research applications. In some industrial settings jarosite formation is encouraged; for example to aid the removal of iron species from solutions in hydrometallurgical processes. In other environments such as bioleaching, jarosite formation can hinder the process by creating a kinetic barrier, in the form of a passivation layer, to the desired reaction. Jarosite is a major component of acidic soils and is present in significant amounts in acid mine drainage environments. There has been

a recent resurgence in interest in jarosite minerals since their detection on Mars by the MER rover *Opportunity*. In this context the presence of jarosite has been recognised as a likely indicator of the presence of water on Mars in the past. It is hoped that study of their formation mechanisms, stability and thermoelastic properties will provide insight into the environmental history of Mars as well as informing terrestrial industrial concerns. To this end we are engaged in a program to study jarosite and its formation and stability behaviour over a range of conditions.

This contribution describes *in-situ* powder diffraction experiments to determine the thermal expansion of a deuterated natrojarosite. Data were collected on the HRPD beamline at the ISIS spallation source where the natrojarosite sample was heated from 10–700K, and at the powder diffraction beamline at the Australian synchrotron where the sample was heated from 80–700K. Isothermal neutron and synchrotron datasets were refined simultaneously.

Analysis of the lattice parameter variation with temperature shows that all cell edges increase smoothly to ~500K where there is a discontinuity. This discontinuity represents the initially non-stoichiometric monoclinic jarosite converting to a stoichiometric, rhombohedral phase, shortly after which $FeOHSO_4$ peaks become visible. Thermal expansion coefficients have been fitted from 10–470K and show that there is most variation in the monoclinic c-axis. This direction is normal to the layers of sulfate tetrahedra and iron octahedra within the jarosite structure and contains more flexible hydrogen bond linkages, which more easily accommodate expansion than the more rigid polyhedra.

The thermal expansion determined here have implications for evolution and geological history of Mars, as well as informing terrestrial concerns over the behaviour of jarosite spoil heaps.

01EV-P16. BIOAVAILABILITY AND FATE OF TOXIC AROMATIC HYDROCARBONS IN FUEL SPILLS IN THE ANTARCTIC MARINE ENVIRONMENT

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Despite the widespread use and transport of fuels in Antarctica there is very limited data available on the behaviour of these fuels in the Antarctic marine environment. The potential impacts of a fuel spill on marine biota are largely unknown. Monoaromatic and polyaromatic hydrocarbons are suspected to be the primary contributors to the toxicity of a fuel in the marine environment. The goal of this study was to provide the necessary information on two key factors contributing to the toxicity of the fuels: the degree of bioavailability and the fate of these compounds once they are released in the Antarctic marine environment.

There are three types of fuel mainly used in the Australian Antarctic Territory: Special Antarctic Blend (SAB) diesel, Marine Gas Oil (MGO) and Intermediate Fuel Oil (IFO). Evaporation into the atmosphere is the process responsible for the majority of the mass loss during the weathering of SAB and MGO, while evaporation plays a lesser role for the heavier IFO. In addition, dissolution of fuel compounds into seawater is the primary process controlling the bioavailability of the fuel compounds to marine organisms.

The experimental work on both these processes was conducted on all three types of fuels at Casey Station, Antarctica. The dissolution experiments were performed with the slow stirring method on Antarctic seawater under typical Antarctic conditions. The mass loss due to evaporation was measured at the actual field conditions during the summer season of 2013–2014. Further experiments were carried out on the depletion rate of the hydrocarbons in the water Accommodated Fraction (WAF) once the WAF was removed from under the fuel spill. The composition of the collected fuel and the WAF samples were then determined by Gas Chromatography (GC) – Flame Ionisation Detection, GC - Mass Spectrometry (MS), and GC x GC Time of flight MS analyses in order to establish the fractionation ratios of individual monoaromatic and polyaromatic hydrocarbons among the three phases (the fuel, the seawater and the atmosphere). In addition, the rate of depletion of individual hydrocarbons was determined. The results confirm that for SAB and MGO the large majority of the toxic aromatic hydrocarbons are evaporated, although for MGO the evaporation rate is slower and the toxic aromatic compounds persist longer in the aquatic environment. In the case of IFO the mass loss due to evaporation is negligible and the toxic hydrocarbons can persist for a very long and still unknown period of time in the marine environment. These data fill a gap on the behaviour of a fuel spill in cold marine environments and will be a useful input on decision making for the prevention and response in the event of a fuel spill.

01EV-P17. MAPPING PARTICLE-SIZE FRACTIONS (PSFS) AS A COMPOSITION

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During morphological description one of the first properties assessed is soil texture. This is because it does not change significantly and because it has greatest impact on management with regard to determining nutrient holding capacity, ability to hold water for plant uptake, and ease of cultivation. There is an increasing need for high-resolution digital prediction of soil texture. However, determining the three particle size fractions (PSFs) using hydrometer or pipette methods is time consuming. In order to add value to limited soil data, ancillary data coupled with spatial and non-spatial statistical methods can be used. However, the most commonly employed technique (i.e. multiple linear regression (MLR) of individual PSFs) does not consider the special requirements of a regionalised composition. Here we demonstrate how ancillary data can be coupled to an additive log-ratio transformation (ALR) of the particle size fractions to meet these requirements. The ancillary data include digitised air photo (e.g. red digital numbers – DN) and electromagnetic (i.e. EM38 and EM31) data to predict soil PSF using MLR and ALR-MLR. We also compare how prediction might be improved by collecting ancillary data on a 1 and 24 m transect spacing. The results show that the use of 1 m transect spacing improved prediction precision by around 24% for clay, 26% for sand and 3% for silt when compared to 24 m transect spacing. However, the MLR-ALR technique had the advantage of adhering to the special requirements of a composition, with predicted values non-negative and PSFs summing to unity at each prediction point.

01EV-P18. SALINITY MAPPING WITH DEPTH USING EM SIGNAL DATA AND INVERSION SOFTWARE

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In agricultural landscapes, natural resource management (NRM) will require data to be collected that can be used to describe the heterogeneous nature of the soil within a given landscape. In arid and semi-arid areas, which are inherently high in primary salts, this is important because subsoil salinity can act as a constraint. Increasingly, geophysical methods are being relied upon to obtain information about the location and extent of soil salinity. One of the most popular is the use of electromagnetic (EM) induction instruments, which measure apparent soil electrical conductivity (□$_a$ mS/m). Previous research has been aimed at using □$_a$ to map the areal distribution of soil using, for example EM38 and EM31 instruments. In this research, we describe how we develop electromagnetic conductivity images (EMCI) from inverting EM38 and/or EM31 □$_a$ data collected along two closely spaced transects (i.e. A and B) and using an EM inversion software package (EM4Soil). The patterns of true electrical conductivity (□-mS/m) produced are shown to compare favourably with existing pedological knowledge with the mounds and depressions of gilgai well resolved. Across the clay alluvial plain the inversion model reflects the main features associated with sandier alluvial sediments, which characterise prior stream channels juxtaposed within a predominantly clay alluvial plain. In addition, we find that calibration equations developed between □ and electrical conductivity of a soil paste extract (EC_e dS/m) along one transect can be used to estimate EC_e along the other. We conclude that the overall approach is potentially useful in generating a single calibration equation that can be used for prediction of EC_e at various depths and across an alluvial clay plain and from EMCI.

ENERGY

01EG-P01. HEAT FLOW IN SOUTHERN AUSTRALIA: IMPLICATIONS FOR GEOTHERMAL ENERGY

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The South Australian Heat Flow Anomaly (SAHFA) has been recognised as a region of anomalously high heat flow when compared to global norms in that it has a low average elevation in relation to its heat flow, which at some sites exceeds 120 mW/m^2. This is in contrast to what would be expected if the heat flow were associated primarily with mantle related heating. The SAHFA primarily reflects anomalously high crustal contents of U and Th contained in granitic rocks. This has been determined from a combination of the large concentration of high heat producing radiogenic elements (HHPRE) within the crustal rocks at depth, sharpness in the spatial distribution of heat flow, and a low level of correlation with seismic activity associated with the individual heat flow anomalies. In addition, the zones of high heat flow typically share boundaries with tectonic terranes (e.g. Olympic Domain) and rock packages, indicative of a crustal HHPRE source of heating.

However, the widespread extent of the SAHFA suggests that upper crustal granites alone are not the overall cause of the elevated crustal heat flows. In part this is supported by the requirement for a non-trivial mantle component in high heat production granites within the SAHFA, suggesting but not proving that the SAHFA may be underlain by compositionally anomalous lithospheric mantle that contributes to the elevated heat flow. The heat flow data currently available in southern Australia is sparse, and as a result the SAHFA is poorly constrained.

The heat flow of a small zone of the SAHFA approximately 200 km north of Adelaide near the Torrens Hinge Zone has been mapped with high spatial resolution in order to better constrain its thickness, boundaries and the way in which it transitions to more typical continental heat flow. The heat flow has been determined using a combination of temperature logging performed on existing drill holes in the field and thermal conductivity measurements made on the corresponding drill core using both an optical Thermal Conductivity Scanner (TCS) and the divided bar method. Lab work to measure the thermal diffusivity and heat generation rates of rock sequences has also been performed.

This work has allowed the delineation of new geothermal energy targets in South Australia, potentially reducing the reliance on non-renewable energies and opening the pathway for a new industry.

01EG-P02. RENEWABLE ENERGIES: THE MAGNITUDE OF THE PROBLEM

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Although the future mix of world energy will continue to include fossil and nuclear fuels, renewable and environmentally cleaner energy sources will play an increasing part as both social pressures and costs of fossil fuels increase. Renewable energy sources are not all equally accessible. The magnitudes of energy dissipations by natural processes give a good indication of the limit of their availability, in principle, as renewable energy sources, since it is not possible to extract more energy than is naturally dissipated. A survey of relevant processes[1] yielded data presented here: solar radiation reaching the land surface, 28 000 terawatts; wind friction, more than 430 terawatts globally with more than 120 terawatts on land; heat-flux from the Earth, 44.2 terawatts globally and 9.6 terawatts on land; river flow, 6.5 terawatts; breaking waves, approximately 5 terawatts; and tides, 3.7 terawatts. The data show that attention needs to be concentrated on two of them in particular; solar and wind are the only ones of sufficient magnitude to be considered as potential replacements for even the present 16 terawatts of human energy use.

[1]Stacey F D & Hodgkinson J H 2013. *The Earth as a cradle for life: the origin, evolution and future of the environment.* World Scientific Press.

01EG-P03. PRELIMINARY RESULTS ON THE ORGANIC COMPOSITION AND THERMAL MATURITY OF THE CARBONIFEROUS NAMOI FORMATION, NORTHERN NSW, AUSTRALIA: A POSSIBLE SHALE GAS PROSPECT?

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The Namoi Formation in the Werrie Syncline, north and west of Tamworth, is part of the well preserved Devonian–Carboniferous fore arc in the New England Fold Belt. The formation consists of olive-green mudstones with lenses of sandstone and oolitic limestone. Mudstone is the dominant rock in most parts of the sequence, which is between 640–914 m thick. Thick, organic-rich mud-stones of sufficient thermal maturity are attracting plenty of attention as shale gas prospects, following the exponential take up of shale gas in the USA. However, little has been published on the organic geochemistry of Paleozoic sequences in NSW, excepting coal-related literature. The aim of this work is to present preliminary results from the first organic geochemistry research on the Devonian sediments at Keepit, northern NSW, Australia.

The organic matter (OM) from the Namoi Formation from different creeks in the Keepit area, Australia was solvent extracted. All five samples contain relatively low levels of OM (1.1–1.6 mg OM/g sediment). The results suggested good preservation of the aliphatic and aromatic hydrocarbon fractions, with no evidence of weathering or biodegradation. *n*-Alkanes from C_{15} to C_{36} are present in all samples, with strong long-chain carbon number predominance.

The results suggest marine sources of OM with a low wax index (max 0.11) for *n*-alkanes, indicating low amounts of higher land plants. Carbon preference indices close to 1.0 suggest the succession is highly thermally mature. A high thermal maturity is also indicated by the relatively low Pr/n-C_{17} (0.16–0.70) and Ph/n-C_{18} (0.48–1.51) ratios. Pr/Ph ratios (0.71–0.76) indicate that the samples were deposited in an anoxic deposition environment. Some samples contain biomarkers suggestive of a marine depositional environment, including the C_{30} sterane index and the C_{31}/C_{30} hopane ratio. A bacterial source for some of the OM could be identified by the presence of tricyclic and tetracyclic terpanes.

Based on the distribution of aromatic hydrocarbons including alkylnaphthalenes and alkylphenanthrenes, the Namoi Formation samples are in the gas window. Based on calibration of the methylphenanthrene index and other ratios with vitrinite reflectance, a calculated reflectance of about 2.1% was derived, which given a normal geothermal gradient would be equivalent to a maximum temperature for the formation during deepest burial of about 205°C, in the main part of the gas generating window. Various polynuclear aromatic hydrocarbons (PAH) were identified in the samples and supported high thermal maturity by the dominance of PAHs over alkylated PAHs.

Based on these preliminary data, the Devonian Namoi Formation is a prospective shale gas source as it has been buried sufficiently to be well within the gas window. Where it is exposed at the surface gas will have been lost, but elsewhere it will be buried beneath other sediments and may still retain gas. Key exploration uncertainties include information on organic richness, lateral variation in thermal maturity, mineralogy, and porosity–permeability relationships.

01EG-P04. GAMMA-RAY RESPONSE AND TOC CONCENTRATIONS WITH RESPECT TO MINERALOGICAL COMPOSITION, TOOLEBUC FORMATION, WESTERN QUEENSLAND

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The Toolebuc Formation is a Lower Cretaceous marine unit, regionally extensive within the Eromanga and Carpentaria basins. The thickness and the organic content of the formation are comparable to those of successful shale gas targets and have prompted industry interest in this unconventional hydrocarbon play. A regional assessment is currently being undertaken by the Geological Survey of Queensland. One of the components of this assessment is the mineralogical study of the Toolebuc Formation.

The Toolebuc Formation can be subdivided into three lithofacies: an upper calcareous mudstone, a middle muddy coquinite and a basal highly kerogenous, slightly calcareous mudstone. These facies are also reflected by the mineralogical composition, wireline log response (particularly gamma-ray) and total organic carbon (TOC) concentrations.

Two transects, consisting of 8 drillholes, were analysed in detail to ascertain the relationship between the mineralogical composition of the sediments (determined by X-ray diffraction), the gamma-ray anomaly of the formation, and its TOC values.

The northwest–southeast transect (T1) comprises GSQ Dobbyn 1, GSQ Dobbyn 2, GSQ Julia Creek 1 and GSQ Jundah 1. The GSQ Dobbyn 1 and 2 are within the Carpentaria Basin and intersect the Toolebuc Formation from approximately 200 m to 400 m. GSQ Julia Creek 1 is located on the shallow northern edge of the Eromanga Basin, where the Toolebuc Formation is about 200 m deep, while GSQ Jundah 1 is in the middle of the Eromanga Basin, where the formation is more than 500 m deep.

The southwest–northeast transect (T2) consists of GSQ Machattie, GSQ Jundah 1, LRH Bessies 1, LRH Euston and GSQ Longreach 1-1A. They are all located in the Eromanga Basin in areas where the formation is between 450 m and more than 900 m deep.

Overall, the marine sediments of the Toolebuc Formation consist of abundant clay minerals: smectites (up to 30%), kaolinite (up to 25%) and micas (up to 15%). Smectite concentrations are highest in the lower kerogenous mudstone in all drillholes. Primary minerals (quartz and feldspars) are always present, but never more than 35%. Pyrite is ubiquitous, generally 2–4%. Calcite concentrations may reach 80% within the shell-rich middle facies.

The formation has a high gamma-ray response starting in the upper mudstone facies, with values of about 200 API, and reaching more than 400 API at the base of or just below the calcite-rich layer. The gamma-ray anomaly is exclusively associated with uranium (~40 ppm).

The TOC values of the formation are usually very high, around 10%, although concentrations greater than 25% have been found in GSQ Dobbyn 2.

High API values and the associated high TOC values fall within the coquinitic facies in the drillholes of T1, while in most of the T2 drillholes, the high API and TOC values persist below the calcitic layer.

These findings confirm that gamma-ray logging can be used to infer the presence and extent of the Toolebuc Formation, and the likely composition and thickness of its shelly lithofacies. High TOC values are likely to be closely associated with the highest API values.

DYNAMIC PLANET

01DP-P01. AUSTRALIAN EARTHQUAKES: WHEN, WHERE, WHY?

Kevin McCue

Australian Earthquake Engineering Society

Earthquakes have the potential to be incredibly destructive of our built environment in Australia as buildings and other structures have not been universally designed to resist dynamic forces acting on their foundations. On the other hand the location and mechanism of earthquakes reflect the stresses acting on the intraplate crust today giving us a diagnostic tool for predicting where and how often future damaging earthquakes could be expected. The benefits of designing to resist collapse during earthquakes are obvious but building code changes are cost driven so any advances in our knowledge of where and when future earthquakes are more likely to occur will make change more palatable, learning from recent disasters such as the Christchurch NZ earthquake.

We summarise current research on historical earthquakes in Australia that shows the post-instrumental earthquakes occur in most of the same broad locations as those in the pre-instrumental period, especially near the major urban areas where there is a well-documented historical record. The locations of up to 150 years of earthquakes, together with the focal mechanisms of the larger post-1965 earthquakes, and better focal depth control from more recent targeted studies gives some degree of confidence for recommending that a continental-scale rheological model could explain them.

01DP-P02. EARTHQUAKE HAZARD IN AUSTRALIA AND THE NEED TO UNDERSTAND TECTONIC PROCESSES

Gary Gibson

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The moderate magnitude Newcastle earthquake in 1989 illustrated that although earthquakes are infrequent in Australia, and large earthquakes are rare, risk is greater than what may be assumed from personal experience.

Earthquake hazard is quantified by ground motion recurrence, and computed using an earthquake magnitude recurrence model (where and how often they occur), and a ground motion model (the level of shaking from any particular earthquake).

Over recent years earthquake recurrence models were developed mainly using recurrence of many small to moderate earthquakes located by seismographs over the past 50 years (magnitudes from 2.0 to about 5.0). For each region, the number of earthquakes exceeding magnitude M is plotted logarithmically against M, usually given a well-defined straight line with a gradient or b-value. The world-average b-value is about 1.0, with higher values up to 1.4 at plate boundaries, and lower values to 0.7 in stable continental areas. A value of 0.8 to 0.85 is typical in Australia.

The b-value is a proxy for stress change during the earthquake, with a high value associated with low stress change earthquakes (weak but active faults), and a low b-value from high stress changes on strong faults with little activity.

Earthquake hazard studies extrapolate the recurrence towards a maximum magnitude that depends on the size of the largest active fault, commonly taken as about Mw 7.5 in Australia. At active plate boundaries, the recurrence is defined by activity in the range from 4.0 to about 6.0 or 7.0, and the long plate boundary allows a maximum magnitude of about Mw 8.5 to 9.5. Extrapolation assumes that all earthquakes are following a single random process. Foreshocks and aftershocks are clearly not random, but non-conservative effects are reduced by declustering the catalogue (using only mainshocks), effectively considering the recurrence of clusters.

Another non-random aspect is that large earthquakes only occur on large pre-existing faults, for example at least 10 km for magnitude 6.0. There are places with obvious large faults and others with few. The linear extrapolation under-estimates activity in areas with faults (e.g. in Australia these are uplifted areas with bounding reverse faults), and over-estimates it in areas with few faults (regions with near horizontal stratigraphy).

Understanding the tectonic processes involved may help to avoid misleading hazard estimates resulting from simple extrapolation.

Since the recurrence intervals for moderate to large earthquakes range from hundreds to many thousands of years, observed seismicity provides little help. However geology provides useful estimates of deformation, uplift or faulting rates during the development of the current stress field (typically the past few million years). This is typically not easy in stable regions where rates are about 1 to 100 m/million years, the low end of this range being comparable with weathering, erosion and deposition rates. The surface outcrop of many active faults is hidden by sediments, but there may be other geological evidence on rates. There is little doubt that in the more active regions, geological evidence suggests higher rates of activity than extrapolation from observed seismicity.

01DP-P03. PALEOMAGNETICS OF THE PALEOZOIC LACHLAN OROGEN: IMPLICATIONS FOR ITS TECTONIC EVOLUTION AND THE EXISTENCE OF AN OROCLINE

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The apparent polar wander path (APWP) for the Australian continent is well defined during the Paleozoic, constraining much of Gondwana's movement during this period. However, key paleomagnetic poles from the Lachlan Orogen, required to constrain the tectonic relationships between southeastern and cratonic Australia prior to *ca* 400 Ma, remain incompatible with the cratonic APWP during this period, provoking much debate over their reliability. In this study we establish 2 new early Paleozoic paleomagnetic poles from previously unsampled Cambrian basalts in northern Victoria. The first located in the Dookie area yielded a mean pole of latitude = 23.2°, longitude = 188.0°, with an A_{95} of 18.2°, with the second, located in the Heathcote area giving a mean pole of latitude = 22.4°, longitude = 85.3°, with an A_{95} of 11.6°. Results were used to re-evaluate the previous paleomagnetic studies within the Lachlan and establish the geographical location for the previously unconstrained central Lachlan at *ca* 500 Ma. Through tectonic reconstructions using the *GPlates* software, the relationship between the central Lachlan, eastern Lachlan/Molong-Monaro terrane, and cratonic Australia from *ca* 500–400 Ma was established, providing a new allochthonous Lachlan tectonic evolution model for this period. As part of this study, paleomagnetic results were used to quantitatively assess a recently published tectonic model of oroclinal folding occurring within the Lachlan during the Silurian. Structural correction representative of the proposed oroclinal folding and subsequent Fisher statistical analysis of measured remanence from each location revealed convergence of magnetisation directions and improved paleomagnetic pole confidence parameters, indicating that magnetisation occurred prior to ~100° of rotation. This suggests that the geological units sampled at each location formed a continuous approximately north–south trending unit between the Cambrian and the Silurian, consistent with published accretionary models and the orocline model.

01DP-P04. BUCKLING OF RIBBON CONTINENTS AND MAGMATIC ARCS: RESULTS FROM ANALOGUE MODELLING EXPERIMENTS

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We use scaled 3-D thermo-mechanical analogue models to investigate the formation mechanism of oroclines, originally linear thrust belts or orogens that have been curved in map-view due to bending or buckling about a vertical axis of rotation. Several ideas have been proposed for the formation of oroclines. The common view is that oroclines develop in response to an along-strike gradient of tectonic forces oriented at a high-angle to the long axis of the orogen. Bending about a vertical axis can be generated in response to a pull produced by a sinking lithosphere, or in response to compression due to the arrival of an obstacle in a subduction zone. An alternative idea is that oroclines develop in response to a tectonic force oriented parallel or subparallel to the long axis of an orogen

causing horizontal buckling and complex geometrical shapes with multiple buckles. Here we employ analogue modelling technique to explore how buckling can produce orocline and what geodynamic setting is required. The experimental setup consists of lithospheric plates made of hydrocarbon compositional systems with temperature-dependant elasto-plastic with strain softening rheology, resting on low viscosity upper mantle. Our results suggest that oroclinal buckling must involve the entire lithosphere. A first series of experiments has been produced where a linear crustal ribbon resting on a mantle lithosphere is brought into a subduction zone. The buoyancy of the crustal ribbon resisted subduction and generated horizontal compression expected to cause buckling. However, in all experiments, regardless of the strength of the Moho, convergence rate or obliquity of collision, the crustal ribbon widened and thickened when entering the subduction zone but never buckled. This indicates that little compressive horizontal stress is transferred through the crust because it is weakened by bending when it entering the subduction zone. A second series of experiments was conducted where laterally unconstrained linear lithospheric ribbons were shortened at a constant rate. The results show that the aspect ratio of the ribbon impacts the wavelength of buckling and that our experimental tank is too small (maximum equivalent length is ~1500 km) to generate multiple buckles. Deformation within the buckling ribbon was precisely monitored. Finally a third series of experiments was conducted where the buckling lithospheric ribbon is laterally constrained by various types of plate boundaries. The results show that if these boundaries resist the horizontal lateral motion of the ribbon, thrusts or strike-slip fault systems may be generated thereby preventing buckling. The reason is that the resisting stress on the lateral boundaries when integrated over the length of the ribbon becomes very large, which causes large driving and deviatoric stresses in the ribbon. It follows that buckling works better when assisted by a pulling subduction causing back arc extension.

01DP-P05. TECTONIC LINKS BETWEEN PROTEROZOIC SEDIMENTARY CYCLES, BASIN FORMATION AND MAGMATISM IN THE ALBANY-FRASER OROGEN, WESTERN AUSTRALIA

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Preserved in the Albany-Fraser Orogen are the remnants of two, regionally extensive basin systems that formed during major tectonic events associated with voluminous magmatism; the 1815–1600 Ma Barren Basin and the 1455–1305 Ma Arid Basin. The two basin systems successively reflect a distinct change in tectonic regime from Paleoproterozoic rifting of the Yilgarn Craton, to the formation of a marginal basin that subsequently closed during the Mesoproterozoic. These basins were inverted during Stage II (1225–1140 Ma) of the Albany–Fraser Orogeny *via* orogen-wide, craton-vergent thrusting that dominates the present-day crustal architecture.

Extensive U–Pb zircon geochronology data demonstrate that the two basins record two cycles of sedimentation. Cycle 1 filled the Paleoproterozoic Barren Basin with dominantly Neoarchean detritus derived from the adjacent Archean Yilgarn Craton. Coeval voluminous, dominantly felsic magmatism modified the southern and southeastern Yilgarn Craton crust at 1810–1800 Ma, 1780–1760 Ma, and during the 1710–1650 Ma Biranup Orogeny, providing a second important detrital zircon source into the Barren Basin. The basin substrate of reworked Yilgarn Craton, abundance of locally derived sediment, and interpreted progressive crustal thinning indicate a largely extensional regime consistent with either a broad continental rift basin or a long-lived back arc basin. No evidence of subduction or an associated Paleoproterozoic magmatic arc has been recognised in the orogen, so for a back arc setting these must have been a substantial distance outboard of the Yilgarn Craton margin.

The relatively quiescent period from *ca* 1600 to *ca* 1455 Ma indicates a change from active, rift- or back arc-related extension, to a proto-oceanic rift, through to a passive margin and adjoining marginal basin that became the substrate for the second depositional cycle that formed the Mesoproterozoic Arid Basin. In contrast to the Barren Basin, the Arid Basin is dominated by *ca* 1455 to 1375 Ma detritus that does not correspond to any known source within the Albany-Fraser Orogen, signifying an external, but proximal, new source. That new source is interpreted to be an oceanic magmatic arc — the *ca* 1410 Ma Loongana arc — that lies within the Madura Province to the east of the Albany-Fraser Orogen. Closure of the marginal basin *via* east-dipping subduction is interpreted to have led to soft collision and accretion of the Loongana oceanic arc at *ca* 1330 Ma. In response to this accretion, Cycle 2 detritus was derived from the oceanic arc and its environs and fed into the Arid Basin *via* a foreland basin system that developed above a craton-vergent fold and thrust belt. This is interpreted to have triggered the earliest magmatism of Stage I of the Albany–Fraser Orogeny at *ca* 1330 Ma. Detritus sourced from the Paleoproterozoic Biranup and Nornalup Zones, which constitutes the second-most abundant age component in the Arid Basin, was mixed with the younger foreland basin sediments. Thus, the Arid Basin evolved from a marginal ocean basin to a foreland basin, before it was intruded by widespread 1330–1280 Ma Recherche Supersuite intrusions and 1305–1290 Ma gabbros of the Fraser Zone.

01DP-P07. WHAT DOES THE DEEP CRUSTAL STRUCTURE OF THE YILGARN CRATON TELL US ABOUT MESOARCHEAN GEODYNAMICS?

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Networks of steeply dipping ductile shear zones that accommodate shortening by oblique slip are common features in the later stages of hot orogens. It is not clear, however, how long-lived these structures were and how they mechanically interacted with lower levels of Earth's crust. Here we propose that the deep crustal structure across the Yilgarn Craton is dominated by a NE-oriented structural trend, which has played an important role in its tectonic evolution.

Seismic reflection surveys of the Yilgarn Craton image the middle crust as a highly reflective layer of variable thickness characterised by a fabric that has dip components to the south and to the east. Gravity and aeromagnetic images show symmetrical structural trends that change from NE–SW in the Murchison and Youanmi Terranes to NW–SE in the in the eastern Yilgarn Craton. Another method of exploring the composition and structure of the lower crust is through time constrained Hf and Nd isotopes from intrusive rocks, which effectively sample various levels of the assembled crustal pile. Maps of Nd and Hf isotopes in the Yilgarn show a distinct N–S-trending linear feature separating juvenile crust from more evolved material with an extensive pre-history. This boundary corresponds to the Ida Structural corridor, which is parallel to domain boundaries within the Eastern Goldfields Superterrane and their internal crustal structure. However, there is also a distinct, older NE trend of radiogenic material within the Murchison domain, which indicates juvenile addition into the crust at least at, or prior to, 2.8 Ga. This juvenile structure separates continental blocks that are > 3.4 Ga old. This 'Murchison Corridor' is oriented parallel to the structural grain of mid- to lower crustal rocks exposed in in the Narryer Terrane, and it is also parallel to the Proterozoic reactivation of the Narryer–Youanmi boundary. The Proterozoic Albany-Fraser Orogen – a magmatically reworked distended margin of the Yilgarn Craton that was later thrust back craton-wards – is another prominent NE-trending structure. It is conceivable that the *ca* 1.8 Ga lithospheric extension fragmented the Yilgarn-Craton by localising deformation along a NE-trending lower crustal fabric. The NE-trend of the east Albany–Fraser Orogen would therefore represent the legacy of a Mesoarchean architecture.

The N–S Youanmi–Eastern Goldfields boundary (the Ida Structural Corridor) separates crust of distinctly different isotopic character. Epsilon Nd values shift by approximately 4 units towards more radiogenic compositions on the east of the structure. Accretion or emplacement of juvenile crust along the Ida Structural Corridor took place at a high angle to the pre-existing NE-trend, similar in geometry – but not necessarily in process – to a hot oblique-rift along a transform margin such as the Gulf of California. We speculate that Neoarchean shortening across the N–S oriented Ida Structural Corridor imposed E–W shortening on the pre-existing NE-trend to the west. This proposition is consistent with the westward decrease in intensity of N–S structures across the Youanmi Terrane.

01DP-P08. PETROGENESIS OF GABBRODIORITE–DIORITE–GRANODIORITE INTRUSION FROM THE MAHAKOSHAL GREENSTONE BELT, CENTRAL INDIA

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Continental rift zones are long, narrow tectonic depressions on the Earth's surface where the lithosphere has been modified significantly in extension. The early Proterozoic Mahakoshal greenstone belt (MGB) in central India is a ~500 km long, ENE-trending mid-continent rift filled with a thick metavolcano-sedimentary sequence. Four distinct magmatic phases are recognised in the western part of MGB. They are komatiite, basalt, diorite and rhyolite. This study focuses on the geochemistry and petrogenesis of gabbrodiorite–diorite–granodiorite (GDG) intrusion. Diorites are among the most intriguing plutonic rocks for petrogenetic studies. This relates in part to their occurrence in varying geological environments and to the presence of enigmatic features.

The GDG intrusion mainly consists of diorite and granodiorite with subsidiary gabbrodiorite with considerable textural modal variations. These lithologies are unmetamorphased and undeformed. The samples of the GDG intrusion have a wide range of SiO_2 contents from 54.90 to 68.34 wt% and the Mg# varies from 32 to 64. All the samples are peraluminous. Abundances of many elements of GDG intrusion show good linear variation on Harker diagrams, which indicate a magma mixing origin. Gabbrodiorites show only moderate fractionation of LREE/HREE indicating minor garnet in the source. Diorites and granodiorites are characterised by strong fractionation of LREE/HREE suggesting significant garnet residue. Geochemical data suggest that the GDG intrusion has the origin of magma mixing. The mixing/mingling event occurred between the crust and mantle derived magmas.

01DP-P09. THE EVOLUTION OF EARLY MARS: DOES MOBILE-LID EXIST IN ITS EARLY AGE?

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Current mantle convection on Mars is in a stagnant-lid convection regime. Many mantle convection models have been built to study the evolution of Mars before, however the early stages of its evolution are not well studied, due to a lack of constraints, and technical limitations. In our study, we model early Martian evolution using mantle convection simulations coupled with a parameterised core energy balance, so that the core evolution can also be dynamically incorporated into the convection simulations. Detailed treatment of melting generation and propagation are problematic in global scale mantle convection models; we use a simplified treatment of the melting process during the evolution and keep track of the changing melt production rate over time. Though many previous Martian models assume a stagnant-lid regime, the existence of early mobile-lid tectonics is still under debate. Hot initial Martian conditions may favour a mobile-lid regime. The existence of a magnetic field on early Mars also suggests that Mars has a short lived geo-dynamo, which requires high core–mantle boundary heat flow, also favouring mobile-lid in early Mars. In our coupled mantle–core model, stagnant-lid convection has barely enough energy to generate an early dynamo, while mobile-lid tectonics results in a strong geodynamo. Using these initial thermal conditions for Mars, our model can produce mobile-lid convection for a reasonable viscosity profile, and yield stress. The convective regime can shift to stagnant-lid convection, for a viscosity increase of one order of magnitude. Such a viscosity increase is likely to happen during the course of Mars' evolution, due to the mantle cooling. So our models provide a possible scenario for early Mars, where it may have been in an initial mobile-lid mode, and shifted to a stagnant-lid regime later on due to interior viscosity increases. However, if mobile-lid convection did occur on Mars, it would have only been operable during its earliest stages. The rapid shift from mobile-lid to stagnant-lid convection is still problematic to produce in numerical experiments, that will require further investigation.

01DP-P10. MODELLING PLANETARY INTERIORS IN ASPECT: VISCOSITY, VOLATILES AND VARYING MASS

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The long-standing debate of the nature of viscosity in planetary interiors is examined by the modelling of a wide range of planetary interiors and formulations of viscosity using the Advanced Solver for Problems in Earth's Convection (ASPECT). Scenarios also include both stagnant and tectonic surface expressions, contrasting rheological and compositional environments, and variations in planetary size, from super-Earths to mini-Earths and other better-examined terrestrial planets. Viscosity is notoriously difficult to define, with numerous publications relying on simplifying assumptions such as a constant or smoothly temperature-dependent interpretation in order to draw conclusions about the nature of convection and tectonics. As such an investigation into the various forms viscosity can take would be beneficial to the academic community as it allows for a comprehensive analysis of the effects of each formulation on a range of models, providing first-approximation guidelines for differences in viscous behaviour and allowing for better understanding and hence better choice of viscosity formulation in future investigations.

Special emphasis was placed on the relationship and relative magnitudes of the temperature- and pressure-dependent viscosity components. While both have been previously formulated as directly proportional relationships, recent forays into high-pressure rheologies and compositional properties suggest that the possibility of high-pressure mineral phases such as post-perovskite, shifts in diffusion mechanism, and in the case of extremely high pressures, the dissociation and metallisation of minerals, may work to decrease the viscosity with increasing depth and pressure. Such effects are particularly important in the deep interior of super-Earths, and as such are likely to play an important role in defining the tectonic regime of such exoplanets. In addition, other properties such as thermal expansivity and diffusivity, to name a few, also vary with temperature and pressure, so it became necessary to consider the effect of varying such properties on thermal evolution. These factors all vary depending on the composition of the planetary interior, with different minerals capable of exhibiting vastly different rheological properties over a wide range of phases. For this reason it became necessary to encompass a wide range of possible values as well as planetary interiors with many constitutive components.

Of particular interest is the effect of volatiles such as water on the properties of the interior, specifically with regard to the variation in thermal and rheological parameters that have been observed in the case of Earth, to have a decisive outcome on the nature of convection and tectonics. While contention remains with regard to the importance of water in the initiation and continuation of the tectonic process on both Earth and exoplanets, it remains a key factor in the resulting surface expression of said processes, as well as lithospheric evolution and biocompatibility. Thus a mathematical formulation for Multi-Phase, Multi-Component Reaction Flow (MPMCRF) was incorporated into the ASPECT models.

In each scenario, the effects of viscosity formulation, compositional properties and MPMCRF was examined over time to identify characteristic trends in the ASPECT models, particularly with regard to the planetary interior's thermal evolution, and the resulting stress and strain occurring in the mantle.

01DP-P11. MODELLING GEOLOGICAL PROCESSES ON ICY SATELLITES

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The presence of salts such as Na_2SO_4 in chondritic meteorites has led to the suggestion that the water-rich icy moons of the Gas Giant planets should have ice mantles dominated by multiply hydrated salts such as mirabilite ($Na_2SO_4.10H_2O$), epsomite ($MgSO_4.7H_2O$) and meridianiite ($MgSO_4.11H_2O$), with implications for the geophysics and astrobiology of these objects. This has been supported by observational evidence from the Near Infrared Mapping Spectrometer (NIMS) instrument aboard the Galileo space craft. NIMS collected multispectral images of the surfaces of Jupiter's icy moons, Europa, Ganymede, and Callisto and these spectra have been interpreted as showing deposits of hydrated alkali salts.

When constructing geophysical models of these icy moons to interpret the observed surface geomorphologies, it is important to know the phase behaviour of the constituent materials under the appropriate pressure and temperature conditions; for the large icy moons we are concerned with pressure up to ~ 5 GPa, and temperatures from 100–300K.

In addition, this system is of concern to the building industry. The weathering of building stone is greatly accelerated by the action of Na_2SO_4-rich water. This brine infiltrates the stone and then, as the temperature and humidity change, solid hydrates crystallise from solution, producing a large volume change, weakening and cracking the stone.

In this contribution we describe work on a candidate mineral, mirabilite, $Na_2SO_4.10H_2O$, detailing neutron powder diffraction experiments teamed with computational (DFT) studies as well as recent complimentary synchrotron X-ray work. The thermal expansion and compressibility have been determined and used to produce a simple model of a diapiric structure which can be used to model features on the Icy satellites as well as Earth and Mars.

01DP-P12. LA-ICP-MS ZIRCON AND TITANITE U–PB DATING OF THE MOONBI GRANITE AND THE AGE OF MOVEMENT ON THE PEEL-MANNING FAULT SYSTEM, SOUTHERN NEW ENGLAND OROGEN

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The Peel-Manning Fault System (PMFS) occurs in the southern New England Orogen (SNEO). Within it is a serpentinite mélange made up allocthonous blocks that vary in age (from late Neoproterozoic to Carboniferous). It separates a Silurian–Carboniferous subduction/accretion complex (Tablelands Complex) to the east from a Carboniferous continental arc-forearc sequence (Tamworth Belt) to the west. Late Silurian–Devonian intraoceanic arc sequences are juxtaposed against the PMFS in the Tamworth Belt. The fault had been active at different times with thrusting occurring initially during the earlier stages of the Hunter-Bowen Orogeny (HBO) and left lateral movement occurring subsequently during the second phase of HBO. The early thrust movement occurred before intrusion of the Moonbi Monzogranite, which cuts the fault. The age of this pluton, however, is poorly constrained. The few Rb–Sr ages currently available suggest ages of 250−245 Ma. A previous LA-ICP-MS analysis gave precise spot ages, but a large range from 283 Ma to 236 Ma. Here we present new results of LA-ICP-MS U–Pb studies of zircon and titanite from the pluton. The zircons contain abundant inclusions, which introduced variable amounts of common lead. Twenty spot analyses gave a weighted mean average, ^{207}Pb-corrected age of 261.9 ± 0.7 Ma, the same as the lower intercept ^{238}U/^{206}Pb age. Analyses of two titanite samples, reduced using the VizualAge_UcomPbine program and calibrated against OLT1 titanite standard, gave a weighted mean average, ^{207}Pb-corrected age of 260.8 ± 2.4 Ma and 260.9 ± 0.9 Ma, consistent with their lower intercept ^{238}U/^{206}Pb ages of 260.8 ± 9.4 Ma and 260.9 ± 2.4 Ma, respectively. The age of 262 Ma is the oldest recorded for the Moonbi Supersuite that previously was dated 260 Ma to 245 Ma. Thus the earlier thrusting on the PMFS is constrained to be older than 262 Ma and is related to the earliest stages of the HBO. Subsequent left lateral movement on the PMFS, recorded by km-scale displacement of the Permo-Triassic Gloucester Basin in the southern part of the SNEO, is not manifest in the Moonbi pluton. Thus the second phase of the HBO had little effect in the Moonbi area, indicating that large parts of the PMFS were mechanically disconnected from one another.

01DP-P13. EPISODIC CRUSTAL GROWTH PATTERNS IN THE LACHLAN OROGEN: WHY DOES MAGMATISM SWITCH OFF IN THE MIDDLE–LATE DEVONIAN?

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The Lachlan Orogen is a complex orogenic belt that has evolved through various continental growth mechanisms including the deposition of passive margin miogeoclines (Adaminaby Group), stepwise accretion/collision of exotic island-arc terranes (Macquarie Arc) and continental Cordilleran or “Andean-type” crustal thickening. The mechanism responsible for switching off continental magmatism in the Mid–Late Devonian is enigmatic but may be related to the arrival of the proto-New England Orogen in the form of the island-arc Gamilaroi terrane in the Late Devonian. Zircon dating of stratigraphically constrained Siluro-Devonian felsic volcanic units near Orange was undertaken to determine the onset and end of continental margin magmatism in the Lachlan Orogen. Initial onset of felsic volcanism within the Lachlan Orogen is marked by the eruption of the Canowindra Volcanics at 432 ± 6 Ma, coinciding with an end to compressional deformation of the early Silurian Benambran Orogeny. The Mullions Range Volcanics occur on the western flank of the Hill End Trough and a new age date of 433.5 ± 4.7 Ma is reported, indicating that both the Canowindra and Mullions Range volcanics erupted coevally during the early Silurian. Ages for these two units are coeval with both the Canowindra and Carcoar Granodiorite but display different geochemistry to the I-type Carcoar intrusive. Anatexis of buried Ordovician turbidites gives the volcanics distinct S-type geochemical affiliations where CaO, NaO_2 and Sr are depleted relative to I-type rocks due to removal of these components during the weathering processes of the buried mature sediments. High Ba in the volcanics indicates crystal fractionation during ascent of the magma. The contrasting geochemistry between the volcanics and the Carcoar Granodiorite are attributed to mid crustal contributions and residence times of magmas in rocks of the Macquarie Arc compared to buried Ordovician turbidite sediments. Zircon U/Pb age dates from the main felsic volcanics of the Dulladerry Volcanics more tightly constrains the termination of felsic volcanism in the Lachlan Orogen to Middle to Late Devonian (385 ± 5 to 377 ± 5 Ma). The bi-modal Dulladerry volcanics show distinct A-type geochemistry with high concentrations of silica (~78–80 wt%), Zr, Y, Nb, Ga and $Na_2O + K_2O$. These alkaline volcanics are widespread throughout the Lachlan also occurring as the Boyd Volcanics at Eden. They represent the last phase of magmatic activity in the Lachlan Orogen before a major eastward step and onset of Carboniferous Currabubula continental arc in the New England Orogen. We suggest that the Late Devonian to early Carboniferous magmatic hiatus in the Lachlan Orogen coincides with the arrival and collision of the intra-oceanic island-arc Gamilaroi terrane in the latest Devonian associated with a doubly-vergent subduction zone beneath both the Lachlan and approaching Gamilaroi terrane. A passive-type arc collision results in the Kanimblan Orogeny and widespread erosion in the Lachlan. The Gamilaroi terrane is preserved in the upper plate position while a new subduction zone intitiates east of the Gamilaroi and is responsible for intrusion of the Bathurst Granite and the development of an Andean-type continental margin in the New England as well as the accretionary Tablelands Complex.

01DP-P14. RELATIONSHIPS BETWEEN THE CAMBRIAN OPHIOLITIC WERAERAI AND DEVONIAN ISLAND ARC GAMILAROI TERRANES AT BARRY STATION, SOUTHERN NEW ENGLAND OROGEN, N.S.W., AUSTRALIA.

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Disrupted sections of Paleozoic ophiolitic rocks of the Weraerai terrane are well exposed within a serpentinite mélange at Barry Station (31°34′53″S, 151°19′2″E). Excellent exposures of intrusive and volcanic phases of the lower portions of the Gamilaroi terrane also occur and are separated from the Weraerai terrane by serpentinite mélange and a thin sliver of the lower Permian Manning Group. To date there has been no geochronology and only a handful of geochemical analyses at this locality. These terranes are juxtaposed against mid Silurian–Devonian accretionary complex of the Djungati terrane to the east and west. Previous studies have established the Weraerai terrane is derived from highly refractory mantle in a supra-subduction zone setting whereas rocks of the Gamilaroi terrane originates from a more fertile mantle source and have undergone substantial fractional crystallisation. Felsic intrusive phases within the Weraerai terrane occur as small bodies on the order of metres across characterised by coarse-grained (pegmatitic), albite–quartz–amphibole mineralogy. Highly altered cores of saussuritised plagioclase crystals within the Weraerai terrane suggest either a prior hydration event leading to partial melting or the mingling of magmas in an oceanic setting. Hydration and remelting of hot, anhydrous gabbro magmas as they move away from a spreading centre has been proposed as a mechanism of plagiogranite formation in places like Oman where high temperature amphibole-bearing (pargasite) plagiogranites occur in the fracture intersections within cumulate gabbros and sheeted dykes. Samples of the gabbro and the plagiogranites have been dated by SHRIMP U–Pb zircon method at 503 ± 22 and 506 ± 22 Ma, respectively confirming the Cambrian ages obtained previously at Bingara (*ca* 530 Ma). The Gamilaroi terrane (diorite, trondhjemite and granodiorite) display arc-like, calc-alkaline compositions, with negative Nb anomalies, whereas the intercalated basalts have MORB to arc characteristics. Zirconium concentrations are extremely low (20–80 ppm) in the felsic trondjemites at Barry Station and as a consequence only a small number of zircons (4) were recovered. The U–Pb zircon age for the felsic units of the Gamilaroi terrane is 402 ± 19 Ma; considerably younger than the Cambrian rocks in the Weraerai terrane. A close spatial relationship exists between the Weraerai and Gamilaroi terrane as they currently lie in close proximity to the Peel Fault but contacts between the two are fault bounded or incorporated into serpentinite mélange making it difficult to determine whether the Weraerai terrane is the basement onto which the Gamilaroi island-arc was built or whether they were spatially separate and allochthonous terranes when they formed outboard of Gondwana somewhere in the Panthalassic Ocean. If the former were the case, then the refertilisation of the mantle responsible for the Gamilaroi terrane would have had to occur after the development of the Weraerai terrane suggesting that the tectonic configuration of this proto-New England oceanic crust from the Cambrian to Devonian was far from simple.

01DP-P15. GEOLOGICAL EVIDENCE FOR MULTIPLE THERMAL EVENTS IN THE POST-INTRUSION HISTORY OF A CIRCUM-PACIFIC TYPE GRANITE, LFB, NSW

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Circum-Pacific orogens, such as the Paleozoic *Lachlan Fold Belt* (LFB) of eastern Australia, typically show episodes of volcanic and plutonic activity punctuated by one or more inferred deformational–metamorphic and / or hydrothermal events. Determining thermo-chronological ages of such events can be challenging if two or more events have affected the rocks. Ideally, information is required about: (a) how many thermal events had affected the rock, (b) what those events were, and (c) whether they can be time-differentiated.

This presentation describes purely geological evidence (independent of other work and constraints) obtained from *post-intrusion alteration minerals* in a *deformed granite* from the Eastern LFB. From thin section and field examination of a range of samples and rock types, we could identify three separate alteration events in the biotite-bearing, S-type *Wyangala Granite* of the Wyangala Dam Spillway and adjoining country in central New South Wales (NSW). All three are low or low–medium grade and have been distinguished particularly in their affect on the biotite. They are:

(1) *autometamorphic alteration* (Winter 2010), due to immediate post-intrusion, but still moderately high-temperature, cooling;

(2) *hydrothermal wallrock alteration* (Evans 1993) associated with steeply dipping, inferred (now ultramylonitised) quartz–epidote hydrothermal veins; and lastly

(3) *regional metamorphic alteration* (Vernon 2004) accompanying regional and local convergent deformation of the granite.

Products (1) are *weakly hydrous* (minor sericite ± zoisite alteration of plagioclase cores) and include lamellar ilmenite + acicular rutile exsolution in and radiating muscovite–ilmenite ± quartz replacements at the margins of former igneous biotite grains. Their random orientation and occurrence in most of the granite samples point to uniform formation in a static environment.

Products (2) involve *notably hydrous* lamellar to patchy chlorite ± random euhedral ?clinozoisite ± very fine mat white mica replacement of the biotite that remained after alteration (1), and replacement of ilmenite exsolution lamellae by granular sphene (titanite). They thus formed after products (1). K-feldspar may be pseudomorphed by blocky ?albite as well. Advanced alteration, implying major losses of K and probable addition of Ca, is spatially associated with former quartz–epidote veins, consistent with propylitic hydrothermal alteration.

Products (3) have been identified on the basis of particular associations with the deformation. The ones that have been recognised are *practically non-hydrous* and occur in most of the samples to varying degrees: especially, very fine dynamically recrystallised / neocrystallised quartz, feldspar, mica and sphene in mylonitic parts of the samples, and quartz–biotite ± K-feldspar, albite and occasional chlorite in healed cracks and synkinematic veinlets in fractured feldspar. The minerals that are restricted to alterations (1) and (2) are generally deformed but absent from the veinlets, putting those events before the deformation.

The absolute temperatures, extent of separation in time and the spatial limits of the hydrothermal temperature anomaly are unknown from these observations alone, but they show that thermal history can be complex in such rocks.

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01DP-P16. CONTROLS ON MINERALISATION AND ARCHITECTURE OF THE SOUTHERN GOULBURN BASIN

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The Captains Flat Special 1:50 000 map sheet area, which covers a segment of the eastern Lachlan Orogen in the Southern Tablelands of New South Wales, was recently remapped by the Geological Survey of New South Wales. The area hosts extensive exposures of the lower middle to upper Silurian parts of Goulburn Basin and adjacent Hill End Trough, which represent marine rift basins that opened across the Lachlan Orogen in the middle to late Silurian.

The Goulburn Basin sequences developed in a back-arc setting on a substrate of Ordovician siliciclastic turbidites and black shale that was deformed and thickened during the preceding Benambran Orogeny. Initial deposition of conglomerate and limestone was followed by the deposition of siltstone-dominated sequences, reflecting the deepening of the basin. In places, the deepening of this marine basin was accompanied by submarine volcanism at discrete volcanic centres, with the volcanic units typically interfingering with the background siltstone-rich packages. These sequences host the Woodlawn and Captains Flat volcanic associated massive sulfide (VAMS) mineralisation. The termination of rifting, and filling of the basin by post-rift turbidites, was possibly the result of uplift during the latest Silurian. This resulted in a transition to subaerial conditions and renewed magmatism occurred in the Early Devonian. As a result, plutons of the Glenbog Suite and Candelo Suite intruded close to the base of the Silurian successions along the eastern margin of the deep-water basin. Extensive ignimbrite deposits were erupted along the eastern margin of the basin. The entire area underwent compressional deformation during the Middle Devonian and early Carboniferous, producing regional-scale folding and complex fault systems.

These fault systems are responsible for the exhumation of the late Silurian felsic to mafic plutons that are related to the mineralised bimodal volcanic centres. The area is interpreted as a tilted crustal slice preserving high-level granitic plutons, which intruded at the base of the Woodlawn/Currawang volcanic centre, close to the interpreted late Silurian sea floor. At the same time, deeper felsic magma chambers (~8 km depth) were intruded by mafic magmas, resulting in localised mixing and mingling (Lockhart Igneous Complex). This crustal architecture is reasonably well preserved in the Woodlawn–Currawang area, but the newly recognised Turallo Fault separates most of the Thurralilly Suite from the late Silurian Hoskinstown Group at Captains Flat. Nevertheless, the presence of the Briars Sharrow Gabbro (a newly recognised member of the Thurralilly Suite) in the late Silurian sequences of the Hoskinstown Group, and the bimodal nature of the volcanic centre at Captains Flat, are consistent with a similar crustal architecture.

Mapping has identified several controls on the mineralisation. Within the basin the volcanic centres associated with the mineral deposits are distinctive in the presence of bimodal volcanism and associated biomodal intrusions (Thurralilly Suite). These intrusions are suggested to be the heat engines for the mineralising systems. Mapping has also identified that both the Captains Flat and Woodlawn deposits are associated with pre-existing basement faults that were apparently active during basin development and potentially provided pathways for the mineralising fluids.

01DP-P17. MAPPING NYNGAN–BOURKE–COBAR — A REGIONAL APPROACH

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Recent geological mapping and research work by the Geological Survey of New South Wales in the Nyngan–Bourke–Cobar region in north central New South Wales has further clarified the nature and extent of basement rocks and provided new insights into structure in the northern part of the Lachlan Orogen.

The most extensive basement component in the wider region — the turbiditic metasedimentary rocks of the Girilambone Group — have been divided biostratigraphically into the Narrama Formation of Lower Ordovician age, and Lang and Ballast formations of late Middle Ordovician age. Several periods of tectonism have resulted in complex folding and four episodes of cleavage development in the Girilambone Group. The first three (S1, S2, S3) are attributed to the latest Ordovician to early Silurian Benambran Orogeny, the fourth (S4) to the period of deformation associated with the closing of the Cobar Basin in the Early to Middle Devonian. The S4 cleavage is the only one common to rocks of the Girilambone Group and the Cobar Supergroup.

A new basement unit of metasedimentary rocks has been defined in the Bourke area — the Booda Formation, of proposed age in the range between late Middle Ordovician and early Silurian (SHRIMP II U–Pb dating of detrital zircons). Lower to Middle Devonian quartz-rich sandstones of the Mulga Downs Group unconformably overlie the Booda Formation at Mount Oxley and the Oxley Range near Bourke.

Rocks of Cobar Supergroup age (latest Silurian–late Early Devonian) have been identified further east of the main Cobar Basin than was previously known. Shallow marine sedimentary rocks and rare felsic volcanic rocks of the basal Cobar Supergroup (Kopyje Group) manifest as folded and faulted slivers, commonly along major faults; and now include the newly named Doradilla Formation southeast of Bourke. The Doradilla Formation consists of skarnified calcsilicate rocks, marble and metasedimentary rocks of suggested late Early Devonian age that form an elongate, sheared, tightly folded synclinal keel within Girilambone Group basement rocks.

The region hosts a series of Siluro-Devonian I-type (predominant) and S-type granitic plutons. A notable exception is the Midway Granite, which is Late Triassic (SHRIMP U–Pb) and a highly fractionated I-type.

Despite a long mining history, the region remains underexplored due to structural complexity and cover sequences. The Narrama Formation contains exhalative horizons and mafic rocks, which host significant Cu-rich volcanic-associated massive sulfide deposits. These pelitic–mafic-hosted deposits include the Tritton and Girilambone mines. Identifying folding relationships in the Narrama Formation is critical to determining ore deposit geometry. The Doradilla Formation is coincident with interpreted faulting along the DMK (Doradilla–Midway–3KEL) line and hosts Sn and minor base metal skarn-related mineralisation. The Midway Granite has been the driver of this skarn system. It is possible that there are as yet, unidentified slivers of rocks of Cobar Supergroup age within the region, which could host Cobar-style base metal ± Au mineralisation.

01DP-P18. SIGNIFICANCE OF RADIOLARIAN BIOSTRATIGRAPHY OF THE SOUTHERN NEW ENGLAND OROGEN, NEW SOUTH WALES

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Diverse and well-preserved radiolarian faunas are rare in the early Paleozoic, but the importance of the result of the ages should suggest some idea on the provenance linkage and terrane amalgamation in the NEO. A moderately well-preserved radiolarian fauna consisting of 12 Devonian taxa was recovered from siliceous strata in both the Djungati and Gamilaroi terranes, in the southern New England Orogen, New South Wales. Fauna includes; *Trilonche davidi* (Hinde), *Tr. hindea* (Hinde), *Tr. echinata* (Hinde), *Tr. minax* (Hinde), *Tr. vetusta* (Hinde), *Tr. elegan* (Hinde), *Tr. palimbola* (Foreman), *Tr. tanheensis* (Luo, Aitchison & Wang), *Palaeoscenidium cladophorum* (Deflandre), *Stigmosphaerostylus* sp., *Helenifore laticlavium* (Nazarov) and *Protoholoeciscus hindea* (Aitchison). Results of radiolarian studies at each site provide reliable age constraints on the timing of sedimentation within each terrane. The Birpai subterrane yielded well-preserved radiolarian faunas that contain *Helenifore laticlavium* (Nazarov), which indicates an early Famennian (Cheng 1986) to late Frasnian age. *Protoholoeciscus hindea* (Aitchison), recovered from the Djungati cherts at the Barnard River indicates a Lower (Emsian) to Middle (Eifelian) Devonian age. The needle-like spines and spumellarians with three-bladed spines, from the Woolomin beds at Chaffey Dam, are indicative of the Middle Devonian or younger radiolarians (Jones & Murchey 1986). Index fossils are scarce even though there is a significant exposure of cherts. This reflects extensive deformation and structural thickening associated with intense thrust faulting at most sites but particularly within the Djungati terrane. The red ribbon-bedded cherts of the Djungati terrane were accreted in a sediment-starved trench possibly associated with an intra-oceanic island arc. Whether the Djungati terrane represents an accretionary complex related to the similarly aged Gamilaroi terrane is difficult to ascertain due to the lack of any stratigraphic or cross-cutting relationships and the presence of massive, schistose serpentinite mélange of the Weraerai terrane at the faulted contact of these two terranes. Structural data collected from a new spillway cut through the Djungati terrane at Chaffey Dam indicates structural vergence to the west with distinct thrust faults dipping towards the east. This may indicate initial accretion above a subduction zone with an east-dipping polarity. Alternatively parts of the terrane could have been rotated. Nonetheless, the Devonian Woolomin beds (Djungati terrane) are distinctly different from the Carboniferous Anaiwan terrane (Tablelands Complex), which displays eastward vergence and includes an abundance of Gondwana-derived volcaniclastic material. The distinct lack of detrital zircons from coarse volcaniclastic sandstones interbedded with red ribbon-bedded cherts from the Upper Barnard River indicates that the source region was essentially juvenile oceanic crust with no Gondwanan inheritance. These Devonian lithologies have inherited structural patterns as a result of processes of accretion and orogenesis throughout the Carboniferous and Permian. The age and structural data reported here lend support to a model proposed by Aitchison (1992), involving collision of the Gamilaroi terrane in the latest Devonian resulting in arc–continent collision and a subduction flip and the onset of continental “Andean-type” subduction in the Carboniferous and development of the volcaniclastic-rich Anaiwan terrane.

01DP-P19. NEW ISOTOPIC DATA FROM THOMSON OROGEN BASEMENT CORES: A POSSIBLE LINK WITH THE CENTRALIAN SUPERBASIN.

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The Neoproterozoic to Paleozoic Thomson Orogen occupies a large portion of eastern Australia but is poorly known due to extensive cover. Currently, models for the tectonic evolution of the Thomson Orogen and its relationship to surrounding elements largely focus on the exposed areas. The long and complex structural and thermal history interpreted from these outcropping rocks raises many questions as to the age and origin of rocks in the vast undercover portion of the Thomson Orogen.

Glimpses of the undercover Thomson Orogen are revealed in basement intersections of petroleum drill cores throughout central and southwestern Queensland. These are dominated by low-grade metasedimentary rocks (dominantly turbidites) with minor volcanic rocks and granites. New *in-situ* zircon analysis for U–Pb (SHRIMP) and Lu–Hf (Laser ablation multi-collector ICP-MS) isotopes are presented here and provide new temporal and provenance information for the rocks occurring beneath cover. Two distinct detrital zircon signatures are identified.

A ‘Pre-Gondwana’ signature is identified in two drill holes on the northwestern margin of the Thomson Orogen, adjacent to the North Australian Craton (GSQ Machattie 1, HPP Goleburra 1). These samples both have near-unimodal zircon age peaks at *ca* 1180 Ma. $\varepsilon Hf_{(900–1300Ma)}$ values from HPP Goleburra 1 display a range of εHf(t) between 0 and 9 representing a moderately juvenile source. These sediments were possibly derived from the Musgrave Province in central Australia during the Cambrian Petermann Orogeny. Comparable detrital zircon age spectra from the Amadeus and Officer basins suggest that the Thomson Orogen was connected and formed part of the greater Centralian Superbasin during this period.

The second detrital zircon signature is identified extensively throughout the Thomson Orogen in basement drill cores (GSQ Eromanga 1, AAO Beryl 1, GSQ Maneroo 1, DIO Naryilco 1, DIO Betoota 1) and the outcropping Puddler Creek Formation and Les Jumelles Beds. This signature is remarkably consistent and characterised by a dominant age peak at *ca* 570 Ma, a lesser population between *ca* 1300–900 Ma and maximum depositional ages of *ca* 495 Ma. This pattern is termed the 'Pacific Gondwana' detrital zircon signature and is widely recognised in eastern and central Australia and Antarctica. $\varepsilon Hf_{(500–700)}$ data for Thomson Orogen rocks with this signature is highly variable with $\varepsilon Hf(t)$ values between –20 and 8 suggesting input from multiple source regions.

Our isotopic work suggests connectivity between the Centralian Superbasin and the Thomson Orogen during and after the *ca* 570–530 Ma, Petermann Orogeny. Parts of the uplifted Musgrave Province remained the dominant source of sediments until at least the late Cambrian when the Pacific Gondwana signature became dominant in the Thomson Orogen and central Australian basins.

01DP-P20. PEEKING UNDER THE COVERS; UNDERCOVER GEOLOGY OF THE THOMSON OROGEN

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The overwhelming majority of the Thomson Orogen is concealed by up to 4 km of cover sequences, significantly hindering geological interpretation of its formation and relationship to surrounding tecontic elements. Here we present a new map of basement lithologies and facies descriptions from approximately 200 basement drill hole intersections covering a large area of the subsurface Thomson Orogen. The map augments a new seamless, predominantly geophysically defined basement map of the southern Thomson Orogen and is combined with new U–Pb SHRIMP and Lu–Hf (LA-ICP-MS) analysis of detrital zircons.

Eight sedimentary and volcanic facies are defined based on detailed core logging and petrography. This includes the extension of four units from the Warburton Basin (Lycosa, Kalladeina and Innamincka formations and Mooracoochie Volcanics), and four new, informal units (*Machattie Beds, Betoota Beds*, *Thomson Beds* and the *Maneroo Volcanics*).

The *Machattie Beds* are identified in two drill holes on the northwestern edge of the Thomson Orogen and are characterised by strong 900–1300 Ma detrital zircon populations and maximum depositional ages of *ca* 650 Ma. They comprise moderately dipping, interbedded fine- to medium-grained quartz–feldspar–lithic sandstone and pebbly sandstone, planar laminated dark grey shale and minor thin siltstone interbeds. A dynamic marine depositional environment varying from deep marine to near storm-wave base is suggested.

The Mooracoochie Volcanics are extended from the Warburton Basin into southwestern Queensland with the identification of a middle Cambrian strongly altered, ignimbrite (DIO Adria Downs 1).

The Lycosa Formation is intersected in 13 drill holes and includes interlaminated black pyritic shale and siltstone to sandstone inferred to have been deposited within a starved basin. The laterally equivalent Kalladeina Formation is identified within two drill holes and inferred to represent a shallow marine, carbonate shelf environment.

The *Betoota Beds* are identified in a single hole in the Thomson Orogen (DIO Betoota 1). Rocks include steeply dipping (~60–70^{o}) siltstone, lithic sandstone and imbricated, polymictic conglomerate indicative of a fluvial depositional environment.

The *Thomson Beds* are widely distributed, being identified in 39 drill cores. They consist of moderately to steeply dipping, interbedded argillite, siltstone to sandstone, graphitic shale and massive sandstone to greywacke. A deep marine, turbidity current and/or density flow type environment is proposed. The *Thomson* and *Betoota beds* both display a characteristic "Pacific Gondwana" zircon provenance and a maximum depositional age of *ca* 495 Ma.

The Innamincka Formation (defined in the Warburton Basin) is identified within DIO Innamincka 2 in southwestern Queensland. The formation includes lower red, calcareous sandstone, occasionally with glaunconite and heavy mineral lamina indicative of a high-energy shallow marine environment/shore face. These are unconformably overlain by horizontally dipping interbedded fossiliferous mudstone, siltstone and sandstone with rare bioturbation likely deposited below-storm wave base adjacent to a carbonate shelf.

The informally defined *Maneroo Volcanics* comprise crystal-rich rhyolitic ignimbrites and coarsely porphyritic shallow-level intrusions identified in five drill holes in the central-northern Thomson Orogen. These are Early Ordovician in age and may correlate with the Seventy Mile Range Group in the Charters Towers Province.

RESOURCES

01RE-P01. WHERE HAS ALL THE COBALT GONE? REGOLITH GEOCHEMISTRY OF COBALTIFEROUS PYRITE DEPOSITS AT BROKEN HILL, NSW

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The stratabound cobaltiferous pyrite deposits at Thackaringa, southwest of Broken Hill, NSW were deposited in a Paleoproterozoic back-arc basin and are possibly related to the main Broken Hill Pb–Zn–Ag mineralisation. The sulfide mineralisation is hosted in what are now quartz–albite ± biotite ± muscovite gneisses, and is mainly pyrite with minor amounts of chalcopyrite, galena and sphalerite. Cobalt is substituted within pyrite grains, or as micro-inclusions, at concentrations up to 6000 ppm.

The deposits have been subjected to deep weathering extending down to >60 m in some areas. Residual profiles exposed in shafts and drill samples on the hills have been stripped back to a silica-dominated saprolite with little preservation of a mottled zone or duricrusts and partially preserved or developed pallid zone. The sulfides have been replaced by gossans displaying both boxwork and more massive styles. Some zones near the fresh rock–saprolite boundary display replacement of sulfides by a mixture of Fe-oxyhydroxides (goethite and hematite), jarosite and sulfur. The areas of low relief are covered with varying depths (to ~5 m) of transported cover dominated by quartz, secondary Fe-oxides, kaolinitic clays and some partially weathered materials, along with variable amounts of calcrete. Soil and stream sediment pH values generally range from 6.5–8.0.

In-situ regolith profiles derived from the mineralised zones are largely stripped of Co and some other mobile chalcophile elements (including the gossans derived from the pyritiferous strata). Despite high Co concentrations in the primary sulfides, even Fe-rich *in-situ* regolith contains <5 ppm Co. Similar behaviour is displayed by Ni and Zn. There are indications of supergene enrichment of As and Mo. Analysis of soils and stream sediments surrounding both Pyrite Hill and Big Hill indicate that Co, Ni and Mo are not being retained within the surficial secondary environment, despite the presence of Fe oxyhydroxides and carbonates. There is a weak Co biogeochemical anomaly in saltbush (*Atriplex vesicaria*). Adsorption isotherms established experimentally on representative materials of the regolith samples indicate low adsorptive capacity of the soils and *in-situ* weathering products of the sulfides.

01RE-P02. NEW INSIGHTS INTO THE MINERAL DEPOSITS OF THE MOLE RIVER REGION, NE NSW

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The potential for economic Ag–Pb–Zn mineralisation was investigated for the Mole River Project (EL6114 and EL6771), located near Tenterfield in the New England region of northern NSW. The project area lies within the New England Orogen, a significant metallogenic province, and contains a number of prospective locations for clastic metasediment-hosted polymetallic vein (CMPV) deposits. This is the first detailed study into the geology and alteration of the Mole River Project and its potential to host economically viable silver deposits.

The geology at Mole River is dominated by subvertically dipping, weakly metamorphosed clastic sedimentary rocks including interbedded siltstone, fine-grained sandstone, and pebbly sandstone with lenses of polymictic orthoconglomerate. There is also significantly more outcrop of felsic volcanic rocks across the area than current mapping suggests, mostly porphyritic rhyolites and rhyolitic tuffs. Outcropping biotite-rich granitoids have been identified in the south of the region, and a series of mafic dykes, mostly of basaltic composition, were also identified at several locations across the study area, including one lamprophyre and one clinopyroxenite. In addition, the Burra silver mine in the south contains an unusual garnet–annite–actinolite–(phogopite) rock and a syenitic granite that is geochemically distinct from the nearby Mole Granite. Both the granites and felsic volcanics have very similar CNREE patterns, being concave down with weak to strong negative Eu anomalies.

Mineralisation occurs as veins of polymetallic sulfides generally within a quartz gangue. Minor gangue phases include muscovite and fluorite. The dominant species include sphalerite, arsenopyrite, galena, pyrite, stannite, cassiterite, and pyrrhotite, along with minor chalcopyrite, covellite, chalcocite, marcasite, native bismuth, sulfosalts, and an unusual Sn–Fe–Cu sulfide that is as yet unidentified, but likely forms part of the stannite group. Silver concentrations are generally low across the region, but are found hosted in sulfosalts (including acanthite, stephanite, pyrargyrite, and freibergite), and in small concentrations (~1 wt%) in galena. Mineralisation was instead found to be richer in Sn and Bi than previously thought.

The mineralisation formed as a result of a granite-related hydrothermal system, possibly one driven by the emplacement of chemically-distinct granites found in the south of the region rather than the nearby Mole Granite. The associated alteration is typically phyllic/sericitic (muscovite, illite, quartz) or propylitic (clinochlore, epidote, clinozoisite, ferroactinolite) in style, and is a result of localised hydrothermal alteration and regional greenschist facies metamorphism. The majority of mineralisation is hosted within the sedimentary lithologies.

Emplacement of mineralisation and associated quartz veining is strongly structurally controlled, with NW–SE trending structures, including abundant shears, joints and faults, acting as fluid conduits while the mineralising hydrothermal system was active. Sulfur isotope analyses indicate a combination of magmatic and meteoric fluid sources were involved in emplacement of sulfide vein mineralisation and accompanying localised, phyllic-style alteration.

In terms of the relationship between mineralisation and alteration style and ore and gangue mineralogy, the CMPV deposits of the Mole River region are similar to the Webbs silver deposit, some 20 km to the SW. The main difference between the two is that the deposits of the Mole River region generally lack the secondary cross-cutting structures seen at Webbs, responsible for the latter being a much larger lode deposit.

01RE-P03. MINERAL INCLUSIONS IN RUTILE AND MAGNETITE

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Mineral inclusions are common features in resistate indicator minerals such as rutile and magnetite. We present petrographic, FEG-SEM, LA-ICP-MS and HRX-CT data for mineral inclusions in magnetite and rutile. Common inclusion types in magnetite and rutile from barren host rocks include silicate phases (e.g. feldspars, mica, chlorite), apatite, zircon and rutile (in magnetite). Magnetite and rutile grains from mineralised rocks host inclusions of minerals, such as sulfides or other ore-related mineral phases, that are directly associated with mineralisation. Chalcopyrite and pyrite inclusions are indicative of magnetite from porphyry and skarn deposits of the southwestern United States. Gold-rich scheelite and pyrite inclusions in rutile are indicative of orogenic gold deposits from the Eastern Goldfields in Western Australia. Resistate indicator minerals such as rutile and magnetite from regolith, glacigenic sediments, stream sediments and other weathered or transported material can preserve mineral inclusions from geological processes that would otherwise alter or destroy them. In combination with minor and trace element compositions of the host grains, mineral inclusions can provide useful petrogenetic information and become a powerful asset for mineral exploration.

01RE-P04. TOWARDS A PREDICTIVE MODEL FOR OPAL EXPLORATION USING A SPATIO-TEMPORAL DATA MINING APPROACH

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Australia produces over 90% of the world's precious opal from highly weathered Cretaceous sedimentary rocks within the Great Artesian Basin. Since opal was first discovered around 1870 until the present day, opal mining has been carried out by private operators working a claim no larger than 50 × 50 m, usually in the direct vicinity of areas that have yielded precious opal in the past. Currently there is no formal exploration model for opal and its formation in the geological environment is poorly understood. Here we make the first systematic attempt to formulate a predictive model for opal exploration using a powerful data mining approach, which considers almost the entire

Great Artesian Basin as a potential reservoir for precious opal. Our methodology uses all known locations where opal has been mined to date. Its formation and preservation in weathered Cretaceous host rocks is evaluated by a joint analysis of large digital data sets that include topography, regional geology, regolith and soil type, radiometric data and depositional environments through time. By combining these data sets as layers enabling spatio-temporal data mining using the GPlates PaleoGIS software, we produce the first opal prospectivity map for the Great Artesian Basin. Our approach reduces the entire area of the Great Artesian Basin to a mere 6% that is deemed to be prospective for opal exploration. It successfully identifies two known major opal fields (Mintabie and Lambina) that were not included as part of the classification dataset owing to lack of documentation regarding opal mine locations, and it significantly expands the prospective areas around known opal fields particularly in the vicinity of Coober Pedy in South Australia and in the northern and southern sectors of the Eromanga Basin in Queensland. The combined characteristics of these areas also provide a basis for future work aimed at improving our understanding of opal formation.

01RE-P05. RAPID TRACE ELEMENT MAPPING WITH PIXE-MAIA ON THE CSIRO NUCLEAR MICROPROBE

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Micro to macro-scale heterogeneity in low-order or self-dissimilar geological assemblages are forcing elemental microscopy to cover increasingly larger areas to uncover the geochemical traces being sought. However, X-ray instrumentation schemes traditionally used in most laboratories are based on single element detectors that are essentially “saturated” at higher incident X-ray fluxes. The need to use filters or reduced beam currents leads to suboptimal scanning speeds and small areas for ppm level sensitivities. With the invention of the Maia X-ray detector array however, these saturation effects are reduced by several orders of magnitude allowing both higher solid angle detector configurations and increased primary beam currents. The rapid scanning afforded by such a system has revolutionised trace element mapping, most notably on the X-ray Fluorescence Microscopy (XFM) line at the Australian Synchrotron. For X-ray excitation however, the highest Z detectable is limited by the source excitation energy. MeV protons on the other hand excite all atoms in the periodic table to varying degrees; a Maia installation on the NMP should provide a level of elemental coverage to complement that provided by the synchrotron. In this paper we discuss the upgrade of the CSIRO NMP to cater for Maia and discuss its application across a variety of geological problems.

01RE-P06. SIGNIFICANCE OF SILCRETE FOR GEOCHEMICAL EXPLORATION: INSIGHTS FROM THE ALBANY-FRASER OROGEN MARGIN, WESTERN AUSTRALIA

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Paleoclimatic change and paleolandscape evolution are significant influences on stratigraphic variation, as well as the mineralogy and geochemistry of the weathering profile. This understanding enhances geochemical characterisation and interpretation of various regolith units. The Albany-Fraser Orogen (AFO) is a deeply weathered terrain that extends along the southern and eastern margin of the Yilgarn Craton in Western Australia.

Regolith profiles were studied from the Neale tenement, northeast of the AFO, based on 32 reverse circulation drill holes. Regolith is developed on undulating Archean–Proterozoic igneous and metamorphic bedrocks that were intruded by gold-bearing mafic rocks (up to 11.7 ppm Au). The regolith attains a maximum total thickness of ~75 m, with *an in-situ* deeply weathered regolith divided, from base to top, into: (1) lower ferruginous saprolite; (2) upper sandy kaolinitic saprolite; and (3) a discontinuous silcrete/grit unit and a transported cover.

The silcrete lenses are indurated and have vitreous appearance and sandy texture. They have a gradual contact with the underlying kaolinitic saprolite and a sharp contact with the overlying transported cover. These lenses consist of matrix- to grain-supported, angular to subrounded, poorly to moderately sorted quartz grains floating in a fine-grained, creamy white, siliceous (opal and chalcedonic quartz), and rarely ferruginous, cement. The formation of silcrete duricrust is restricted to the low relief areas in the undulating landscape, and elsewhere changes laterally into areas of poorly cemented grits, where the contact between the *in-situ* weathering profile and transported cover can not be recognised.

The mineralogical and chemical composition of the silcrete duricrusts indicate that they have >95 wt% SiO_2 (avg. ~86 wt%) with 5 wt% Al_2O_3 (min. ~0.5 wt%) and Fe oxides (avg. ~ 0.5 wt%), reflecting the dominance of quartz and amorphous silica and less frequent residual clays and Fe oxides. The alkalis and alkaline earth elements are highly depleted in the silcrete from intensive weathering. Meanwhile, high field strength elements such as Ti, Zr, Hf, Nb and Ta are concentrated as anatase, ilmenite and zircon. Titanium and Zr reach maximum concentrations of ~5% and 700 ppm (avg. ~1 wt% and ~ 260 ppm), respectively.

The silcrete duricrust represents a transitional stage from a humid and warm climate with a high water table and generally acidic conditions which dominated during the formation of deep, *in-situ* weathering profile to an arid climate, alkaline environment with a lower water table associated with the formation of silcrete and the overlying transported cover.

For intensively mineralised bedrocks the overlying regolith has Au and other heavy metals concentrated in the lower ferruginous saprolite and depleted in the kaolinitic saprolite, silcrete and the transported cover. This is mainly attributed to the impermeable nature of the silcrete duricrust, a thick transported cover, low water table and the low salinity of the groundwater. All these parameters represent impediments against vertical hydromorphic dispersion of metals from the basement to the surface. However, areas dominated by poorly cemented grits may represent permeable windows for vertical and lateral hydromorphic dispersion.

01RE-P10. GEOCHEMICAL FEATURES OF GOLD ORE DEPOSITS OF BLACK SHALE TYPE EXEMPLIFIED BY SUKHOY LOG AND GOLETS VYSOCHAISHIY DEPOSITS

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The Bodaibo gold-bearing province encompasses 10 gold-bearing deposits and numerous gold occurrences, the majority sitting within the same stratigraphic horizon. Researchers currently identify two geological-geochemical sources of ore components for these deposits. In the magmatic-hydrothermal model proposed by Laverov, the source of gold is endogenous fluid, while in the metamorphic-metasomatic model the source is the host rocks, as assumed by Buryak. Our team studied geological-structural, mineralogical-petrographic and geochemical features of the well-known deposits, Sukhoy Log and Golets Vysochaishiy. To clarify the role of organic carbon in ore formation, we investigated the forms of occurrence and distribution of its insoluble and soluble forms and reconstructed settings for host sequence formation. The identified geologic-structural characteristics indicate that deposits are located within sequences with siderite–chalcophile geochemistry due to their formation in the back-arc zone. They were formed under greenschist facies regional metamorphism and sit within anticline fold-rupture structures, where ore is hosted by zones of schistosity and intense plastic deformation, with increased permeability. Mineralisation consists of stockwork-type ore bodies with a veinlet-impregnated pattern of mineralisation. Cross-cutting quartz veins are not present.

Based on their mineral composition, sulfide ratio and secondary alteration they could be referred to as gold–sulfide or carbonate–quartz–pyrrhotite–pyrite types. Gold is finely dispersed with assays of 850–900‰. Geochemical investigations of host rocks and ores suggest similar conditions for formation of these deposits with Si, Al, Ti, K, Na, Ca, Mg and Mn showing decreased contents from host rocks to ore zone. The amount of iron and other elements of siderophile affiliation (Co, Ni, Bi) increases in the ore zone, whereas the lithophile (Ce, Ba, Mo, B) and LILE elements, diminishes. It was observed that REE are transported from the ore zone, with an insignificantly increased negative europium anomaly Eu/Eu*. In addition, Se contents increase from unaltered rocks to mineralised to ore-bearing schists (Sukhoy Log – 0, 37→0, 65→1, 49ppm; Golets Vysochaishiy – 4→1, 7→4, 1). The increase of Se contents is over 3-fold due to the presence of organic matter. Organics in these deposits are finely dispersed graphitic carbonaceous material lying in interstices of non-metallic minerals of the host rocks. Carbon bulk content varies within 0.4–6.4 wt% and the soluble component (bitumoids) in carbonaceous schists does not exceed 0.00n%. Gold concentration in bitumoids from ore zones reaches 0.9 ppm.

The bitumoids, as relics of primary dispersed carbonaceous material in metamorphosed schists, preserved gold both in zero-valence state and chemically-bound form. In ore, bitumoid gold is primarily concentrated in asphaltenes.

After comparison with deposits of magmatic-hydrothermal genesis, e.g. Vetvisty, Pogromny and Zun-Kholba, the conclusion is that deposits of metamorphic-metasomatic type differ in some structural and geochemical evidence from those of magmatic-hydrothermal type, e.g. increase of siderophile group of components, with decrease of the others; REE and LILE alteration.

01RE-P11. CARBONACEOUS MATERIALS DISTAL TO MACRAES GOLD DEPOSIT, NEW ZEALAND

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Carbonaceous material (CM) is quite common in gold deposits, especially sedimentary-hosted orogenic gold deposits. A spatial association between CM and gold has been recognised for many years. This association has been taken by some to imply an important role for CM in the source and/or mobility and/or deposition of gold during ore-forming processes. However, the details of the mechanism by which CM contributes to the ore-forming processes is still poorly understood, though it is potentially of great significance for geochemical prospecting for gold deposits. Hence, we examined rock samples distal to Macraes Gold Deposit, New Zealand, which is hosted by greenschist facies rocks, to investigate the links between CM and the source of gold.

CM was found by optical microscopy, confirmed by scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS), and was analysed by Raman spectra at CSIRO laboratories in Perth. Raman spectra are sensitive to the changes of crystallinity and structure of CM and are widely used in research on CM because of the capability for high spatial resolution *in-situ* analysis compared with traditional techniques.

Petrographic analysis and acquisition of Raman spectra facilitated identification of four kinds of carbonaceous materials with varying maturity and origins. In prehnite–pumpellyite and pumpellyite–actinolite facies rocks, CM 1, which is grey and with a rounded shape, coexists with framboidal pyrite and is indicated to be the lowest maturity CM by Raman spectra, indicating an *in-situ* origin. CM2 is yellow with low reflectivity in reflected light; this CM is well organised and associated with carbonate veins. CM2, like CM1 is found in the lowest grade samples and may have been deposited by fluids from deeper in the sequence. At the highest metamorphic grades studied (greenschist facies), CM 3 has similar morphologic features to CM 1 but the Raman spectra suggest that this CM is more mature than CM 1. CM 3 is well organised and may have formed from CM 1 with increasing temperature. CM 4 is grey and anhedral and has a small grain size (up to 0.01 mm) but is detectable by Raman spectra. It is less well crystallised than CM 3 and is found associated with sulfide minerals. CM 4 may have contributed to the deposition of sulfide minerals in late-metamorphic fluids and is of particular interest as such fluids transported gold into the Macraes deposit.

Further analysis will focus on the gold distribution in organic matter. Results will contribute to a new understanding of the contribution to gold deposits by carbonaceous materials.

39TH SYMPOSIUM ON THE ADVANCES IN THE STUDY OF THE SYDNEY BASIN

SBS-P01 GEOLOGICAL CHALLENGES AT ROCGLEN OPEN CUT COAL MINE

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Introduction

The Rocglen open cut coal mine is located 25 km north of Gunnedah in northwestern New South Wales, Australia, on the southern margin of the Maules Creek Sub-basin, a structural subdivision of the Gunnedah Basin.

Rocglen is owned and operated by Whitehaven Coal Limited (WCL). Mining commenced in 2008. Annual coal output is 1.3 million run-of-mine tonnes, which is washed and/or blended with other WCL product at WCL's Coal Preparation and Train Loading facility near Gunnedah. Product is exported through the Port of Newcastle.

Regional Geology

The sediments of the Maules Creek Sub-basin comprise the Early Permian Bellata Group, including the coal-bearing Maules Creek Formation (MCF). The MCF contains multiple coal seams in a sedimentary sequence dominated by lithic conglomerate and sandstone, which has been interpreted as being deposited in a braided fluvial system. The coals are held to be thicker and closer together on the western side of the basin, with the sequence thickening and the coal seams split by increasingly thick sections of clastics to the east.

Regional dip is about 3^{o} to the northeast. To the west of Rocglen a series of north-northwest trending half-grabens defined by high-angle normal faults, downthrown to the east, are post-depositional and related to the commencement of Early Permian extension (Thomson 1993).

Local Geology

The geology of Rocglen is significantly different from other coal deposits in the sub-basin.

Rocglen is bounded on the west by the Roseberry Fault, which is upthrown to the east unlike the sub-parallel faults seen at Vickery to the west. East of Rocglen the Hunter-Mooki Thrust defines the eastern margin of the basin.

Minor faulting, dykes and an intrusive stock are also present within the deposit.

In contrast to the gently dipping strata seen elsewhere in the sub-basin, the Rocglen coal deposit occurs on a north-northwest trending fold system. From a central anticline, the strata dip to the west at up to 15^{o} and more steeply to the northeast at 20^{o} or more into a syncline.

The eastern boundary of the deposit is defined by a subvertical upturn to subcrop that is inferred to be controlled by post-depositional northwest-trending thrust faulting in the floor of the coal sequence.

Five coal seams are recognised and named, in ascending order, the Belmont, Belmont Tops, Lower Glenroc, Upper Glenroc and Roseberry seams.

All of the seams are thicker and more banded than their correlatives to the east. In the initial exploration holes at Rocglen, this was thought to be due to structural thickening. However, subsequent work has shown that these thick coals are entirely due to depositional factors.

A new subregional geological model shows that the Belmont seam is equivalent to the Stratford/ Tarrawonga seam, and the Glenroc seams to the Shannon Harbour, Flixton and Therribri seams (Dawson, this volume). Regional isopachs show a progressive thickening of these seams to the east. The Belmont seam true thickness is up to 17 m at Rocglen.

Non-coal sediments comprise lithic conglomerate, sandstone, mudstone and also thin limestone beds which are present intermittently between the Belmont and Upper Glenroc seams. In the Rocglen mine a thin diamictite can occur immediately above the Upper Glenroc seam.

The depth of weathering is generally in the range of 35–50 m, but may exceed 50 m in the east in unconsolidated recent deposits.

Steeply dipping strata, thick low strength unconsolidated deposits and also very high strength, jointed conglomerates are all responsible for pit wall instability at various locations around the mine.

Mining Geology

Thick coal, seam splitting, relatively steep dips, intrusions, minor faulting and pit wall instability all pose challenges to mining and require a flexible and innovative mining system.

Reference

Thomson S. 1993. Leard–Maules Creek Alluvial/Lacustrine System. *In:* Tadros N. Z. ed The Gunnedah Basin, New South Wales, p. 169–195. Geological Survey of New South Wales, Memoir Geology 12.

SBS-P02 COAL EXPLORATION REPORTING – 1830 STYLE

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The first systematic mineral exploration work in Australia was conducted by John Henderson of the Australian Agricultural Company in Newcastle between 1827 and 1830. This included field mapping, inspection of the existing convict-worked government coal mines, and boring to test the level, thickness and quality of the coal seams.

Copies of Henderson's original reports still survive in the Butlin Archives of the Australian National University. The large scale plan and sections of the 1830 exploration and mine planning were drawn by Henderson and the AACo surveyor John Armstrong, and are now held by the Turnbull Library in New Zealand. A version of the sections was used in the Royal Commission on mine subsidence in Newcastle in 1908, but the plans have not been on public display before.

The accuracy of the surveying means that the collar position and level of the bores can be located to within one or two metres. The detail included in the plan has also been used in conjunction with contemporary art work to prepare an 1830 ”street-view” of the town.

The geological data contained in the reports and plans are directly relevant to present and future planning of the inner city area of Newcastle, and the location of early shallow mine workings.

Alexander Turnbull Library, National Library of New Zealand

Sections:

Reference Number	:	MapColl-os817gbhm/1830/Acc.3327		
Physical Description	:	Ink on paper, coloured, 73 x 127 cm.		
		scales:	horizontal	3 chains to 1 inch (1:2376)
			vertical	30 feet to inch (1:360)

Plan:

Reference Number	:	MapColl-817.95gbbe/1830/Acc.3580-		
		ink on paper, coloured, 60 x 100cm		
		scale:	horizontal	3 chains to 1 inch (1:2376)scale

TUESDAY 8 JULY

ENVIRONMENT

02EV-P01. HYDROGEOLOGY BASELINE DATA – GETTING IT RIGHT

Liz Webb

EMGA Mitchell McLennan

Baseline data for groundwater is required for assessment of impacts for new projects and modifications in NSW. Several guidelines, policies and legislation drive the collection of baseline groundwater data for assessment and approval. Monitoring networks need to be carefully designed in the early stages of projects to ensure that key requirements, such as two years of baseline data, can be adequately met.

Baseline monitoring network design for projects such as large coal mining developments, coal seam gas exploration, and hard rock quarries require targeted baseline information and monitoring networks that need to be tailored for the specifics of the project and the likely project impacts. Understanding the local and regional hydrogeology, likely project impacts, and the legislation, are key considerations in designing baseline-monitoring networks. Developing a really simple indicative conceptual model is a prudent first stage in determining where to site monitoring bores.

In NSW the Aquifer Interference Policy (AIP) is a primary driver in the design of the monitoring networks, and meeting these requirements is generally sufficient to meet requirements of other NSW and Commonwealth government policies. The AIP requires two years of baseline groundwater be collected and assessed and also has clearly defined minimal impact assessment triggers that classify an impact as minimal or otherwise.

In early February 2014 the NSW Office of Water (NOW) released the *Groundwater Monitoring and Modelling Plans – Information for Prospective Mining and Petroleum Activities* (NOW 2014), which is a practical document that provides guidance for establishing a groundwater-monitoring network that will meet the requirements in the AIP.

Other legislation/processes that need to be considered are: NSW Gateway process (NSW Government 2013); Significant impact guidelines 1.3: Coal seam gas and large coal mining developments – impacts on water resources

(Australian Government 2013); Commonwealth Government Independent Expert Scientific Committee (IESC 2013) and the Australian groundwater modelling guidelines (Barnett *et al.* 2012).

Data from the network needs to answer key questions on the hydrogeological strata, depths, thicknesses; hydraulic behaviours; interaction between layers; and connection to surface waters. An assessment will need to conceptualise the groundwater regime, establish baseline conditions, assess impacts (numerical model), inform mitigation, and plan for ongoing monitoring.

Designing a monitoring bore network in the Sydney Basin should consider:

- all water sources (i.e. Sydney Basin, Permian coal, alluvium, coastal sands) that are in the immediate project vicinity and/or likely to be impacted;
- nested construction to consider potential vertical flow;
- up and down hydraulic flow path;
- a triangulation of three sites as a minimum;
- monitoring at the extent of the predicted impact; and
- known sensitive receptors.

The frequency of data collection is dependent on the system dynamics, with alluvial sediments requiring more frequent monitoring than sandstone or fractured rocks. Water levels are best captured using down hole loggers at 12 hourly intervals, and quality sampling should be monthly and quarterly.

02EV-P02. DEEP METEORIC LEACHING AND ITS IMPLICATIONS FOR GROUNDWATER RESIDENCE TIME IN A DISSECTED HAWKESBURY SANDSTONE PLATEAU (KULNURA-MANGROVE MOUNTAIN AQUIFER, NSW, AUSTRALIA)

Stuart Hankin[1], Dioni Cendón[1,2], John Paul Williams[3] & Ian Graham[4]

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In the Kulnura-Mangrove region, groundwater extraction for potable water supply and for industrial activities such as farming and mining, can co-exist provided the main recharge areas are protected, pumping does not exceed recharge, and knowledge of the basic parameters within the aquifer are known through appropriate studies. In this study, groundwater residence time in the Kulnura-Mangrove Mountain aquifers was assessed over multiple years using environmental tracers (H_2O stable isotopes, $\delta^{13}C_{DIC}$, ^{3}H, ^{14}C and $^{87}Sr/^{86}Sr$) and general hydrogeochemistry.

The Kulnura-Mangrove Mountain aquifer is mostly hosted in its upper part by the Hawkesbury Sandstone, where intense and deep sandstone weathering profiles have resulted in enhanced groundwater storage. Weathering reactions favoured by the local geological setting has transformed the original Hawkesbury Sandstone quartz arenite into a semisolid or friable sandstone with variable weathering depths where most of the original carbonate cements have been leached, resulting in higher porosity and permeability. XRD analyses show an upper zone down to ~50 m and even 90 m in some areas where all carbonates and probably feldspars have been dissolved and the derived products goethite and kaolinite have formed. With depth, carbonates, mostly siderite, are present representing fresher or less-weathered sandstone. Isotopic analysis of dispersed carbonates shows consistent values with their depositional environment and devoid of ^{14}C.

The study incorporated whole rock analysis from samples recovered during well construction at four sites to better characterise water–rock interactions. Based on hydrogeochemistry, isotopic tracers and mineral phase distribution from whole rock XRD analysis, two main groundwater zones are differentiated in areas not disturbed by groundwater extraction. A shallow zone where oxidising Na–Cl-type waters with low pH and EC contain ^{3}H and ^{14}C activities consistent with very modern groundwater affected by bomb pulse signatures (up to 116.9 pMC). In this shallow zone the original Hawkesbury Sandstone has been deeply weathered, enhancing storage capacity for groundwater down to ~50 m in most areas and up to ~90 m in the Peats Ridge zone. The deeper groundwater zone is also relatively oxidising with a tendency towards Ca–HCO_3 type waters, higher pH and EC, no ^{3}H and ^{14}C activities consistent with residence times from 0.9 to 11.8 ka BP, depending on the specific areas. The original sandstone is less weathered with depth, favouring the dissolution of dispersed carbonates and a transition to a fractured-rock flow type aquifer, both impacting on groundwater mean residence times.

02EV-P03. MODELLING COASTAL SALINITY USING A DUALEM-421 AND INVERSION SOFTWARE

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Rising sea levels owing to climate change are a threat to freshwater coastal aquifers. This is because saline intrusions are caused by increases and intensification of medium–large-scale influences including sea level rise, wave climate, tidal cycles and shifts in beach morphology. Methods are therefore required to understand the dynamics of these interactions. Whilst traditional borehole and galvanic contact resistivity (GCR) techniques have been successful, they are time consuming as they require physical insertion of electrodes. Alternatively, frequency-domain electromagnetic induction (FEM) is potentially useful as no physical contact with the ground is required. Herein we describe the collection of DUALEM-421 data along a single transect and its subsequent inversion using a quasi-2D model embedded within the EM4Soil inversion software package. The resulting electromagnetic conductivity images (EMCI) are compared with a rudimentary set of data (i.e. soil wetness and ECb taken from various auger holes. The results are also described in terms of hydrogeological zones from the incipient dune to the beachface across Long Reef Beach. We also describe how a much larger set of DUALEM-421 data collected in parallel transects, and at low and high tides, were subsequently inverted using a quasi-3D algorithm (EM4Soil). The results suggest that owing to the lack of significant effect of daily tidal cycles, the saline intrusion is most likely influenced by medium–large-scale drivers including local wave climate and morphology along this wave-dominated beach. Further research is required to elucidate the influence of spring-neap tidal cycles, contrasting beach morphological states and sea level rise.

02EV-P04. ARSENIC RELEASE AND MOBILITY AND ITS RELATION TO ORGANIC SOURCE REACTIVITY AND QUALITY

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Arsenic in groundwater is a worldwide problem but the governing processes are not completely understood. Naturally occurring sources of arsenic in rocks and sediments are released into the environment through a variety of geochemical processes. This study investigates possible release mechanisms of arsenic in a flood plain aquifer, located in New South Wales, Australia. The association between organic matter and dissolved inorganic groundwater constituents with As(III) and As(V) was studied in the current work in order to gain a better understanding of the environmental fate and mobility of arsenic in the flood plain aquifers. Water samples were collected from the river, groundwater and hyporheic zone for analysis. Since arsenic is redox sensitive and its mobility is reliant upon its redox state, As(III) and As(V) were separated *in situ* by using a As(V) specific zeolite absorbent. Organic matter fluorescence analysis was also performed using a Horiba Aqualog scanning spectrophotometer to determine organic matter constituents and quality. In general, the water samples were recorded as depleted in dissolved oxygen and a high correlation between dissolved Fe(II) and dissolved As(III) was observed. Results suggest that the arsenic release is driven by iron oxide reduction in the presence of organic matter. Measurement of the fluorescence excitation–emission matrices (EEM) and subsequent parallel factor analysis (PARAFAC) reveal different fluorescent DOM fractions, and hence variable contributions by DOM to this reduction process in the river, groundwater and hyporheic zones.

02EV-P05. SUBMARINE GROUNDWATER DISCHARGE AND ITS CORRELATIONS TO SEAGRASS MEADOW DISTRIBUTIONS IN SALAMANDER BAY (AUSTRALIA)

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Management of groundwater resources, coastal development, and conservation policies can have large impacts on coastal ecosystems, particularly if physical attributes are altered. There is little understanding of the role that

submarine groundwater discharge (SGD) plays in seagrass ecosystems. The potential relationship between SGD and seagrass distributions was therefore assessed to provide insight into potential impacts of water quality changes caused by groundwater management policies. The study was done in three stages at Salamander Bay, NSW, testing the hypothesis that seagrasses would not occur in areas of freshwater discharge.

Firstly, four groundwater monitoring wells were installed to determine stratigraphy and repeatedly measure water levels over 1.25 years. Results show that a saline, perched groundwater table exists above a low permeable silt/clay layer. Hydraulic head of aquifers above and below the peat layer are affected by tidal variation. Wells furthest from the shoreline had the highest water elevations (~2.5 mAHD) indicating general groundwater flows towards the coast. Vertical groundwater flux estimates in wells closest to the coast alternate between discharge and recharge regimes depending on tidal variation.

Secondly, pore water was sampled from both the seagrass meadows and intertidal sand regions using a porewater sampling probe at two separate locations in Salamander Bay; Soldiers Point and Foreshore Drive (FSD). Salinity measurements of these samples were used to determine if fresh SGD occurred at each location. ANOVA and linear regression were used to test if groundwater salinity had a statistical relationship with the presence of seagrass. High pore water salinity at FSD indicates minimal fresh SGD, and no relationship was found. Other drivers, such as tidal variations, are likely to dominate seagrass distributions at this location. However, at Soldiers Point, substantially lower pore water salinity suggests greater fresh SGD. This was supported by ANOVA analysis, indicating decreased seagrass density at lower pore water salinities.

Lastly, chemical and nutrient analysis was conducted on groundwater and pore water samples respectively. Groundwater in the upper aquifer layers was chemically similar to surface water, yet more dilute, supporting that surface water intrusion is mixing with fresh groundwater in the upper aquifer layer. Generally very low nutrient concentrations were detected at both sites suggesting that nutrient distribution patterns are currently unlikely to influence seagrass patterns.

Overall, fresh SGD limits seagrass distribution due to varying the salinity conditions in pore water. However, the impact of SGD is shown to be restricted by both the quantity of groundwater discharging at a certain point, and local geological heterogeneity. Changes to the management of groundwater resources in coastal areas may therefore result in changes to seagrass ecosystems by altering discharge rates and subsequent surface water composition.

02EV-P06. SLOW SLIDING OF GAS HYDRATE-BEARING LANDSLIDES ON THE HIKURANGI MARGIN, NEW ZEALAND

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It has long been hypothesised that gas hydrates facilitate submarine landslides. Solid and potentially cementing gas hydrate is generally thought to increase sediment strength. The driving factor for gas hydrate-related slope instability has thus been assumed to be hydrate dissociation causing sediment weakening and overpressure. However, clear evidence for this process has yet to be found. Analysis of seismic data from the Tuaheni Landslide Complex (TLC) east of New Zealand's North Island, suggests that gas hydrate itself may lead to seafloor weakening. This appears to occur in the form of plastic, creeping seafloor deformation rather than the catastrophic events typical of submarine slides. This observation could have wide-ranging implications for assessment of the hazard posed by hydrate-bearing submarine slides as well as more generally, for seafloor morphological processes.

The TLC displays morphological features that are typical of active, creeping terrestrial slides. The TLC is underlain by bottom simulating reflections (BSRs), free gas at the base of gas hydrate stability (BGHS) and indicative of a presence of gas hydrates. Crucially, the upper limit of creeping coincides with the pinchout of the BGHS at the seafloor. We thus hypothesise that slow sliding is related to gas hydrate. Out of several possible processes that may link gas hydrates to seafloor "creeping", we consider the most likely mechanism that interstitial gas hydrate, like ice, may exhibit plastic behaviour leading to slow deformation, similar to that of terrestrial rock glaciers. Our presentation will focus on analyses of data from several 2-D seismic surveys combined with bathymetric data and gas hydrate-related modelling. We will also present first results from a 3-D seismic survey planned for April–May 2014. These studies ultimately underpin plans for drilling. Our efforts dovetail with a planned remotely operated seafloor drilling expedition using the MeBo system in 2016 for sediment coring. Proposed IODP drilling with the D/V JOIDES Resolution, if approved, will then focus on logging-while-drilling and retrieval of pressure core samples for shore-based analyses.

02EV-P07. METHANOGEN PROPENSITY OF SELECTED LOW RANK COAL FROM AUSTRALIA, INDONESIA AND JAPAN

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Over the last few years, the increasing demand for energy and the success of several studies supporting the production of real time biogenic methane from coal have increased the interest in developing coal as a methane bioreactor across a range of coal basins and different settings in different countries. Jurassic, Paleogene and Neogene coals in the Asia–Pacific region are thought particularly prospective because they are composed predominantly of reactive group macerals –vitrinite and liptinite, with minor inertinite.

This post cruise project of IODP Chikyu 337 aims to study selected low rank coals from Shimokita Peninsula, Japan (Paleogen); Bukit Asam South Sumatra Basin, Indonesia (Neogen); and Walloon Surat Basin Queensland, Australia (Jurassic), in relation to their bioavailability. An enrichment study is currently being conducted to examine bioavailability potential as well as to investigate the methanogen community's role in producing methane in coal. Culture enrichment has been prepared using Indonesian formation water as an inoculum and 7 coals from Australia, Indonesia and Japan as a substrate. Methane gas production from culture enrichment is measured and monitored regularly using gas chromatography. Gas samples from culture tubes are also evaluated for their isotope signatures. Cultures are subjected to DNA analysis for microbial community profiling with analysis being done at 4 different stages of growth (lag, log, peak and stationary phase). The results of this experiment will be reported in this paper.

02EV-P09. ROCK MAGNETIC SIGNATURE OF GAS HYDRATE IN DEEP MARINE SEDIMENTS OF THE PERUVIAN MARGIN

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The direct study of the distribution of marine gas hydrate is made difficult by the conditions in which it occurs and because it dissociates easily during core recovery. Gas hydrate has been identified in nature by indirect evidence through drilling or seismic data. The base of the hydrate zone is usually defined by a bottom simulation reflection (BSR), which results from a seismic velocity contrast between overlying, higher-velocity sediment containing gas hydrate and underlying sediments containing free gas. Distribution and concentration of gas hydrate above the BSR is usually inferred from proxies of hydrate dissociation in cores — such as freshening of pore waters, which is reflected in low chlorinity, and reduced core temperature. Other proxies are based on well-logging techniques (resistivity, velocity).

Rock magnetic techniques were shown to be effective proxies for the presence of gas hydrate on Ocean Drilling Program (ODP) legs 146, 164 and 204, through the detection (at very low proportions) of iron sulfides (greigite and pyrrhotite). Coordinated rock magnetic and microbiological studies from ODP legs 146 and 164 confirmed a characteristic rock-magnetic signal related to *in-situ* bacterially mediated changes in the magnetic mineral assemblage. Position on a Day plot of hysteresis parameters, expressed as the index D_{JH}, has proven to be a reliable indicator not only of the present distribution of gas hydrate, but of past accumulations in cases where the hydrate zone has migrated. Plots of D_{JH} show characteristic inflections both at the modern base of hydrate stability, and at past still stands of the base of the hydrate zone marked by seismic 'fossil BSRs'.

Hydrate-bearing sediments were drilled by ODP on the lower slope of the Peru Trench at sites 688 and 1230. D_{JH} gradually increases with depth through the upper parts of the gas hydrate stability zone. This increase is coincident with intervals where the sediments show higher porosity and microbiological studies detected an increase in biological activity. Likewise, intervals with higher values of D_{JH} correlate well with recovery of gas hydrates in cores and lower pore-water chlorinity values. At Site 1230, D_{JH} gradually decreases down hole below a depth of ~200 m below seafloor (mbsf), matching other proxies which suggest reduced hydrate concentration. At Site 688, where drilling continued through and below the base of hydrate stability, D_{JH} similarly decreases down hole below about

300 mbsf. Superimposed on this trend is a small increase in D_{JH} just above the BSR, a sharp decrease at the BSR, and a down-hole recovery in D_{JH} in the 20 m below the BSR. This behaviour matches the characteristics seen at the BSR in other hydrate sites. Like other sites known to have a 'fossil BSR', an additional, similar but stronger response is seen at Site 688 about 60 m below the modern BSR. At the Cascadia Margin sites sampled during legs 146 and 204, this lower inflection in D_{JH} was inferred to be the position of the base of gas hydrate stability at the end of the last glacial. In the Peru Margin, we interpret this feature in the same way.

02EV-P10. IODP EXPEDITION 347 (BALTIC SEA): A HIGH-RESOLUTION TEST OF THE PYRITE TRACE ELEMENT SEAWATER PROXY

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With ever-increasing emphasis placed on environmental change, shelf areas and enclosed basins are the most prone to the impacts of climatic variations. Effects such as oxygen depletion, water column stratification and temperature variations are focused in these geographical settings, and can be recorded by the behaviour of trace elements in this changing depositional environment. The Baltic Sea Basin is in a unique position to have experienced and recorded a multitude of environmental changes on a large scale. Over 1.6 km of sediment was drilled and logged as part of the IODP Expedition 347 (completed in November 2013), with the Onshore Science Party phase completed in late February 2014. Presented here is a summary of the sedimentology and preliminary geochemistry from sites across the Baltic Sea, one of the world's largest modern intercontinental basins. This Mission Specific Platform focussed on the extreme climatic variations experienced by the Baltic Sea Basin over the Pleistocene and Holocene, exploring not only the fluxes between freshwater and marine conditions during the past glacial periods but also between anoxic, hypoxic and oxic conditions, driven by salinity and temperature gradients and periods of increased stratification.

During Expedition 347, a unique and continuous sequence of sediment was recovered which spanned the last glacial cycles and into the overlying Holocene freshwater and marine sequences. Several sites (i.e. Little Belt (BSB-3), Bornholm Basin (BSB-7) and Landsort Deep (BSB-9)) contain abundant organic-rich muds and record many of the key transitions in the development of the Baltic Sea Basin. Each of these shifts can be accompanied by variations in salinity, oxygen content and, importantly, fluxes in trace metal. Black mud horizons in these cores are conducive to the degradation of organic matter and production of pyrite and Fe-monosulfide precursors. Work by Large *et al.* (2014), utilising LA-ICP-MS, has shown that sedimentary pyrite from marine black shales may have the ability to record first-order changes in seawater chemistry through geological time, thereby providing a new potential proxy.

The preliminary data presented here uses the above method to understand trace element content of pyrites collected from the Baltic Sea Basin. The unique archive in these cores has allowed for the first high-resolution test of this seawater proxy and its ability to capture trends in the context of geologically short timescales. In this project, the ability of pyrite to record trace element changes on varying timescales will be tested, with particular reference to that of the general residence times of elements in seawater. In addition, our initial interpretations of Baltic Sea Basin evolution over this time period will be discussed. The Baltic Sea also provides a new and suitable analogue for ancient restricted seas. Understanding how redox sensitive metals behave in such environments has implications for ore deposit modelling and wider understanding of periods of oxygen stagnation and depletion in the geological record.

Reference

Large *et al.* 2014. Trace element content of sedimentary pyrite as a new proxy for deep-time ocean–atmosphere evolution. *Earth and Planetary Science Letters* **389**, 209–220.

ENERGY

02EG-P01. SULFATE FORMATION AS A POTENTIAL CO_2 STORAGE SELF-SEALING MECHANISM IN WET SUPERCRITICAL CO_2–CAPROCK REACTIONS

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The main focus of CO_2–water–rock reactivity studies relevant to CO_2 storage have been in the bulk aqueous phase where CO_2 dissolves in formation water forming carbonic acid with resulting initial reactive rock dissolution. At reservoir conditions with injection below 800 m, CO_2 exists in a supercritical (sc) state, and this buoyant supercritical gas head will be in contact with caprock. The $scCO_2$ phase was previously believed to be unreactive to rock. However, formation water present dissolves into $scCO_2$, and this resulting wet $scCO_2$ phase has been recently observed to have reactivity to rock. Recent studies of natural analogue CO_2 storage systems have shown high reactivity in the gas leg area just above the water line in CO_2 rich basins (Australia and New Zealand), with enhanced precipitation and reduced porosity at sealing units (1, 2).

Impurity gases (e.g. O_2, SO_2, NOx) will be present in stored industrial CO_2 streams, and a proportion of these are expected to remain in the $scCO_2$ gas head, potentially in contact with cap-rock. The impacts of wet $scCO_2$ and impure wet $scCO_2$ to caprock have so far mainly been unknown, and warrant investigation for storage security.

Laboratory scale wet $scCO_2$–clay–SO_2–O_2 and wet $scCO_2$–caprock–SO_2–O_2 reactions at reservoir *in-situ* conditions have shown the precipitation of secondary sulfates including gypsum, alunite, jarosite concentrated along surface edges and cracks. This may be a mechanism for self-sealing of cap rock during impure CO_2 storage.

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02EG-P02. TRACKING OF CO_2 GEOSEQUESTRATION USING DOWNHOLE GRAVITY GRADIOMETRY, OTWAY BASIN, VIC

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Carbon dioxide sequestration is a vital technique for the mitigation of greenhouse gas emissions and anthropogenic global warming, though questions remain regarding the safety of CO_2 geosequestration, and the ability to prevent any leakage or migration. Down-hole gravity gradiometry can monitor the mass distribution and migration of injected CO_2, however little work has been performed to assess the sensitivity and uncertainties of down-hole gradiometry techniques in real geological scenarios. Here we model the injection and migration of CO_2 at the CO2CRC sequestration site, Otway Basin, Victoria. We present forward models of down-hole gravity gradiometry response in order to gain an understanding of the behaviour of CO_2 once injected into geological storage. We assess the sensitivity and uncertainty of the response to model unknowns, to help constrain the required precision of developmental down-hole gravity gradiometers. Our presentation will demonstrate the theoretical response cause by the injection of CO_2.

RESOURCES

02RE-P01. THE AUSTRALIAN REMANENT ANOMALIES DATABASE – A RESOURCE FOR THE INVESTIGATION OF REGIONAL MAGNETISATION EVENTS

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Australia has magnificent national magnetic field coverage, managed by Geoscience Australia, and composed in large part of surveys flown by State and Territory Governments as part of pre-competitive data initiatives. This magnetic field data is the most widely and intensely used of all Australian geoscientific datasets. Magnetic field variations from crustal sources are due in approximately equal amounts to induced magnetisation in the local geomagnetic field direction, and remanent magnetisation, which may be oblique to the present field. At present, many magnetic field interpretations disregard remanent magnetisation, except where its influence is so pronounced that it cannot be avoided. This neglect is a common reason that deep drill-holes fail to intersect their targets, and is also a missed

opportunity to recover additional geological information from magnetic field data. Recovered magnetisation direction is a basis for correlation of sources of different magnetic anomalies, a pointer to their absolute age, and may highlight post-magnetisation rotations.

CSIRO and Geoscience Australia have established a national remanent anomalies database (the first of its kind in the world). The database can be accessed through the Auscope portal, and supplies details of anomalies recognised to be in large part due to remanent magnetisation. At present the database contains just over 250 entries, inverted to derive their magnetisation direction. Geo-located images of the anomalies, anomaly grids, and inversion models can be downloaded. A more extensive set of automated magnetisation estimates is currently being added to the database. These solutions have been derived by a new search algorithm, which adaptively finds the optimum magnetisation direction to correlate various data transforms. The automated solutions are individually less reliable than inversions of the hand-picked anomalies, but provide a higher density regional mapping of magnetisation direction, from which we hope it will be possible to recognise the extent of regional thermal events, and possibly to map tectonic boundaries between areas of differently rotated magnetisations. The inversion solutions are currently being used to validate the automated search results, and to further refine the search algorithm.

Magnetisations recovered from magnetic field interpretation are vector resultants of induced and remanent magnetisations, in widely varying and poorly predictable ratios. Presently, tools are being developed to analyse the recovered magnetisation directions, including searches for populations of magnetisation, which can be reasonably explained as resultants distributed about a great circle. Ultimately, magnetisation directions are best compared to those directly measured on oriented samples. We have updated the Australian segment of the world paleomagnetic database, in preparation to display that information in conjunction with the anomaly database. However, much Australian paleomagnetic and rock magnetic data (particularly from older mineral exploration programs), which would be of great value in interpretation of magnetic field data, are poorly documented and difficult to access. A major objective of the remanent anomalies database is to disseminate information about remanent magnetisation to a broad geoscience community, particularly for application in improved geological interpretation of magnetic field data. We hope that the database can be extended as a community effort of government, industry and academic geoscientists.

02RE-P02. REMANENCE ANOMALIES IN THE WESTERN TASMANIDES

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Prominent negative 2D aeromagnetic anomalies, with strike extents of the order of tens of kilometres, occur at several locations across the western Lachlan Orogen and the neighbouring Delamerian and Thomson orogens. Although these anomalies correspond spatially to strongly deformed rocks, inversion of the anomalies suggests a uniform reversed polarity remanence direction, which is independent of local bedding orientation. Negative 2D anomalies in the Stawell gold field of Victoria are associated with mineralised turbiditic metasedimentary rocks. Magnetic petrophysics of samples from the Stawell gold field establishes that the remanence is carried by a population of pyrrhotite grains that have distinctive magnetic hysteresis properties that imply a high stability against viscous remagnetisation. This pyrrhotite population is associated with zones where fluid expulsion during early Silurian Benambran deformation of the turbidites was concentrated, a process also resulting in gold endowment. Negative 2D anomalies in the Cobar–Bourke region, and on the southwestern margin of the Thomson Orogen, are also associated with zones of concentrated deformation of meta-turbidites during the Benambran–Bindian–Cobar sequence of orogenic events in the latest Ordovician to early Devonian. Similar pyrrhotite development in mineralised, high-flow zones may also be implicated in these cases. At this stage, the source of extended negative anomalies in the Cooper Basin region can only be speculatively assigned to a related process in the underlying Thomson Orogen basement.

Anomalies sourced in rocks of the Stawell gold field and the Girilambone Group near Cobar both invert to yield remanences corresponding to a paleomagnetic age in the Silurian to early Devonian. A similar paleoremanence was directly measured in an oriented sample from the Stawell gold field. A widespread late Ordovician to early Devonian overprinting episode, presumably associated with the series of compressive deformations comprising the Benambran, Bindian and Cobar orogenies, appears to be responsible for these remanence anomalies. Magnetic overprinting driven by fluid expulsion due to late Ordovician through early Devonian compression of marine sediments appears to characterise the western Tasmanides, and remanent anomalies produced by this mechanism may be useful indicators of mineralisation.

02RE-P03. PALEOPROTEROZOIC SEDIMENTATION AND CONTEMPORARY BASIN TECTONICS IN THE LOWER WYLOO GROUP, WESTERN AUSTRALIA

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The Paleoproterozoic (2.45–2.22 Ga) lower Wyloo Group unconformably overlies the glacial diamictite bearing Turee Creek Group of rocks and is unconformably overlain by the upper Wyloo Group. The lower Wyloo Group is made up of the Beasley River Quartzite (BRQ) and the Cheela Springs Basalt. The sedimentological account of the lower Wyloo Group is limited, such that the sequence-building pattern is largely unknown. Previous work suggested a marine origin for the Beasley River Quartzite (Martin *et al.* 2000 and references therein), based on paleocurrent analysis, but this was disputed for at least part of the BRQ on the basis of observed eolian features (Mazumder & Van Kranendonk 2013). This paper presents new mapping and high resolution sedimentary facies analysis of the lower Wyloo Group and infers the stratigraphic sequence building pattern for the first time.

The lowermost polymictic Three Corner Conglomerate Member of the Beasley River Quartzite contains subrounded to rounded BIF, chert, quartzite, and quartz pebbles and associated subordinate coarse sandstone, which we interpret as alluvial fan–fluvial complex. The overlying medium to fine-grained sandstone of the BRQ, which contains spectacular heavy mineral layering, dunes, low amplitude ripples, and pinstripe laminations, are interpreted as beach deposits with eolian reworking. The dominant, quartz-rich sandstone member of the BRQ is largely fluvial, based on association of poorly sorted fining-upward sandstone units, trough cross bedding, asymmetric ripples, and fluvial architectural elements. The topmost fine-grained sandstone and siltstone unit of the BRQ (the Nummana Member) is largely eolian, based on the presence of large dune and interdune (adhesion features, pinstripe lamination) facies. Our nearshore to eolian interpretation for the BRQ is compatible with the inferred subaerial eruption of the overlying Cheela Springs Basalt.

The occurrence of the terrestrial lower Wyloo Group of rocks on top of the marine Turee Creek Group clearly indicates relative sea level fall after the worldwide glaciation and the contact between the two therefore represents a sequence boundary.

The preservation of the lower Wyloo terrestrial succession is here interpreted to be the consequence of basin subsidence during rifting. Such subsidence might have taken in intracontinental or continental margin rifts, or back-arc or transtensional setting. As there is no evidence of a contemporaneous arc, nor an orogen during lower Wyloo sedimentation, we suggest a continental rift setting for the lower Wyloo Group.

02RE-P04. AGE CONSTRAINTS OF THE DEGRUSSA CU–AU–AG VOLCANIC HOSTED MASSIVE SULFIDE DEPOSIT AND ASSOCIATED MINERALISATION OF THE YERRIDA, BRYAH AND PADBURY BASINS, WESTERN AUSTRALIA

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The Paleoproterozoic Yerrida, Bryah and Padbury basins are located on the northern margin of the Archean Yilgarn Craton. Mineralisation within these basins dominantly occurs as epigenetic gold deposits (Peak Hill, Fortnum and Horseshoe mining centres) with lesser VHMS (Horseshoe Lights and DeGrussa) and epithermal copper (Thaduna).

The DeGrussa Cu–Au–Ag Volcanic Hosted Massive Sulfide (VHMS) Deposit is located in the Narracoota Formation, the lowest mafic volcanic unit of the Bryah Basin. The deposit consists of four ore lodes, cut and separated from each other by two large faults, with a combined strike length of 800 m and estimated resource of 14.33 Mt @ 4.6% Cu and 1.6 g/t Au. DeGrussa is hosted in turbiditic sediments and mafic basalts and intrusive dolerite units of the Narracoota Formation. The contacts of the ore deposit are typically associated with chlorite schist and a talc–carbonate exhalite unit. Sulfides are massive and fine grained consisting of pyrite, chalcopyrite and pyrrhotite with lesser sphalerite, galena, marcasite, magnetite and molybdenite. Chalcocite forms the main copper bearing mineral, along with malachite, azurite, chrysocolla, cuprite and native copper in the supergene ore zone. Greenschist facies metamorphism has affected the rocks.

A number of geochronological techniques were employed in order to date mineralisation of the DeGrussa mine including Rhenium–Osmium (Re–Os) on molybdenite, Pb isotopes on galena and pyrite, and U–Pb on zircon. Re–Os geochronology of molybdenite resulted in two primary depositional ages of 2027 ± 7 Ma and 2011–2013 ± 7 Ma (DeGrussa, Conductor 1 and Conductor 4) correlating to Pb–Pb model ages on galena between 2030–2040 ± 50 Ma (DeGrussa and Conductor 5) (Stacey & Kramers 1975). U–Pb on zircons on intrusive dolerites within the mine sequence provided concurrent ages of 1991–2003 ± 7 Ma with regional intrusive granodiorite rocks providing ages of 2012–2018 ± 10 Ma. Remobilisation of DeGrussa sulfides is exemplified by Re–Os ages of pyrrhotite at 1982–1984 ± 8 Ma and Pb–Pb pyrite ages of 1980 ± 30 Ma.

Unlike prior studies (i.e. Dyer 1991; Windh 1992; Thornett 1995; Harper *et al.* 1998) the Pb evolution model of Stacey & Kramers (1975) was used to determine Pb model ages. The alternative model, Cumming & Richards (1975) that has been used to determine deposit ages across the Capricorn Orogen region tends to underestimate the age by approximately 100 Ma when compared to the Re–Os ages. Re-calculation of epigenetic and VHMS mineralisation across the basins using the Stacey & Kramers (1975) model provides the following ages: Horseshoe Lights VHMS 1985–2000 ± 35 Ma, Nathans 1652 ± 30 Ma, Peak Hill 1890–2110 ± 30 Ma, Horseshoe/Belltop 1995 ± 30 Ma, Mikhaburra 1945 Ma, and Labouchere 1830 ± 30 Ma. These new ages coincide with major orogenic events in the region – the Glenburgh from 2005–1960 Ma (DeGrussa, Horseshoe Lights, Peak Hill, Horseshoe/ Belltop, Mikhaburra), Capricorn from 1830–1780 Ma (Labouchere, Peak Hill), Mangaroon from 1690–1620 Ma (Nathans, Fortnum), and the Mutherbukin from 1280–1250 Ma (Thaduna).

02RE-P05. THE AGE OF MAGMATIC AND HYDROTHERMAL ZIRCON AT OLYMPIC DAM

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The world class Olympic Dam iron-oxide Cu–U–Au–Ag–REE deposit on the eastern margin of the Gawler Craton is the world's largest uranium deposit and one of the largest in gold and copper. It is also rich in REE's, fluorine and iron. The principal ore minerals are Cu sulfides and U oxides. The deposit is hosted by the Olympic Dam Breccia Complex (ODBC), a large body of hydrothermal breccia that lies entirely within the Roxby Downs Granite (RDG), an evolved pluton of the Burgoyne Batholith of the Hiltaba Suite.

The transition between fresh and chlorite–sericite–hematite-altered RDG defines the boundary of the ODBC. Brecciation progresses from weak, incipient microfracturing of the RDG into largely barren granite breccia on the periphery of the system, through to mineralised hematite-rich breccia to a barren quartz–hematite breccia core. The hematite-rich breccia locally includes domains of polymictic volcanic breccia containing clasts of Gawler Range Volcanics and a small proportion (<1–2%) of bedded fine sandstone clasts. The ODBC also contains thick (>350 m) intervals of bedded sedimentary facies. All facies are cross cut by chloritised and sericitised mafic dykes. There are two main alteration assemblages: an upper bornite + chalcocite zone and a deeper and peripheral chalcopyrite + pyrite zone.

SHRIMP U–Pb zircon dates are available for a range of these facies, including fresh to weakly altered RDG, granite breccias, polymictic volcanic breccia, heterolithic breccia containing a mix of hematite, granite and volcanic clasts, hematite breccias containing chalcopyrite–pyrite mineralisation and bornite mineralistion, gold-bearing hematite breccia from the silicified margin of the barren hematite–quartz core, and sericitised and chloritised mafic intrusions. Seventeen dates collected over 4 analytical sessions agree within experimental uncertainties when corrected for instrumental mass fractionation, and have a pooled $^{207}Pb/^{206}Pb$ age of 1593.1 ± 1.2 Ma (MSWD = 0.19, P_{equiv} = 1.0). When the standard uncertainties are included, the age becomes 1593.1 ± 5.6 Ma. The low to moderate U and Th zircon is probably all magmatic, regardless of the facies from which it was extracted. Of 377 zircons analysed, only 6 grains are inherited, and only ~ 5% experienced some isotopic disturbance.

In contrast, analyses of hydrothermal zircon from a sericite–hematite–altered dyke display a scattered array of discordance extending to the origin, reflecting metamictisation of the very high U and Th grains. The hydrothermal zircon contains hematite–chlorite–chalcopyrite–sericite inclusions and very high enrichments of heavy REEs. A fairly tight discordia can be fitted to select analyses of the least damaged (lowest U and Th) grain areas, producing an upper concordia intercept age of 1605 ± 14 Ma, and two grains returned a few concordant analyses at 1605–1590 Ma. These results indicate that the hydrothermal system and formation of the ODBC are contemporary with the Gawler Range Volcanics/Hiltaba Suite magmatic event. The pattern of discordance is consistent with isotopic resetting in response to later-stage, lower temperature recharging of the system over a period of about 450 million years.

02RE-P06. STYLES AND CONTROLS ON BIF-HOSTED IRON ORE IN ARCHEAN TERRANES, COMPARISON BETWEEN THE PILBARA AND YILGARN CRATONS

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Meso-Archean Banded Iron Formations (BIF, ~30% Fe) occur within greenstone belt successions of both the Yilgarn and the Pilbara cratons, some of which contain high-grade magnetite, hematite- and/or goethite-rich ore deposits (53–62% Fe) of about 10 to 200 Mt in size. In the Yilgarn craton, recent studies have demonstrated the importance for the upgrade of BIF of (i) early, multistage hypogene alteration related to structural complexity, and (ii) later supergene alteration, associated with long-term exposure to weathering. In contrast with BIF-hosted iron ore from the Yilgarn, the timing and processes involved in the formation of the Pilbara iron deposits are poorly constrained. This contribution is an overview of the various lithostratigraphic and tectonometamorphic settings of BIF and BIF-hosted iron ore in the Pilbara craton. We attempt to identify some first-order controls on fertilisation and mineralisation of BIF in the Pilbara and provide a comparison with the Yilgarn.

Three distinct ages of BIF deposition are recognised in the Pilbara craton at *ca* 3.25, 3.19 and 3.02 Ga (Pincunah Member, Paddy Market and Cleaverville formations, respectively). Most iron ore deposits in the Pilbara are hosted by the Cleaverville Formation and are dominated by goethite enrichment, indicating the predominance of supergene processes in the upgrade of the BIF. In comparison, the Pincunah Hill Member and Paddy Market Formation display more spatially restricted exposures and host fewer iron deposits (e.g. Mt Webber). The Cleaverville Formation was deposited after the accretion of the East Pilbara Terrane with the West Pilbara Superterrane and is therefore recognised throughout the entire craton. However, the Pilbara craton displays a strong heterogeneity in terms of the distribution and size of economic iron ore occurrences. That is, most known deposits are concentrated in the East Pilbara Terrane (e.g. Abydos, Wodgina, McPhee Creek, Corunna Downs) and in the eastern part of the Central Pilbara Tectonic Zone (e.g. Pardoo, Mt Dove). These correspond to areas of both substantial thickening of BIF units and long-lived deformation histories. The role of late stage felsic intrusions in hypogene iron ore formation in BIF is presently untested.

Iron ore occurrences hosted by BIF in the Yilgarn Craton are concentrated in the western parts of the craton (i.e. west of the Ida Fault), with about 85% located in the Youanmi Terrane and the remaining 15% in the Narryer Terrane. In these terranes, supergene-modified hypogene iron ore deposits are controlled by multiply reactivated structures that allow the flow of early hypogene and late supergene fluids through BIF, resulting in the removal of silica and enrichment in iron in BIF. First-order controls on BIF-hosted iron deposits are the greater abundance of thick BIF macrobands in the western terranes, the siting of paleocratonic boundaries that control areas where thick sequences of BIF were deposited, and the likely involvement of felsic intrusions in the formation of hypogene orebodies. The absence of thick laterite overlying BIF-hosted iron ore deposits in the Yilgarn, compared with the Pilbara, suggests a difference in weathering intensities on exposed BIF in either craton since the Cenozoic.

02RE-P07. RECONSTRUCTING THE FACIES ARCHITECTURE, PHYSICAL VOLCANIC PROCESS AND EMPLACEMENT OF THE HOST ROCK SUCCESSION OF THE ARCHEAN TEUTONIC BORE, JAGUAR AND BENTLEY VOLCANIC MASSIVE SULFIDE DEPOSIT, YILGARN CRATON, WESTERN AUSTRALIA

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Teutonic Bore, Jaguar and Bentley volcanic hosted massive sulfide deposits are situated in the Eastern Goldfields of the Archean Yilgarn Craton, Western Australia. The VMS complex is situated in the Gindalbie Terrane (2695–2680 Ma), which is a bimodal rhyolite–basalt volcanic belt, enriched in high field strength elements, consists of felsic calc-alkaline volcanic rocks, quartz-rich sedimentary rocks, layered mafic complexes and mafic sills, formed during a period of regional extension in a back arc setting. The VMS deposits are hosted by a bimodal mafic and felsic volcanic succession with associated volcaniclastics and mudstones, and are located along strike over a 12 km distance. The rocks are metamorphosed to lower greenschist facies and have undergone moderate deformation.

The stratigraphy is divided into a hanging wall facies association and a footwall facies association, which are commonly separated by sulfide mineralisation. The dominant lithofacies are coherent basalt, rhyolite, andesite and dolerite, which form concordant, tabular bodies black mudstone, with minor graded bedded sandstones (turbidites) and rare polymictic conglomerates, represent the ambient deep water facies that are intercalated with the volcanic units. The basalt is present in both the hanging wall and footwall and contains both massive and pillow basalt facies, indicating that at least some basalts were seafloor lavas. However, monomictic volcanic breccia, commonly with peperitic textures, occurs at the tops and bottoms of many basalt units, indicating that they intruded into unconsolidated sediments. The rhyolite is mainly present in the footwall and is highly altered. Dolerite occurs as late intrusions with coarse crystalline textures.

The Teutonic Bore and Jaguar VMS deposits each consist of one steeply dipping lens of massive polymetallic sulfide underlain by stringer mineralisation. The Bentley deposit consists of three lenses of massive sulfide that are split by a late dolerite intrusion. The massive sulfide consists of pyrite, sphalerite, chalcopyrite and pyrrhotite. The mineralisation is mainly hosted by black mudstone but also occurs in pillowed basalt above the rhyolites and also replaces the brecciated portions of basalts and volcanoclastics. The sulfide lens occurs as: 1) massive bodies without any dominant fabric; 2) banded bodies of pyrite, sphalerite, pyrrhotite and chalcopyrite replacing the pyrite at places; and 3) stringer and disseminated patches. The sulfide shows replacement textures with basalt and black mudstone, and therefore represents subseafloor mineralisation that postdates sedimentation and basalt emplacement. The disseminated sulfide occurs both in the hanging wall and footwall as patches and blebs. Hydrothermal alteration extends into the hanging wall, which also supports a late mineralising event. The facies and texture indicates non-explosive volcanism in deep submarine environment.

02RE-P08. THE STRUCTURAL STYLE OF A NEW GOLD DISCOVERY IN AN OLD GOLDFIELD: CASTLE HILL GOLD CAMP, YILGARN CRATON, WESTERN AUSTRALIA

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The +2 Moz Castle Hill Camp, in the Coolgardie Domain of the Archean Yilgarn Craton, is a recent discovery in an underexplored, historical goldfield. Mineralisation is predominantly hosted by quartz tension veins within a tonalitic pluton called the Kintore Tonalite. Initial reconnaissance mapping of the Mick Adam pit suggested that steeply-dipping tension veins may have formed during regional extension, contradicting mineralisation models established for deposits proximal and more regionally. Further assessment, in the form of detailed pit mapping and diamond drill-hole logging, indicates the story may be far more complex with multiple populations of tension veins interpreted to have developed synchronously. Based on vein geometries we propose that mineralisation occurred during transient stress changes and vertical escape of over-pressured fluids. Vein orientations were influenced by local bulk strain heterogeneities around the tonalite pluton, as well as earthquake-related dynamics. In this manner, the multiple vein orientations and the observation that mineralisation relates to incremental extension, does not require a revision of the established regional structural sequence.

02RE-P09. DO THE OCEANS PROVIDE A REALISTIC ALTERNATIVE MINERAL RESOURCE?

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There is growing interest in the mineral potential of the seafloor. For example the resource potential for manganese nodules is estimated at over $1 billion. However, there are still many unanswered questions surrounding the likely composition and magnitude of marine mineral resources, the technology required to extract them and the potential environmental and socio-economic impacts of mining in the marine environment. There is also a tendency to regard all these questions and potential issues as similar, despite the wide spectrum of deposit types.

Australia's territorial waters have significant potential in terms of a variety of non-biogenic resources such as: heavy minerals (e.g. rutile, ilmenite, zircon); precious metals and other minerals (e.g. gold and diamond placer deposits, Mn oxides); and bulk materials (e.g. sands and gravels). Australia's current seafloor mining industry is small and confined to near-shore dredging operations; it is long-lived and generally accepted by the local community. By contrast, more recent proposals to mine the seafloor, notably in NSW (sands and gravels offshore Sydney and the Central Coast) and the Northern Territory (Mn oxides offshore Groote Eylandt), have engendered significant community protest, resulting in state-wide moratoriums for seafloor mining.

In Australia, debate around seafloor mining is hampered by a lack of regional baseline data and rigorously tested models. The likely environmental impacts are unclear and predictions and analysis are done in an *ad hoc*, opportunistic, even reactionary manner (c.f. research into the impact of dredging in the Port of Gladstone). Public debate about potential impacts has tended to treat all sites as similar, whether they are for nearshore bulk material excavation or offshore mineral extraction. However, the geology, ecology, hydrodynamics and atmospheric conditions of each site varies in the marine setting as it does on land, and so the current tendency for lumping all seafloor mining into one basket is misleading and leads to misperceptions in the wider community.

Regionally, the margin of the Pacific Ocean is host to numerous hydrothermal ore deposits including fields of mineral-rich “chimneys” venting hot fluids up to ~350°C at ~1500–2500 m water depths. Recently attention has returned to the open ocean’s abyssal plains where resources identified include: manganese nodules (Mn–Co–Ni–Cu rich); cobalt crusts (Co–Ni–Pt rich); and REE-rich muds. There is vigorous debate about the likely impacts of a new seafloor mining industry in the region and a number of regional initiatives have been targeted at developing a holistic approach using education programs and community stakeholder engagement to deliver a regulatory framework through which seafloor mining can be governed.

There are clear economic opportunities for a seafloor exploration and mining in Australia and the SW Pacific. However, the currently precarious position of this nascent industry, due to high levels of uncertainty surrounding its likely impacts, means that its future depends on an improved knowledge base that allows open and transparent communication channels between stakeholders, and improves understanding and underpins the local and international policy and regulatory processes.

02RE-P10. INVESTIGATING IRON MINERALISATION IN CHOGHART AND CHADORMALU IRON DEPOSITS, BASED ON MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS OF APATITE IN BAFQ MINING DISTRICT, YAZD PROVINCE

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Chadormalu iron deposit occurs 65 km north of Bafq town, 180 km northeast of Yazd city; and Choghart iron deposit is located 12 km northeast of Bafq town, 130 km southeast of Yazd city. Both deposits occur in central Iran zone and are Infracambrian (late Proterozoic–early Paleozoic) in age. The genesis of the Bafq iron deposits is very debatable and in the last 100 years many geologists who studied the area have proposed different genetic models, including: magmatic, sedimentary, volcanic, metamorphic, hydrothermal and exhalative models. In this study magnetite and apatite geochemistry and geothermometric measurements of fluid inclusions in apatite are used to determine geological processes related to ore deposition. The obtained results along with field observations and petroghraphic evidences in Choghart and Chadormalu show that both deposits are similar to Kiruna type and magmatic–hydrothermal deposits such as El Laco iron deposit in Chily. Recently, Kiruna type deposits are classified as IOCG deposits. REE content of apatites and magnetites in Choghart and Chadormalu are very high and ∑REE ranges between 5781–16460 in apatites, and between 22–774 in magnetites. Distribution of REE, major and minor elements in apatite and magnetite reveal that similar geochemical processes have operated in Choghart and Chadormalu, and show the similarity of genesis of these deposits with those of Kiruna type IOCG. However, evidence points to the important role of hydrothermal activity, and ore replacements from high salinity and temperature fluids. Salinity of fluid inclusions ranges between 15 and 56 wt% NaCl equivalent, homogenisation temperature varies between 310 and 475°C and estimated pressure (using Baker software) is between 2.6–3.4 Kb. Salinity and homogenisation temperature of ore forming fluids is similar to magmatic fluids and brines. The results of this study show that both hydrothermal and magmatic processes are responsible for ore formation in Choghart and Chadormalu deposits.

02RE-P11. IMPUTATION OF LEFT CENSORED GRADE DATA OF THE KULUMADAU EPITHERMAL GOLD DEPOSIT AND IMPLICATIONS FOR SUBSEQUENT MULTIVARIATE ANALYSIS

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Principal component analysis (PCA) is a well-established multivariate statistical technique, popular for analysing multivariate geochemical data. PCA uses eigenvector analysis to redistribute the total variance in a multivariate dataset with the aim of condensing a large portion of that total variance into a smaller number of independent variables (the principal components) that are linear combinat-ions of the original variables and reflect the effect of various phenomena affecting the dataset. PCA may aid in the recognition of geochemical patterns that can be related back to geological processes.

Geochemical datasets commonly contain censored variables where concentrations fall above or below the detection limits; this data is often referred to as “less thans” or “greater thans”. Substitution is the most popular method for dealing with censored data, involving replacement of censored data with a single arbitrary value (usually 1/2 or 1/3 of the lower level of detection). Numerous studies have shown that substitution is inferior to other replacement methods as it produces a low range signal, which may not exist, and may obscure other signals, which do exist. This significantly biases the mean and results in misleading regression models. With regards to PCA, substitution may result in pseudo-correlation between variables thus leading to erroneous geological interpretations. Albeit greater than 25 years since substitution methods were known to be wrong, this practice for dealing with censored data is common place in research and referred by industry as the “industry standard“. Multivariate analysis requires concentrations for a single variable to be greater than 0 for every given sample. Thus, censored data cannot simply be deleted or substituted for 0 as other elemental relationships for that sample will be lost.

The current study looks at the imputation of left-censored Au, Cu, Pb and Zn data from the Kulumadau epithermal Au deposit, Woodlark Island Papua New Guinea, using standardised probability distribution models. Lower levels of detection were defined using Q–Q and probability plots. Numerous probability distributions were fitted to each element. Goodness of fit tests were applied to evaluate which distribution models best approximate each variable. Once determined, the estimated parameters for the most appropriate probability distribution were used to create a synthetic dataset. Data below the defined lower level of detection from the synthetic dataset were randomly sampled and used to impute the left-censored data.

PCA was then carried-out and the results compared for grade data utilising substituted values and the various realisations obtained for the distribution-based imputed values. Prior to PCA, datasets were transformed using centred log-ratios to circumvent problems associated with closure. Results of the PCA utilising distribution-based imputation yielded geological interpretations more consistent with field observations and petrographic studies, than that of the substituted dataset.

02RE-P12. GEOCHEMICAL ZONATION AT MICRON- TO METRE-SCALE AT THE SUNRISE DAM GOLD MINE

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Interrogation and 3D visualisation of whole rock multi-element data can be used to recognise large scale chemical zonation associated with mineralisation and to identify chemical architecture that may have acted as conduits for ore fluids. We report the results of a multi-scale characterisation study of the Vogue ore body at the Sunrise Dam Gold Mine (SDGM).

SDGM is located 55 km south of Laverton in Western Australia. The mine, owned by AngloGold Ashanti, is the second-largest gold deposit in the Yilgarn Craton. The deposit sits within the structurally complex Laverton Domain, and is hosted in a sequence of shallowly dipping Archean metasedimentary and metavolcanic rocks, intruded by dolerite and porphyritic microgranite and granite. Gold mineralisation is largely hosted within shear zones and breccia zones associated with the later stages of compressional deformation and the majority of the gold is vein-hosted.

In this study a pXRF data set of >80 000 analyses was collected and a lithochemical schema developed and used to create a 3D model of Vogue region. A comparison of the schema data with logging data demonstrates that this approach can provide an objective approach to logging and is not unduly affected by later alteration. A comparison of pXRF and XRD data collected on the same samples demonstrates that K concentrations measured by pXRF correlate strongly with white mica content. Therefore K concentration data can be used to map the distribution of sericite alteration at Vogue, highlighting steep domains that cross-cut lithology. XRD analyses indicate that high gold grade intercepts are associated with a shift from calcitic to dolomitic carbonate compositions.

Isocons created from pXRF spot analyses collected on drill core around different vein populations at Vogue also indicate a local scale addition of K and Mg as well as trace elements including As and Sb. Sulfides in mineralised veins host numerous inclusions of Au, tellurides and sulfo-salts and have highly tortuous grain boundaries compared with sulfides in similar, but unmineralised, veins.

3D visualisation of geochemical data sets at Sunrise Dam allows recognition of the chemical architecture that may not be recognised through logging of drill core alone. Microanalysis of samples allows definition of the mineral phases that control the observed chemical signatures and the nature of alteration related to gold deposition events.

02RE-P13. THE PETROLOGY, GEOCHEMISTRY AND ORE GENESIS OF THE ALKALINE REE TOONGI DEPOSIT, DUBBO NSW

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The Toongi rare metal deposit is located approximately 20 km southeast of Dubbo in central New South Wales, and is one of the world's largest in-ground resources of zirconium, hafnium, niobium, tantalum, yttrium and rare earth elements. The deposit is one of several Late Triassic trachytic intrusions in the Dubbo area (Meakin *et al*. 1990), yet is one of only two igneous bodies with economically viable rare metal contents. The trachyte bodies form elliptical, flat-topped sills and flows that commonly feature concentric flow banding. Petrographic analyses of fourteen alkaline bodies revealed that the trachytes are finely porphyritic and comprise predominantly of potassium feldspar, albite, arfvedsonite and aegirine–augite phenocrysts surrounded by a fine-grained feldspathic trachytic groundmass. Three stages of hydrothermal alteration were identified in the Toongi Deposit and each are associated with mineralisation. The first stage is characterised by pseudomorphic replacement of primary microphenocrysts (possibly fayalite) by an unknown Zr-phase, which may be non-crystalline. The second stage involved precipitation of REE-carbonate(s) around the Zr-phase pseudomorphs, and the crystallisation of a second generation of the Zr mineralisation as texturally complex, ultra-fine grained intergrowths of the Zr-phase, eudialyte, natroniobite and REE-carbonates. The third stage of hydrothermal alteration resulted in the crystallisation of late stage, euhedral (Y)-milarite ($(CaY)_2KBe_3Si_{12}O_{30}$) and quartz grains within vesicles. The vesicles are thought to have acted as conduits for fluid flow during hydrothermal alteration.

Bulk-rock major and trace element concentration data (acquired by XRF and LA-ICP-MS, respectively) was used to test the relationship between mineralisation and igneous and hydrothermal processes. For most of the igneous bodies, crystal fractionation, as monitored by decreasing TiO_2 contents and Eu anomalies, correlates well with increasing rare metal concentrations. However, Y, REE, Zr, and Nb concentrations in the Toongi deposit are nearly an order of magnitude higher than in the most fractionated unmineralised trachyte bodies. Furthermore, there is no correlation between fractionation indices (i.e. Eu* or TiO_2) and rare metal concentrations in the Toongi deposit, indicating that a separate process, interpreted to be hydrothermal alteration, has amplified the ore metal grades. The fluids responsible for the transportation of the ore metals are proposed to be enriched in F, Be and SiO_2, which transported the rare metals as F–OH–complexes in highly alkaline (pH ~12), low temperature (≤350°C) fluids.

The proposed model for genesis of the Toongi deposit involves the shallow emplacement of highly fractionated trachytic magma(s), possibly during continental extension and/or mantle plume activity. Soon after emplacement, an influx of fluorine-rich hydrothermal fluids exsolved from a deeper-level magma reservoir(s) are inferred to have transported the bulk of the ore metals into the Toongi igneous body as rare metal–fluorine–hydroxide complexes. Rare metal precipitation from the fluid may have resulted from pressure and/or temperature changes, or reaction of the fluid with the trachytic host rock.

Reference

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02RE-P14. CONSTRAINING SOURCE AND DURATION OF TIN MINERALISATION AT ARDLETHAN, NSW: AN EXAMPLE OF MULTI-MILLION YEAR TIME-SCALES FOR MAGMA-DRIVEN HYDROTHERMAL SYSTEMS FROM U/PB DATING OF CASSITERITE

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The Ardlethan Tin Field of the central-west Lachlan Fold Belt is one of Australia's most economically significant tin systems. Here, tin mineralisation occurs in a number deposits spatially associated with a series of highly fractionated S-type granites and intrusions of the Late Silurian to Early Devonian. Of these intrusives, the 414.7 ± 2.3 Ma (SHRIMP, Bodorkos *et al*. 2013) geochemically specialised Ardlethan Granite is currently inferred, on basis of field and geochemical observations, to be the primary source of tin. At present this system is not well-enough understood to use as a model for predicting new discoveries. Accordingly, this study focuses on: (1) constraining the timing and hence source of the metals; (2) the timespan over which the mineralising system was active; and (3) characterising patterns in the geochemical evolution of the fluids that fingerprint this system. Our approach involved measuring U–Pb isotopes and trace element concentrations in the primary ore mineral cassiterite (SnO_2) using LA-ICP-MS at the University of Newcastle. Cassiterite samples used in the study were collected from 7 individual deposits occurring over an area of about 90 km^2.

The cassiterite U–Pb data yield precise ages that distinguish individual deposits within the tin field and collectively indicate that tin mineralising conditions were continuously active for up to 6.5 Ma, albeit across different locations through the system. The minimum duration consistent with the data is *ca* 1.8 Ma. Such a long multi-million year duration of ore forming conditions is interpreted to reflect the protracted history of granite pluton emplacement observed at Ardlethan combined with the large size and high heat production capacity of Ardlethan Granite, in particular. The geochemical data for cassiterite show remarkably limited variation between the individual deposits that are separated in time and space across the mineralised field. In this light, the geochemical and geochronological data from cassiterite suggests that a single, large-scale, long-lived fluid source was responsible for formation of the deposits of the Ardlethan Tin Field. Of interest also is the potential for using detrital cassiterite geochemistry coupled with age as a powerful ore field provenance indicator.

The results of this study demonstrate that LA-ICPMS U/Pb geochronology and geochemistry can be applied to cassiterite to produce reliable and precise mineral deposit ages, which in turn can help answer critical questions on ore genesis and related exploration geoscience problems.

02RE-P15. ENTRAINMENT, ASCENT AND BACKFLOW OF SULFIDE LIQUIDS AND THE FORMATION OF MAGMATIC NI–CU–PGE DEPOSITS

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Sulfide liquids that precipitate from silicate magmas after sulfide saturation represent a volumetrically small portion of magmatic systems, but they are responsible for the formation of orthomagmatic Ni–Cu–PGE sulfide deposits. Compared to silicate melts, immiscible magmatic sulfide liquids have lower viscosities (by 1 to 3 orders of magnitude), higher densities (>1500 kg/m^3 higher) and lower solidus temperatures (~150°C lower, depending on their composition). These properties hinder the withdrawal of sulfide liquid from magma staging chambers and its ascent to higher structural levels, and allow for late-stage mobility and downward movement through existing magma conduits and into country rocks by percolation along grain boundaries and fractures.

Prior to emplacement towards higher crustal levels, sulfide liquid will have a tendency to accumulate and pond at the bottom of staging chambers. Later mobilisation and upward or lateral withdrawal of sulfide can occur by viscous entrainment within relatively buoyant (mafic) magma. Analytical solutions and laboratory experiments applied to the low viscosities, high densities and relatively high volumetric flow rates expected within mafic melt–sulfide liquid systems predict that significant vertical draw up of sulfide liquid can occur within ascending mafic magmas at high, yet realistic flow rates (10–1000 m^3/s), under transitional to turbulent flow regimes. At lower flow rates and within non-inertial regimes draw up is hindered by interfacial tension. There are several possible fates for sulfide liquid after it is entrained: 1) it can be pulled back down by gravity into the lower staging chamber; 2) it can breakdown into filaments and droplets that are carried to higher levels of the system and re-aggregate in structural traps to form massive sulfide bodies; or 3) it can be transported to higher levels as a coherent body where it will occur as late-stage injections of sulfide cutting across older silicate magma phases.

There is evidence that both (2) and (3) have occurred in Ni–Cu deposits such as Voisey's Bay (Labrador, CAN), Eagle (Michigan, USA), and Sudbury's late offset dykes. However, in these systems there are also strong indications both within magma conduits and in country rocks that sulfide liquids have migrated downwards after aggregating or being emplaced at higher levels. The dynamics of such backflow and sulfide percolation are analogous to the behaviour of dense non-aqueous phase liquids (DNAPL) in near-surface environments. In fractured systems sulfide backflow is strongly controlled by the column height of the dense liquid. Because dense fluids flow downwards, this column generates a higher vertical body force when the down-flowing liquid network remains interconnected. The fluid must overcome the capillary pressure to enter a fracture, and because this is inversely proportional to fracture width, progressively thinner fractures can be intruded as a body of dense fluid percolates downwards. This process, along with late stage backflow of sulfide liquid into mushy silicate magma hosted within intrusions, can explain the presence of thin (cm to m sized) massive sulfide injections into wall rocks as well as larger bodies associated with structural complexities in conduits as observed in some deposits.

02RE-P16. MICROSCALE CONTROLS ON GOLD DEPOSITION

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Mine and core-scale variations in chemistry and mineralogy that accompany mineralisation are essential vectors for successful exploration. In order to understand why deposits form where they do it is also necessary to examine the microstructural setting of the mineralisation. The reaction microstructures that accompany mineralisation provide the key not only to the deposition mechanism but also to which minerals the associated changes in bulk composition are accommodated. We have studies gold-bearing samples from two deposits from the Yilgarn Craton of Western Australia to identify key reactions that accompany mineralisation and how these influence the sites of gold mineralisation at the micro-scale.

Mineralisation at the Junction deposit is accompanied by a reaction between biotite and calcite to produce siderite, dolomite, muscovite and chlorite. Where calcite is locally absent (on the scale of 100s of microns), the same reaction occurs but does not produce dolomite. The gold has exploited the volume change associated with the reaction. Dolomitisation and sideritisation of calcite results in porosity being created and this is filled with gold where the porosity is adjacent mica grains. Growth of muscovite at the expense of biotite also produces space that is filled with both gold and carbonate. The gold {111} planes are parallel with the muscovite basal planes indicating that the muscovite acted as a ‘template’ on which the gold grew.

At the Argo deposit, St Ives, gold is accompanied by ilmenite breakdown and a W anomaly. Dendritic ilmenite needles are reacting to TiO_2 and gold grains (both nano- and micro-scale) are found within the porous mesh of fine-grained rutile. The cause of this may be both the creation of porosity and the production of rutile, which is used industrially as a substrate for gold thin film deposition, in the same way as mica. Detailed examination of the ilmenite dendrites shows that they contain scheelite as fine-grained inclusions. During breakdown these scheelite inclusions are released and W is incorporated into the growing TiO_2 phases, anatase and brookite. These microstructures raise the possibility that the W anomaly pre-dates gold mineralisation despite its spatial association.

These studies show the importance of understanding micro-scale processes when forming a genetic model for gold mineralisation, highlighting the need to understand the mineralogical host for both the gold and associated elemental variations.

02RE-P17. HIGH SENSITIVITY MAPPING OF MICRO-GALVANIC METAL TRAPPING JUNCTIONS IN MIXED SulfIDES USING MECHANICAL FREE SCANNING LASER MICROSCOPY AT CRYOGENIC TEMPERATURES

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Percolating meteoric waters in the supergene environment react with micro-galvanic cells formed between contacting sulfides minerals. Under oxidising conditions the sulfide phase with the lowest rest potential preferentially dissolves sourcing electrons to the galvanic cell. These electrons transfer into the sulfide phase with the highest rest potential, typically pyrite, and quantum mechanically tunnel from surface states into fluid redox states at the right pH Metal complexes electrostatically attracted to the Helmholtz layer at the surface can be reduced leading to ore genesis such as finely grained gold mineralisation in sedimentary deposits. Mapping the sites of micro-galvanic interaction in sulfide assemblages and correlating their existence with elemental heterogeneities is an important step in predicting mineralisation events and their textures. However, mapping galvanic junctions using photocurrent mapping on a Scanning Laser Microscope is extremely time consuming due to the poor nature of the rectifying heterojunctions formed between naturally occurring sulfides. One means of improving the quality of these heterojunctions, and as a result the sensitivity of the technique, is to use cryogenic temperatures. Here we report on preliminary measurements made on an arsenian pyrite sample from Otago, NZ made as a function of temperature from 400K to 78K.

02RE-P18. EXHALATIVE HORIZONS AND VOLCANIC-ASSOCIATED MASSIVE SULFIDE (VMS) DEPOSITS IN THE ORDOVICIAN GIRILAMBONE GROUP, NEW SOUTH WALES

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Recent mapping by the Geological Survey of New South Wales provides a stratigraphic and structural framework for VMS deposits in the Lachlan Orogen in northern central New South Wales. These copper-rich, pelitic–mafic-hosted deposits include those at Tritton, Girilambone and Tottenham. Exhalative horizons are found throughout the region with some spatially associated with mineralisation. This study examined these exhalative horizons, including their relationship with the Tritton ore zone, using pyrite geochemistry, sulfur isotopes, whole rock geochemistry and petrography. The results support a syngenetic origin for both mineralisation and the exhalative horizons.

VMS mineralisation is hosted by turbiditic sequences of the Lower Ordovician Narrama Formation (Girilambone Group). Footwall mafic rocks are of mid ocean ridge basalt (MORB) affinity (Burton 2011). Mineralisation consists of pyrite-rich banded, massive sulfides and chalcopyrite–pyrite zones, with subeconomic stringer and discontinuous veins in the footwall sequence (Jones 2012). Exhalative silica–iron horizons immediately overlying the ore zones may be laterally extensive and mineralised. Overlying mineralisation are hangingwall turbidites, a soft-sediment breccia with massive sulfide clasts (Jones 2012) and quartzite of the Budgery Sandstone Member (Narrama Formation). Alteration zoning includes proximal Fe-chlorite to distal Mg-chlorite in the footwall, silicification of the ore zone, and carbonate-altered hangingwall assemblages (Jones 2012). Deformation of the sequence in the Benambran Orogeny and later events folded the mineralised sequence into its current geometry, with some remobilisation of copper. Regional metamorphism peaked at lower greenschist facies.

The study supports a model in which hydrothermal fluids sourced from MORB-affinity mafic rocks mixed with seawater in unconsolidated turbidites, resulting in temperature-controlled precipitation of cuperiferous pyrite and other metals into preferential pelitic host rocks. At Tritton, pyrite geochemistry indicates copper was present as chalcopyrite within early-stage pyrite. Elevated Ni and Co values within early-stage pyrite indicate mafic-derived fluids. The presence of U–Th-rich rims around pyrite and lack of Ba support an inhalative/subseafloor process. Pyrite geochemistry indicates hot, oxidised fluids cooled, resulting in metal precipitation, with overlying exhalative silica–iron horizons forming by precipitation of spent-fluids on further cooling and in more reduced conditions. Sulfur isotope analysis from the ore zone and exhalative horizons at Tritton suggest a mixing of magmatic fluids with reduced seawater sulfate. The highly magnetic nature of the exhalative horizons provides a useful vector for exploration, as they contrast with magnetically featureless metasedimentary rocks in regional magnetic datasets.

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02RE-P19. GEOLOGY, MINERALISATION AND ALTERATION OF THE KULUMADAU EPITHERMAL DEPOSIT, WOODLARK ISLAND, PAPUA NEW GUINEA

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The Kulumadau gold deposit on Woodlark Island, Papua New Guinea, represents low- to intermediate-sulfidation epithermal mineralisation that is predominately hosted within argillic-altered fault zones, unusual for epithermal style mineralisation.

Woodlark Island is located within the Papuan Islands Terrane, a continuation of the onshore Eastern Fold Belt. The basement on Woodlark Island comprises Cretaceous to Eocene low-K, tholeiitic ocean ridge basalts believed to be *en-echelon* to the onshore Papuan Ultramafic Belt, and is overlain by a sequence of Miocene limestones and overlying volcanic/subvolcanic rocks of the Okiduse Volcanics; the latter of which hosts the known primary gold mineralisation on Woodlark. Unconformably overlying the Okiduse Volcanics is the Quaternary–Pleistocene sediments of the Kiriwina Formation, which cover ~85% of the island. Approximately 20 km east of Woodlark is the active NE-trending strike-slip Nubara Fault of which most of the regional structures on Woodlark appear to mimic.

The Kulumadau deposit (3.8 Mt @ 2.3 g/t) is located at the juncture of a regionally significant fault (parallel to the Nubara Fault) and smaller subsidiary faults. The host package comprises calk-alkaline andesitic subaerial volcaniclastics; primarily pyroclastic flows, their epiclastic equivalents and a thick package of growth faulting-related debris avalanche breccias. The hydrothermal mineralising event appears to be related to mid-Miocene monzodiorite intrusives. The bulk of mineralisation is contained within subvertical milled-matrix breccia lenses with bonanza gold grades encountered in quartz–carbonate ± base metal sulfide veins adjacent to these. Ore minerals disseminated throughout mineralised lenses include pyrite, sphalerite, chalcopyrite and galena. Alteration around the deposit is zoned with the lens itself characterised by an argillic assemblage (illite–quartz–chlorite–pyrite–adularia) enveloped by a phyllic halo (illite–quartz–pyrite) and at depth by quartz–adularia–epidote. At the margins of the deposit, propyllitic hematite–chlorite ± calcite alteration is encountered with sporadic massive (>0.5 m width) anhydrite veins grading into a propyllitic chlorite–quartz ± pyrite alteration. Elevated gold grades exhibit a spatial affinity with the brecciated lenses and at the juncture between propyllitic hematite and argillic/phyllic alteration.

Mineralisation at Kulumadau appears to have occurred in a submarine environment with anhydrite–hematite alteration marking the edge of the paleo-hydrothermal system. Epigenetic fluids appear to have exploited normal faults consistent with the locally extensional regime required for epithermal deposits. Fluid mixing appears to have been an effective mechanism for precipitation of high-grade gold. The presence of elevated molybdenum at depth within the epidote-altered zone indicates a potential porphyry source at depth.

02RE-P20. INTERPRETATION OF SILICATE MINERALOGY USING THE ASTER TIR SPECTRAL LIBRARY AND ASSOCIATED DATABASE

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Thermal Infrared (TIR) spectroscopy has been undertaken since the 1970's to investigate the structure and composition of silicate minerals (Vincent & Thomson 1972). In particular, TIR spectral signatures measured as directional hemispherical reflectances (DHR) of various minerals and rocks have been interpreted with the control of laboratory analytical data. TIR spectroscopy of various felsic to igneous and metamorphic rocks was found to identify specific silicate minerals such as quartz, feldspars, garnets and pyroxenes (Salisbury & D'Aria 1992). Further studies by Cudahy *et al*. (2009) indicated that the chemical composition of plagioclase and other minerals associated with mineralisation could be interpreted by TIR spectral signatures. Cudahy *et al*. (2009) also demonstrated that spectral processing techniques (e.g. fitted curves and band ratios) developed for mineral interpretation using DHR equivalent emission spectroscopy, can also be applied to HyLogger™ bidirectional TIR spectroscopy. The application of TIR spectroscopy to estimate quartz content, igneous rock SCFM composition (e.g. SCFM = SiO_2 / (SiO_2 + CaO + FeO + Fe_2O_3) and quartz crystallinity have also recently been undertaken using emission spectroscopy and public domain spectral libraries (Hewson & Cudahy 2013). Such studies are greatly assisted by the publicly available ASTER DHR Spectral Library (ASL) (http://speclib.jpl.nasa.gov/) Baldridge *et al.* 2009) and its ancillary database, sourced from Johns Hopkins University (JHU), Jet Propulsion Laboratory (JPL), and the United States Geological Survey (USGS). In particular, the ASL associated ancillary data provides a compositional control from petrographic, XRD mineralogical and XRF chemical analysis. In this study, examples of the processing interpretation of TIR rock spectral signatures for quartz, SCFM, plagioclase content and composition are described using the ASL spectral library and ancillary database. In particular, studies using the ASL data indicated that quartz content could be predicted ($R^2 = 0.71$) using a relative band depth spectral parameter for the 8.61 μm quartz reststrahlen feature. A R^2 correlation of 0.44 was observed between this spectrally derived quartz content and the SCFM. Preliminary results for interpreting ASL plagioclase content and composition using similar relative band depth parameters, produced R^2 correlations of 0.36 and 0.63, respectively.

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02RE-P22. NON-DESTRUCTIVE GEOMETALLURGICAL LOGGING FOR PROSPECT EVALUATION

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At the exploration stage of a prospect drill core is in short supply and geometallurgy needs to concentrate on non-destructive testing. The principle aims of geometallurgy at this stage are to define the spatial domains in processing behaviour and to support decisions about the preferred mine and mill design. The early definition of spatial domains that may influence the crushing, grinding, extraction (and environmental) performance of ore allows the effective design of a metallurgical testing regime. The aim is to have geometallurgical parameters for each assay interval.

It is very important to accurately record the original characteristics of the drill core. High quality photography under controlled lighting of clean, well prepared core is an essential first step. If the core is oriented, then photographs of whole core can be used to generate most of the required geotechnical data for early mine planning. Good quality photography can be used to improve manual core logging (by providing accessible images of previously logged core for comparison) and in some cases automated logging of core texture and colour may be appropriate.

The use of an IR method such as Hylogger®, as part of alteration mapping can provide extra constraints that will improve modal mineralogy estimates that can be made from assay data. Modern multi-element assays can be used to calculate mineralogy from assay provided a "nearly-complete" digestion method is used. It is usually necessary to support this method by measuring the mineralogy by QXRD at regular intervals. In most cases, measuring the mineralogy every tenth sample is suitable as a support method. Multi-element assays can also give the first indication of the distribution of many of the likely penalty elements (e.g. As, U, Bi) across the prospect.

For comminution behaviour it is very useful to have some independent measurement of the rock strength. Non-destructive impact hardness measurements (e.g. EQUOtip) and sonic velocity can be measured on drill core without reducing its value for other applications. Point load testing has similar value as a comminution proxy but is much more destructive. RQD (rock quality designation) and GSI (geological strength index) measurements can also be useful as proxies for crushing and grinding hardness.

02RE-P23. USING GEOCHEMICAL DATA TO DISTINGUISH WASTE ROCK IN NUGGETY GOLD DEPOSITS, AN EXAMPLE FROM THE GIANT SUNRISE DAM DEPOSIT, WESTERN AUSTRALIA

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Gold distribution in vein-hosted hydrothermal ore deposits is commonly nuggety (i.e. occurs as very localised concentrations of gold). In such cases, samples for gold assay from diamond drill core may return low gold grades despite their host rocks being mineralised. This means that if decisions are based on gold assay values alone, mineralised material may be misclassified as waste. As well as the obvious need to classify waste during mining so that is separated from the ore, it is also important to be able to map waste material early in the mine planning process so that infrastructure can be appropriately located.

It is common practice in nuggety orebodies to use more spatially continuous proxies for mineralisation to help define the boundaries of mineralised regions, such as alteration intensity or vein density. However, manually derived proxies are open to human interpretation and error, and hence may be inconsistently applied. We present a method for automating the use of multi-element geochemical data as a proxy for mineralisation. Automation has the advantage of repeatability and fast processing time.

In order to automate the process, we apply a probabilistic approach to quantify the relationship between gold assay values and a chemical subcomposition. We demonstrate how conditional probability can be used to determine the most likely waste rock from diamond drill core samples from the Sunrise Dam Gold Mine in Western Australia. In a trial of the method, almost 22% of samples, which had gold assays values at background levels had a high probability of being mineralised based on their Rb–Sb–Cr subcomposition. This is a strong indication that these samples should not be classified as waste without further investigation.

02RE-P25. USING THE HYLOGGER IN MAPPING STRATIGRAPHIC BOUNDARIES IN SEDIMENTARY BASINS: EXAMPLES FROM THE MCARTHUR BASIN, NORTHERN TERRITORY

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Researchers that compile and interpret basin-wide stratigraphic data are faced with the issue of inconsistent 3D stratigraphic mapping. One factor that has hindered this process is stratigraphic logging of drillcore by many different geologists in different mineral and petroleum companies over several decades, with little relogging or comparison between drillholes. Another factor is changes in stratigraphic nomenclature over time, which may lead to redundancy of some stratigraphy. NTGS is using the HyLogger to assist in highlighting inconsistencies in stratigraphic logging, by scanning its core facility drill core with the HyLogger. Initial comparisons of logged stratigraphy with HyLogged mineralogy show inconsistencies both within holes and between neighbouring holes. For example, logged stratigraphic boundaries (particularly unconformities) commonly do not show expected sharp mineralogical or textural contrasts, or the dominant mineralogy does not match that described for a particular stratigraphic interval. These results assist in targeting zones that require further geological re-logging and validation.

HyLogger outputs can highlight mineralogy and other physical changes that may be unique to a particular stratigraphic interval, such as changes in the composition of mineralogy, changes in albedo, core colour changes and cyclic changes in mineral ratios (such as quartz:carbonate with depth). HyLogger imagery may highlight fracture/breccia zones, which can delineate areas of structural deformation. These results can be used in conjunction with other externally generated data (gamma logs, TOC, petrography, XRD) to gain a better understanding of lithological changes within various stratigraphic units.

Understanding the regional stratigraphic framework is key to developing an effective exploration strategy. Currently the NTGS is addressing this issue in the McArthur Basin by bringing together disparate one- and two-dimensional datasets into a 3D environment. This allows disparate datasets to be viewed concurrently and aids in developing a coherent understanding that fits all data. The HyLogged datasets are a key input in identifying lithological boundaries that constrain the surfaces within the model.

02RE-P26. HYPERSPECTRAL IN THE DOMAINING OF RESOURCE MODELS

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Spatial modelling of hyperspectral data applied to mineral deposits has historically focussed on the characterisation of and exploration for mineralisation (e.g. Hauff *et al.* 1989), including more recent advances in fingerprinting fertile fluid conduits involved in the localisation of ore (Roache 2008). A further application of measuring the contrasting mineralogical and geometric controls on mineralisation may be employed to the definition of mineralised domains within the resource estimation field. This is particularly pertinent for the accurate estimation and mining of resources in structurally- and mineralogically-complex lode gold deposits. This paper presents mineralogical indices derived from SisuRock short wave infrared images.

The Sunrise Dam gold mine is a multi-million ounce gold producer in the Eastern Goldfields of Western Australia. Mineralisation is marked by narrow, high-grade shoots within a sheared or brecciated host. The nuggetty gold distribution presents a challenging problem in ascertaining the continuity and orientation of mineralisation, particularly where there are multiply-oriented ore-hosting structures.

Within the GQ mining domain, both shallow-dipping shear zones and steeply-plunging breccia pipe-hosted mineralisation are associated with ankerite/dolomite and muscovite alteration phases, but the relatively high white mica abundance and shortest wavelength white mica within the steep pipes adds sufficient contrast to separate the two lode styles. In conjunction with the continuity defined by the broad carbonate and white mica alteration envelope, the mineralogical distinction between shallow and steep lodes is suitable for the geological domaining of resource models.

Within the shallow-dipping Midway Shear Zone in GQ South, the carbonate composition index spatially-defines two obliquely-intersecting shear planes that may mark the formation of mineralised splays that diverge from the large mineralised structures. Localised shoots of anomalously-wide, potentially-high grade lodes may also form at their intersection. The identified orientations and positions of these structural elements are important in deciding the anisotropy of the resource block model.

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02RE-P27. LOGGING THE REGOLITH PROFILE OF COOPER PEDY, SOUTH AUSTRALIA

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A series of several hundred auger samples taken at 2 m intervals, from Cooper Pedy, Lambina and Andamooka opal fields were scanned using the HyLogger™ 3-3 instrument at the South Australian Drill Core Facility in Adelaide. The instrumentation rapidly measures drill core using infrared reflectance spectroscopy, and high-resolution linescan digital imagery. The spectral range includes 380 nm–2500 nm (visible and short wave infrared, VSWIR), and also 6000 nm–14 500 nm (thermal infrared, TIR). Reflectance spectroscopy can identify a range of different minerals, from iron oxides in the visible wavelengths, through to clay minerals and carbonate species in the SWIR and tectosilicates in the TIR. These minerals are important for identifying the weathering profile and the relationship to opal formation.

Precious and potch opal are found in deeply weathered, Early Cretaceous, white to mauve, marine Bulldog Shale. Weathering during the Cenozoic Period, with a periodic lowering of the water table, produced a kaolin-rich weathered, bleached and porous silty or sandy claystone down to a depth of about 40 m. Below this the fresh shale is a dark grey, silty or sandy smectite-rich claystone, commonly pyritic and carbonaceous. Precious and potch opal, commonly with associated alunite, gypsum and iron oxides, are generally found near the base of the upper weathered zone infilling cracks, joints and occasionally replacing fossils. Minerals identified using *The Spectral Geologist (TSG)*, specialist software were alunite-Na, alunite-K, gypsum, kaolinite (both well crystalline and poorly crystalline), montmorillonite, opal, quartz, albite, dickite, goethite and hematite.

The spectral characteristics were then extracted from TSG, and plotted across each region, using GOCAD modelling software, producing a regional regolith profile for the Cooper Pedy area. The modelled profile reflects smectite–montmorillonite dominates the top ten metres, and grades down into a zone rich in gypsum. Underlying the gypsum is a zone dominated by well crystalline kaolinite zone, and finally at the base lies the alunite. The alunite zone is dominated by sodium-rich alunite species although the potassic species is also present in places.

02RE-P30. SPECTRAL PROFILING OF MINERALS IN THE ETHERIDGE PROVINCE, NORTH QUEENSLAND, USING HYPERSPECTRAL CORE LOGGING

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Infrared spectroscopy has been used for many years to characterise different hydrothermal alteration styles of rocks. With the development of automated drill core scanning spectrometers (HyLogger™, CSIRO), visible-near-shortwave-infrared (VNIR/SWIR: 400–2500 nm) and thermal infrared (TIR: 6000–14 000 nm) reflectance spectra can be non-destructively collected from the surface of the drill cores and their compositional information can be quantified at a rapid rate. Absorption features due to the electronic/vibrational processes form the diagnostic criteria to identify minerals such as phyllosilicates, hydroxyl silicates, sulfates, carbonates and iron-containing minerals in the VNIR/SWIR region and the remaining hard rock minerals like quartz, feldspar, amphiboles, pyroxenes, etc. in the TIR region.

The Etheridge Province is one of the largest exposed geological provinces in North Queensland. It outcrops over most of the Georgetown Region and the eastern part of the Coen Region, extending from Woolgar in the south to the Lockhart River in the north. Even though the rocks in the northern (Chillagoe northwards) and the southern part may have been deposited roughly synchronously, zircon dating and other studies showed different structural and metamorphic histories, and hence they are designated into the northern Yambo and southern Forsayth subprovinces. The Forsayth Subprovince is a late Paleoproterozoic metasedimentary succession with associated metabasalt and metadolerite. Rocks of this subprovince were undergoing intense deformation at *ca* 1590 Ma, postdated by S-type granitoid plutonism at *ca* 1560 Ma, accompanied by deformation and low pressure–high temperature metamorphism. The late Paleoproterozoic–early Mesoproterozoic Yambo Subprovince consists of intensely deformed metasedimentary and meta-igneous rocks formed after 1640 Ma that underwent high-grade locally granulite-grade metamorphism associated with I-type and S-type granitoid plutonism at 1590–1560 Ma.

Recent SHRIMP U–Pb geochronology has established the Etheridge Group in the Forsayth Subprovince to be similar in age to the base-metal mineralised eastern part of the Mount Isa Region (1720–1650 Ma), which also draws stratigraphic correlation with the Broken Hill region. These correlations significantly enhance the potential of the Georgetown Region for base-metal mineralisation. The rocks of the Paleoproterozoic sequence in the Forsayth Subprovince have a high potential for disseminated replacement gold deposits and the Mesozoic felsic intrusives favour the concentration of uranium. The carbonaceous and pyritic nature of the Etheridge Group and the widespread intrusion of the felsic igneous rocks of variable age provide a fertile environment for mineralisation of different styles, favouring a range of commodities. Podiform chromite deposits and nickel–cobalt-bearing laterites are most likely to be in economic concentrations associated with serpentinite bodies flanking the inlier. Copper can be associated with the Broken Hill style Ag–Pb–Zn deposits in the Mount Isa Province. Mesoproterozoic rocks in the Sandy Creek area (Woolgar Inlier) are known to host epithermal deposits. Mineralisation is commonly accompanied by alteration halos and the identification of the alteration assemblages can describe the presence of mineralising systems. Five holes HyLogged in the Etheridge province were interrogated to better understand the mineralisation profiles in the region.

02RE-P32. SKARN GANGUE MINERAL ASSEMBLAGE CHARACTERISATION USING SWIR-TIR-SPECTROSCOPY

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Gangue mineral assemblages of skarn deposits are diverse. Accurate and objective characterisation of this mineral diversity, including variations in mineral chemistry, is important for understanding a given skarn system. Hyperspectral remote sensing data have been successfully applied for mapping, for example, Al↔Fe composition of garnets in skarn systems (Cudahy *et al.* 2000).

For this paper, the gangue mineral assemblage of drill core samples from the Antamina skarn-hosted Cu–Zn–Mo deposit, Peru, was interpreted from hyperspectral shortwave infrared (SWIR: 1–2.5 μm) and thermal infrared data (TIR: 6.0–14.5 μm) collected from drill core samples using a HyLogging™ system (Yang *et al.* 2011). At Antamina, a quartz monzonite porphyry intruded Upper Cretaceous sedimentary rocks of the Jumasha and Celendin formations, resulting in a complex pattern of skarn alteration that developed along the contact and was crosscut by later stage hydrothermal breccias. Mineralisation at Antamina comprises mainly Cu, Zn, Mo ± Ag and Bi, with the majority of Cu–Zn ore present in exoskarn and Cu–Mo ore in endoskarn. Some of the key mineralogical parameters that can be used to distinguish endoskarn from exoskarn and respective subtypes on the base of HyLogging™ data are 1) garnet composition, 2) amphibole composition, 3) vesuvianite content and 4) wollastonite content.

TIR data were used to identify compositional variations of garnet, ranging from grossular ± andradite in the endoskarn to andradite ± uvarovite in the exoskarn, based on shifts of the inner SiO_4 tetrahedra stretching modes in the 10 to 12 μm wavelength region. However, 'hydro-grossular' (i.e. hibschite) was detected in exoskarn samples by the combined use of SWIR and TIR wavelength regions and confirmed by X-ray diffractometry (XRD), suggesting a complex pattern of Al↔Fe^{2+} and Fe^{2+}↔Cr composition across the garnet populations in the skarn. Endoskarn samples are characterised by a high vesuvianite content (up to 65% acc. to XRD), whereas some parts of the exoskarn showed a high content of wollastonite (up to 47% acc. to XRD). Vesuvianite was identified on the base of its diagnostic SiO_4 tetrahedra stretching mode in the TIR at around 9.9 m. Wollastonite was characterised by a diagnostic spectral signature between 9 and 11 m, which considerably overlaps with garnet, vesuvianite and pyroxene. This overlap of spectral features compromised the quality of the quantification of wollastonite. Amphiboles, as well as their corresponding compositional variations, were readily interpreted from the SWIR wavelength region. The hyperspectral data suggest that amphiboles are mainly represented by tremolite in endoskarn samples, whereas other calcic amphiboles with lower Mg/Fe ratio are evident in exoskarn samples.

In summary, combined hyperspectral SWIR-TIR drill core data allow an objective classification of different skarn gangue mineral assemblages. This has the potential to improve characterisation of different ore types, therefore having implications for geometallurgy, as well as for mineral exploration.

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02RE-P33. INTEGRATION OF HYLOGGING DATA WITH GEOCHEMICAL, WELL LOG AND BIOSTRATIGRAPHIC DATA IN THE GEORGINA BASIN, QUEENSLAND AND NORTHERN TERRITORY, AUSTRALIA

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Geoscience Australia is currently assessing selected Australian sedimentary basins for their unconventional hydrocarbon resource potential, in collaboration with the Northern Territory and state governments. A study of the southern Georgina Basin is in progress, involving the compilation of a cross-border dataset of all accessible open file seismic, well, geological and geochemical data that will be publicly released in mid-2014. Major geochemical resampling of old wells has generated new information on source rock characteristics, kerogen kinetics, and gas and oil isotope geochemistry in the Georgina Basin. Preliminary 3D geology and 1D petroleum systems models have also been generated.

Several cores from the Georgina Basin have been HyLogged by the geological surveys of Northern Territory, Queensland and New South Wales, using HyLogging facilities funded by AuScope Pty Ltd and CSIRO as part of the National Collaborative Research Infrastructure Strategy (NCRIS) and AuScope National Virtual Core Library (NVCL) Project. Geoscience Australia currently has a project underway to reprocess the raw HyLogging data using a common set of mineral scalars, to create an internally-consistent, basin-wide dataset. An initial composite HyLogging data package was publicly released in March 2014, including reprocessed data for 14 wells in the southern Georgina Basin, information about the processing methods used, and metadata. A second stage of the project will involve interpretation of the reprocessed data from these wells, to further examine the relationships between the spectroscopic and mineralogical properties measured by the HyLogger, and core total organic carbon (TOC), XRD, XRF and ICPMS compositional data, well log data, and biostratigraphic data. Initial work has indicated interesting trends, such as the apparent relationship between gamma intensity, core SWIR albedo (mean shortwave infrared reflectance) and quartz content. Peaks in gamma intensity broadly align with troughs in albedo, suggesting that the reduced albedo is a result of increased TOC content. However, in others cores (or even the same core), peaks in gamma intensity also appear to correlate with potassium-rich phases such as white micas and other clay minerals, thus the gamma correlation does not appear straightforward. Other preliminary observations indicate that using HyLogging data provides (i) the opportunity to review the existing formation picks in the basin from a mineralogical perspective, (ii) new information on variations in calcite/dolomite proportions in the carbonate sequences, (iii) the ability to map apatite distribution, and (iv) mineralogical evidence of sedimentary cyclicity. It is thus hoped that integrated interpretation of the HyLogging data and other data types will enable clearer delineation of the lower Arthur Creek Formation (and the 'Hot Shale' within) and other prospective source/reservoir units in the Georgina

Basin, and therefore assist in constraining target intervals for future unconventional hydrocarbon resource assessments.

DYNAMIC PLANET

02DP-P01. EPISODES OF RAPID EXHUMATION FOCUSSED IN CENTRAL ASIAN FAULT ZONES WITHIN THE TIEN SHAN, ALTAI AND SAYAN

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Central Asia represents the world's largest and most active intracontinental deformation zone between the Tibetan plateau and the Siberian craton. This region was reactivated several times during its geological history as response to collisions at the distant plate margins and hence represents an excellent natural laboratory to investigate the timing and spatial distribution of intracontinental deformation. We present multi-method thermochronological results (apatite and titanate fission track; and apatite and zircon U–Th–Sm/He data) to elucidate the thermal history of the Tien Shan, Altai and Sayan Mountain Ranges. It was found that most of the Central Asian rock exposures surfaced during the middle–late Mesozoic and only its dissecting fault zones record evidence for subsequent Cenozoic deformation.

Besides the occurrence of some older, Early Mesozoic geomorphic features (such as internally drained plateaus or old erosion surfaces), most of the current relief is related with an important phase of Late Jurassic–Early Cretaceous uplift and exhumation that has been documented throughout most of Central Asia. This episode of relatively slow cooling and exhumation is thought to be associated with collisions of Gondwana-derived, Cimmerian Blocks to Eurasia in the south and to the closure of the Mongol-Okhotsk Ocean to the northeast. Major fault systems within the Tien Shan record Cenozoic episodes of fault-induced rapid exhumation during the Early Paleogene (*ca* 60–45 Ma) and Late Oligocene (*ca* 30–25 Ma) to Miocene (*ca* 10–8 Ma)[1]. The first major pulses of these fault-reactivation events coincide remarkable well with the 'soft` (*ca* 50 Ma) and `hard` (*ca* 25 Ma) collisions of India with Eurasia, arguing that the India–Eurasian convergence is the main driving force behind Cenozoic mountain building in the Tien Shan. For the Altai and Sayan Ranges, rapid fault-induced exhumation occurred during the Late Cretaceous–Early Paleogene (*ca* 90–60 Ma), which is thought to be a far-field response to the collapse of the Mongol-Okhotsk orogen between the Siberian and North China–Mongolian continental blocks[2,3]. Furthermore, the main east–west striking structural fabric (the Sayan fault system) documents Late Cretaceous–Early Paleogene rapid exhumation over its entire length, from the Altai and Sayan Ranges to the Baikal region, suggesting that the exhumation of the Altai and the initiation of rifting in the Baikal region are likely interconnected[3]. After a long period of subsequent thermal stability, the Altai and Sayan region were subjected to a renewed phase of Plio-Pleistocene (*ca* 3–1 Ma) reactivation[2,3], which is likely related with the ongoing India–Eurasia convergence that induced fault-reactivation much later as documented for the Tien Shan region.

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2DP-P02. THE ELASTIC–ANELASTIC TRANSITION IN OLIVINE AT HIGH TEMPERATURE AND ITS SEISMOLOGICAL IMPLICATIONS

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With increasing temperature, fine-grained polycrystalline materials undergo a transition from elastic to anelastic behaviour, involving grain-boundary sliding recoverably accommodated by elastic distortion of adjacent grains – according to the classic theory of Raj and Ashby. This model, recently revisited by Morris and his colleagues, predicts shear-mode dissipation localised in temperature-period space as a Q^{-1} peak with height of order 10^{-2}. Notwithstanding a recent exploratory study (Jackson *et al.*, *Phys. Earth Planet. Interiors*, in press), experimental data for fine-grained polycrystalline olivine are yet to provide unequivocal evidence of the expected dissipation peak and associated dispersion of the shear modulus. Accordingly, we have embarked on a new series of measurements on synthetic olivine polycrystals in which the specimens are enclosed within copper, rather than the usual steel, jackets for the forced-oscillation experiments at high temperature and pressure. In this way, we avoid the complicating effects of uncertainties in the mechanical behaviour of the jacket arising from the sluggish ferrite–austenite phase transition in mild steel. The previously mentioned exploratory experiments have already yielded a tantalising glimpse of a possible dissipation peak. The results of follow-up torsional-oscillation tests on more nearly optimal specimens, tested over a wider range of temperature, are described. We also report constraints on the recoverability of the inelastic strain from complementary microcreep tests, and the outcomes of exploratory flexural-oscillation measurements. Such improved documentation of the onset of anelastic behaviour in polycrystalline olivine promises a firmer framework for interpretation of seismological models of variations in shear wave speeds and attenuation in the Earth's upper mantle.

02DP-P03. THERMOTECTONIC EVOLUTION OF THE SOUTHWESTERN YILGARN CRATON, WESTERN AUSTRALIA

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The Yilgarn Craton in Western Australia comprises large areas of Precambrian rocks and it is commonly assumed that the craton has maintained a relatively flat landscape for a prolonged period of time. This has led researchers to suggest the Yilgarn Craton might have undergone minimal post-cratonisation tectonism. An extensive geochronology database exists for the craton, however most ages involve high temperature chronometers (e.g. U–Pb zircon, titanite) to determine the crystallisation ages of the Precambrian rocks. Fewer studies have utilised moderate temperature thermochronometers to understand the tectonic processes and denudation/uplift mechanisms affecting the region. This study reports the first $^{40}Ar/^{39}Ar$ biotite and white mica results from Archean granite basement rocks in the southwest Yilgarn Craton. Together with previous Rb/Sr biotite and apatite fission track (AFT) results, these data provide new insights into the post-cratonisation evolution of southwestern Australia.

Previous biotite Rb–Sr results indicate a rather gradual decrease in age from *ca* 2500–2300 Ma to *ca* 510 Ma towards the western margin of the craton. Single-grain biotite $^{40}Ar/^{39}Ar$ dating results show consistent ages of *ca* 2500 Ma across most of the craton, before decreasing abruptly to 1300–1000 Ma over a narrow transitional zone ~30–40 km wide, and then decreasing further to *ca* 620 Ma at the western edge of the craton. In contrast to the young biotite ages, most of the white mica samples show older ages ranging from *ca* 2400 to 2200 Ma. Possible reasons for the younger biotite results include: 1) a general increase in the degree of alteration of biotite from east to west causing loss of both Rb and K and, hence younger ages; 2) a thermal episode(s) that corresponded to sinistral movement of the Darling Mobile Belt during Proterozoic times; and 3) post-cratonisation tectonism, such as cooling by exhumation after tectonic burial. Alteration of the biotite and tectonic burial of the basement rocks are deemed the most plausible causes of the decreasing biotite ages. The overall late Proterozoic white micas may be hydrothermal alteration products as they often occur as fine-grained micas and intergrowth with biotite and plagioclase.

Keywords: thermochronology, $^{40}Ar/^{39}Ar$ dating, Yilgarn Craton

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02DP-P04. CONTRASTING DETRITAL RUTILE AND ZIRCON AGE SPECTRA FROM AN ACTIVE RIVER SAND EXAMPLE, KLAMATH RIVER, CALIFORNIA

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Provenance studies of clastic sediments have been dominated by age spectra acquired from analyses of many zircons in a single sample since the advent of spot (ion microprobe) studies a few decades ago. Zircon has been the focus because it contains low-common Pb concentrations and is a high U and Th-bearing robust mineral in the sedimentary cycle. It is dominantly of igneous origin and has a high closure temperature (~900°C). Rutile, on the other hand, is also quite robust in clastic sediments and it is almost exclusively of metamorphic derivation with a lower closure temperature (~600°C). It contains more common Pb than zircon but because rutile is Th-adverse, a reliable common Pb correction can be applied. Because of these contrasting features each mineral type should give a different "age finger print" and, when taken together, should give substantially more information about the source of a particular sand or sandstone.

The Klamath River of northern-most California was selected for study because its catchment is essentially just one geological province. An active river sand sample was collected from above the Pacific Ocean tidal zone near the mouth of the ENE–WSW flowing river. The Klamath Province is well studied and consists of Cambrian to Cretaceous metamorphic rocks that are cut by Jurassic to Cretaceous plutons. The river does flow over younger Franciscan (Cretaceous) rocks near the coast. The zircon study gave the expected age results based on zircon dating of outcropping plutons. The $^{206}Pb/^{238}U$ ages are: *ca* 180, 160–150 and 145–130 Ma. The zircons were sampled in the way that is common to this type of study. Based on cathodoluminescence work on the polished epoxy mounts, complex grain boundaries were avoided, and either inclusion-free zircon tips or cores were ablated using a 30 micron Excimer laser beam drilled to a depth of about 20 microns. The ablated material was analysed by ICP-MS and 17 isotopes were analysed: the 3 dominant Pb masses, ^{238}U, ^{232}Th, the major elements in zircon (^{29}Si, ^{91}Zr, ^{177}Hf) and 9 trace elements: ^{31}P, ^{49}Ti, ^{89}Y, and 6 REEs. The resulting age spectrum gave no indication of the metamorphic rocks that dominate the Klamath Province. In the rutile study, epoxy mounted and polished grains were ablated with a 47 micron beam (~30 microns deep) and the following isotopes were measured: the 5 for U–Pb dating, and ^{24}Mg, ^{27}Al, ^{49}Ti, ^{51}V, ^{91}Zr, ^{181}Ta, ^{93}Nb, ^{51}Co, ^{53}Cr, ^{65}Cu, ^{66}Zn, ^{89}Y, ^{118}Sn, ^{177}Hf, and ^{182}W. The resulting age spectrum (208-common Pb based $^{206}Pb/^{238}U$ ages) overlapped with part of the zircon age range (160–150 Ma) but also yielded ages of 220–215 Ma, 380–265 Ma and one at 500 Ma. One rutile of Franciscan age (104 Ma) was encountered. These ages of metamorphism can be reconciled with the known geology. Our conclusion is that rutile captures much more of the known geological history of the Klamath Mountains than does zircon, and that the study of both mineral species gives a better provincial age "finger print" than either alone.

02DP-P05. EVALUATION OF AN INTRACRATONIC APATITE FISSION TRACK ANOMALY IN THE GAWLER CRATON

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A previous low-temperature thermochronology survey of the basement rocks of the central Archean–Proterozoic Gawler Craton, South Australia, yielded a number of samples with anomalously young apatite fission track ages that appear to postdate the regional Paleozoic (*ca* 400 Ma) exhumation of the craton. If confirmed, these younger ages would indicate that some areas of the craton underwent localised reheating during the Cretaceous–Paleogene (*ca* 120–40 Ma), which challenges the concept of cratonic interiors as regions of long-term thermal, structural and erosional stability. In order to take a more in-depth look at the Cretaceous–Cenozoic thermal evolution of the region, additional basement samples from the region were collected. These samples were analysed using apatite fission track to investigate potential sources for the apparent reheating event, as well as its spatial and physical characteristics.

Fission track ages ranging from 330.2 ± 36.8 to 540.0 ± 86.1 Ma were recorded for 21 newly analysed samples. These ages are similar to those obtained elsewhere on the Gawler Craton and do not appear to support the hypothesis of a Cretaceous reheating event. However, some samples exhibit relative short mean track lengths (MTL) (~11–11.5 µm), compared to the lengths (~12.5 to 14 µm) that are typical for samples of the Gawler Craton. Thermal history modelling of these samples allow for, but do not require, a mild and short-lived reheating event (up to 80°C) during the Cretaceous, before cooling to near-surface temperatures in the Paleogene.

A possible cause for Cretaceous–Paleogene reheating is the Jurassic–Paleogene Eromanga Basin, which has its modern margin approximately 400 km north of the study area, although the widespread distribution of outliers in the study area suggests a much more extensive cover in the past. Given its present day maximum sedimentary thickness of ~1.5 km and high geothermal gradient of up to 50°C/km, it is feasible that burial by the sediments of the Eromanga Basin could have caused moderate overprinting of parts of the Gawler Craton.

02DP-P06. TOWARDS A BETTER UNDERSTANDING OF THE RHEOLOGY OF SERPENTINE BEARING ROCKS IN SUBDUCTING SLABS

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The process of serpentinisation changes the rheology of the altered rocks and may have important implications for tectonic activity occurring within the oceanic lithosphere, causing weakening and promoting the formation of fault structures, and strain localisation. However, the rheology of serpentine-bearing rocks is poorly understood, especially during the prograde dehydration, due to lack of experimental data. Deformational experiments were performed using a Griggs apparatus to constrain the rheology of serpentine at high temperatures and pressures. The samples of serpentinite used in these experiments were taken from two different locations, one from Belvidere Mountain near Eden Mills, Vermont, USA, and the other sample from Roxbury Mines, Vermont, USA. The samples were deformed at 1 GPa of pressure, and temperatures ranging from 550–725˚C, at a constant strain rate of $1\times10^{-5}s^{-1}$, to determine the role of dehydration reactions on serpentinite rheology. These experiments were designed to determine the effect of increasing temperature on two different serpentinites, and to mark the point at which serpentine (specifically, antigorite) breakdowns to produce forsterite, enstatite, and talc.

Our experimental results imply that under the conditions tested, the majority of samples are comparatively weak (<50 MPa). Increasing temperatures led to a phase change from a predominantly antigorite assemblage, to one dominated by enstatite and forsterite. This dehydration reaction produced fluids, which increased the pore pressure of the samples, reducing their strength. Petrographic and SEM analyses confirm the change in mineral assemblage during dehydration, and the expected assemblages conform with those observed by Ulmer & Trommsdorff (1995). Comparison with recent experimental data on pure antigorite show that at a temperature range of 550–725˚C, the majority of the samples tested here are comparatively weak and display lower strength (<50 MPa) than pure antigorite (645–1255 MPa), probably due to effect of minor serpentinite phases (such as lizardite) present in the starting material.

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02DP-P08. COMPARISON OF ZIRCON U–TH/HE AND RADIATION DAMAGE AGES FOR STANDARD ZIRCONS

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U–Th/He dating is one of the earliest geological dating techniques to be developed and zircon U–Th/He is a widely used thermochronology technique. A zircon U–Th/He age is interpreted as the time interval since the zircon was effectively closed to He loss by thermally-controlled production-diffusion processes. Diffusion studies have determined a zircon helium closure temperature range of 180–220°C over a range of cooling rates. A complementary thermochronometry approach involves the thermally-controlled crystallographic annealing of zircon, with a “radiation damage age” defined as the time needed to generate the observed radiation damage. This study compares radiation damage age estimates with conventional U–Th/He ages for Temora and Sri Lankan zircon U–Pb standards. Results demonstrate that both the U–Th/He and the radiation damage ages are younger than zircon U–Pb ages, and that radiation damage ages are equivalent or slightly younger the U–Th/He age for the same zircon population. This finding suggests that radiation damage annealing continues below the He closure temperature. However, this will need to be confirmed by further measurements and by improvements in the calibration of the radiation damage age technique.

02DP-P09. CONTINENTAL EMERGENCE IN THE LATE ARCHEAN RECONCILES EARLY AND LATE CONTINENTAL GROWTH MODELS

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The analysis of ancient sediments (Rare Earth Element composition of black shales, isotopic strontium composition of marine carbonates, isotopic oxygen composition of zircons) suggests that continental growth culminated around the Archean–Proterozoic transition. In stark contrast, the geochemical analysis of ancient basalts suggests that depletion of the mantle occurred in the Hadean and Eoarchean. This paradox may be solved if continents were extracted from the mantle early in Earth's history, but (1) remained mostly below sea level and covered by flood basalts throughout the Archean, and (2) were unable to sustain high mountain belts and plateaux (>~3000 m) until the late Archean.

We present a model to estimate the area of emerged land and associated isotopic strontium composition of the mantle and oceans as a function of the coupled evolution of mantle temperature, continental growth and distribution of surface elevations (hypsometry). For constant continental hypsometry and four distinct continental growth models, we show that sea level was between 500 and 2000 m higher in the Archean than at present, resulting in < 12% of emerged land, compared to ~ 28% at present. If in addition the hot Archean lithosphere could not sustain high relief, as little as 2–3% of Earth's surface would have been emerged in the Archean. Using a geochemical box model for the strontium isotopic composition of the mantle and oceans, we show that a reduced area of emerged continental crust can explain why the geochemical fingerprint of continents extracted early in Earth's history was not recorded at the surface of the Earth until the late Archean.

02DP-P10. TESTING THE EXISTENCE AND EVOLUTION OF THE CEDUNA RIVER USING ZIRCON U/PB AGE AND LU/HF ISOTOPE DATA

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The Ceduna Delta represents a vast Cretaceous stacked delta system located in the Bight Basin and is currently the focus of considerable petroleum exploration. It has been suggested that the upper part of the delta (Santonian–Maastrichtian) has a different source to the lower Cenomanian delta (MacDonald *et al.* 2012). The Cenomanian delta is thought to be sourced from a continent scale river system, the Ceduna River, which originated in Queensland and flowed through the centre of the continent. The Santonian–Maastrichtian delta conversely, is thought to have formed after the doming of northern and eastern Australia. This study aims to test the existence and evolution of the Ceduna River by distal provenance, by comparing the detrital zircon U/Pb age distribution and Lu–Hf isotopic composition of samples from the Late Cretaceous Winton Formation with samples from the Gnarlyknots-1 well within the Ceduna Delta of the Bight Basin. Zircon U/Pb data from the Gnarlyknots-1 well shows that the Santonian–Maastrichtian delta has a basin-proximal provenance, which challenges the widely accepted model involving a Ceduna river system. The abundant Permian–Cretaceous zircon U/Pb ages may have sourced from the New England fold-belt, however these ages were also obtained within paleochannels in the Eyre Peninsula, which may be sourced from formerly present, but currently eroded Permian sandstones at the onshore margin. Older zircons mainly indicate Delamerian, Flinders Ranges and Antarctic provenances (MacDonald *et al.* 2013). New Lu–Hf data will further characterise the sources of the Ceduna Delta sediments.

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02DP-P11. HOW MELT MOVES THROUGH THE CRUST: EVIDENCE FOR REACTIVE DIFFUSE POROUS MELT FLOW UNDER STATIC CONDITIONS IN THE HOT LOWER CONTINENTAL CRUST.

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Chemical evidence of mid- and upper-crustal igneous rocks suggests that melt must have migrated through the lower crust. However, how this is achieved remains unclear. Until now, there have been few studies investigating the possibility of porous flow of melt through the crust, even though porous melt flow in the mantle is widely accepted.

In this study, we investigate granulite-facies gabbroic gneisses of the Pembroke Granulite, Milford Sound, New Zealand, which record evidence consistent with pervasive percolation of a reactive hydrous melt. The gabbroic gneisses display mineral assemblages consistent with widespread hydration reactions, spatially associated with magmatic hornblende + feldspar dykelets and blebs. Hydration reactions formed coronas at contacts between original plagioclase feldspar ($An_{26–42}$) and orthopyroxenes and clinopyroxenes. Coronas are characterised by symplectitic intergrowths of hornblende + quartz ± plagioclase ($An_{17–26}$) and are variably developed between samples. All samples lie on a continuum of hydration defined by the development of corona structures. Progression of the reaction is associated with decreasing anorthite content in plagioclase feldspars from igneous compositions ($An_{26–42}$) towards a melt signature, which is retained by feldspars from the inner coronas ($An_{17–19}$). Undeformed hornblendes in the symplectites and in the magmatic dykelets and blebs indicate that hydration occurred post-deformation. Garnet overgrows hydration reaction products, indicating hydration occurred before partial melting at conditions of 8–14 kbar and ≥750°C.

As aqueous fluids are unstable at these PT conditions, our observations suggest that the observed hydration reaction and chemical changes are the result of diffuse porous flow of silicate melt rather than aqueous fluids. This model therefore proposes the first direct evidence of reactive diffuse porous melt flow under deformation-absent conditions in the hot lower continental crust.

WEDNESDAY 9 JULY

ENVIRONMENT

03EV-P01. IRRIGATION BORE WATER IN THE CONDAMINE CATCHMENT: BASELINING GROUNDWATER QUALITY AND ASSESSING PATHWAYS OF HYDRAULIC CONNECTIVITY

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The expansion of coal seam gas production adjacent to the irrigation farming districts in the Condamine Catchment has raised concerns about the impact of gas production on groundwater in adjoining aquifer systems. To assess the risk, and to be able to detect any future changes in groundwater properties, existing groundwater chemistry data sets need to be updated and expanded. Historically, the testing of groundwater chemistry in the Condamine Catchment has focused on the Queensland Government groundwater-monitoring network, but it is unlikely that these samples come from the same sand and gravel bodies from which the irrigation bores extract groundwater. We report the result of 20 groundwater samples collected from bores that supply irrigation water for cotton and other crops. These samples were collected in January 2014 at the end of the pumping season, when the aquifer system is at peak stress for the year.

We compare the major ion chemistry recorded in the irrigation bores to that measured at selected sites from the QLD government groundwater-monitoring network and with historical results reported in the literature. A hydrochemical facies analysis of these data provides one assessment of the likelihood of hydraulic connectivity between the Walloon Coal Measures, other bordering Great Artesian Basin formations and the valley filling sediments of the Condamine Alluvium.

The results highlight variation in groundwater chemistry within the Condamine Alluvium, particularly in the Cecil Plains and Dalby regions, where there are signs of water mixing. As a result, further research into the area to explain the baseline data sets would provide a better understanding of hydraulic connectivity and the potential effects of CSG on the groundwater.

03EV-P03. HYDROGEOCHEMICAL CHANGES IN CSG PRODUCED WATERS DURING THE LIFE OF A GAS WELL – An ISOTOPE FORENSIC STUDY

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Produced waters from methane bearing coal seams have a characteristic chemical composition. These waters are typically brackish to saline, have a high pH, are chemically classified as Na–HCO_3 type waters with low concentrations or are devoid of sulfate, calcium and magnesium. They may also contain barium, strontium, fluoride, ammonia, and other trace metals. The geochemical evolution of these characteristic waters has been studied by a number of published researchers, and processes include microbial sulfate reduction, biogenic methanogenesis, precipitation of carbonate and other minerals, and ion exchange.

AGL Upstream Investments Pty Ltd (AGL) owns and operates the Camden Gas Project (CGP), which has been producing gas for the Sydney region since 2001 and currently comprises 144 gas wells that target the Permian Bulli and/or Balgownie coal seams, lying approximately 550–700 m below ground level. The water produced from gas wells in the CGP area is typically slightly to moderately saline (>5000 µS/cm EC), and has the other chemical characteristics of water produced from methane-bearing coal seams. However, during routine monitoring events in recent years, produced water from a subset of AGL gas wells was found to have a different chemical composition that was atypical to the majority of gas wells. The 'atypical' gas wells produced low salinity water (average 250 µS/cm EC), which had a lower pH than typical gas wells, high concentrations of iron, zinc and manganese, but low or negligible concentrations of major ions with the exception of bicarbonate.

Three possible scenarios for the origin of the low salinity water were identified including, hydraulic connection between targeted CSG coal seams and shallow aquifers or surface water; residual potable water trapped during hydraulic fracture stimulation of gas wells; and formation of low salinity condensed water in gas wells. To test the validity of each proposed scenario, a hydrogeochemical and isotope forensic investigation was undertaken. The chemical and isotopic characteristics (tritium, and stable isotopes of water (^{18}O and ^{2}H)) of potential water sources were assessed.

The 'atypical' gas wells did not contain tritium ruling out surface water or potable water used in hydraulic fracture stimulation and hydraulic connection between the target coal seams and these zones, which are both modern waters containing tritium. Furthermore, water used in hydraulic fracture stimulation is potable water from the Sydney water supply and contained elevated fluoride, whereas the atypically wells had low fluoride. Groundwater from the Triassic Hawkesbury Sandstone (approximately 120–300 m below ground level) had a meteoric origin, as indicated from ^{18}O and ^{2}H, however the 'atypical' produced waters had depleted ^{18}O and ^{2}H signatures, plotting on a trajectory from the meteoric water line characteristic of condensation.

Condensation can occur in unconventional gas wells due to changes in pressure, temperature and water flows. At the pressures associated with unconventional gas wells large amounts of water can move as vapour. Pressure or temperature drops in the gas wells can cause liquid to "flash" evaporate and water vapour to condense. The consequences of flashing high salinity coal seam water are the precipitation of solids in gas wells and/or associated piping and infrastructure, and the formation of low salinity water derived from condensation. These processes which result in the formation of low salinity water or condensed water have been observed in older AGL gas wells that are declining in production producing low volumes of gas (<320 Mscf/day) and water (<22.26 L/day). This study has highlighted the geochemical changes in produced waters during the life cycle of a gas well, a process that has not been reported widely in literature for unconventional gas wells.

03EV-P04. ASSESSING THE ROLE OF FAULTS AS POTENTIAL AQUIFER INTERCONNECTIVITY PATHWAYS IN THE SOUTHERN RICHMOND RIVER CATCHMENT, NEW SOUTH WALES, AUSTRALIA

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The Northern Rivers region of NSW has been the subject of significant petroleum exploration in recent years. Exploration targets include conventional gas and coal seam gas resources contained within sedimentary formations of the southern Clarence-Moreton Basin.

Seismic surveys in the area indicate that geological faults in the Bungawalbin Creek catchment extend from petroleum target formations (Kangaroo Creek Sandstone; Walloon Coal Measures) to the top of the consolidated stratigraphic profile. In the upper part of the seismic profiles, however, the seismic signal is weak and does not allow confirmation of existence of connective pathways to shallow alluvial aquifers along the drainage system.

Consolidated aquifers in the Clarence-Moreton Basin are typically confined with generally low to moderate permeabilities (e.g. Grafton Formation <0.1 m/day and Walloon Coal Measures 0–10 m/day (McKibbin 1995)). However, faults and shear zones may provide highly conductive conduits for fluid flow, enabling vertical and/or lateral movement of water, or migration of gas, between formations. Such conduits could allow interaction between consolidated sedimentary formations and shallow alluvial aquifers and surface water.

Alternatively, fault zones may be highly impermeable and could act as barriers to lateral flow. Combinations of high and low permeability within each fault zone are also possible.

This study uses geomorphology, existing seismic and magnetic data and exploration borehole logs to locate and characterise fault structures in the study area. Hydrochemical data from shallow alluvial aquifers are compared to that from bedrock aquifers to assess whether vertical interaction between aquifers may occur.

Alluvial groundwater chemistry data collected during the 1970’s and 1980’s indicate that these groundwaters have elevated sodium concentrations in wells close to known faults (Drury 1982). While the general understanding on spatial variability of the hydrochemistry of the different aquifers is still limited due to a generally poor data coverage, these high sodium concentrations appear to be consistent with the chemistry of groundwater from deeper aquifers, suggesting that groundwater has migrated upwards through the faults to the surface.

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03EV-P07. A BASELINE GROUNDWATER METHANE SURVEY IN THE RICHMOND RIVER CATCHMENT; A POTENTIAL COAL SAM GAS EXPLORATION AREA

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Unconventional natural gas extraction, such as coal seam gas (CSG), is rapidly expanding globally and a number of exploration wells have been drilled in the Northern Rivers district in NSW. However, the effect of unconventional CSG on groundwater systems is not well understood. CSG production processes may lead to a range of environmental issues such as aquifer depletion and changes in groundwater quality. Few studies have assessed these potential impacts in Australia, and no previous studies have focused on the Richmond River Catchment.

CSG is mainly composed of methane (CH_4), which is trapped within coal seam pores and fractures. CH_4 is a potent greenhouse gas with a global warming potential 72 times greater than carbon dioxide (CO_2) over a 20-year period. We hypothesise that CH_4 may be used as a tracer of changes in aquifer connectivity potentially associated with CSG exploration.

In order to better monitor and understand the implications of CSG production on aquifer connectivity, baseline research on the chemical composition of groundwater is critical. We have sampled 98 groundwater bores, measuring water parameters such as CH_4, CO_2, carbon isotopic CH_4 signature ($\delta^{13}C–CH_4$), carbon isotopic CO_2 signature ($\delta^{13}C–CO_2$) and radon (^{222}Rn). Groundwater CH_4 concentration from bedrock bores averaged 5.07 μM while groundwater CH_4 from Quaternary sediment bores averaged 54.6 μM. Isotope analysis can provide information regarding the source of groundwater constituents. $\delta^{13}C–CH_4$ ranges for bedrock bores was –88.45 to –35.08‰ while Quaternary sediment bores had $\delta^{13}C–CH_4$ ranging from –90.88 to –27.36‰. Since CH_4 is unlikely to be of thermogenic origin, the carbon signatures indicate the biogenic CH_4 production pathways of CO_2 reduction and acetate fermentation. The heavier carbon signatures are indicative of CH_4 oxidation. This research delivers a snapshot of current groundwater dynamics to enable comparisons of ‘before and after’ CSG exploration.

03EV-P08. THREE-DIMENSIONAL GEOLOGICAL AND CONCEPTUAL MODELS AS A FRAMEWORK FOR NUMERICAL GROUNDWATER MODEL DEVELOPMENT: AN EXAMPLE FROM THE CLARENCE-MORETON BASIN

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The Clarence-Moreton Basin in New South Wales and Queensland is one of six nationwide priority regions where the potential impacts of future coal seam gas extractions and coal mining on water-dependent assets are being assessed through a national programme of Bioregional Assessments. The Clarence-Moreton Basin is an elongated intracratonic sag basin that contains sedimentary sequences of Middle and Late Triassic to Lower Cretaceous age with a combined thickness of up to approximately 3500 to 4000 m. Overlying the basin sedimentary sequences within the Clarence-Moreton bioregion (the eastwards draining part of the basin) are five major catchment systems (Lockyer Valley, Bremer/Warrill, Logan/Albert in Queensland, and the Richmond and Clarence river catchments in NSW), which host important alluvial groundwater and surface water resources that are intensively used for irrigation. In addition, these catchments host significant assets such as groundwater-dependant ecosystems (e.g. springs and wetlands).

In order to predict the potential impacts of depressurisation associated with coal seam gas extraction from the Walloon Coal Measures (major target of CSG exploration in the Clarence-Moreton Basin), an accurate understanding of the links between different components of the hydrological system is essential. Prior to the development of numerical models, it is critical to describe potential connectivity pathways between deep and shallow aquifers, as well as interaction between groundwater and surface water.

In order to assist with the development of reliable conceptual models that describe these interactions and constitute a road map to bioregional assessments, we have constructed a 3D geological model from elevation (DEM), stratigraphic, seismic and lithological data using GoCAD (Paradigm) 3D geological modelling software. The 3D geological model represents the major alluvial, sedimentary and volcanic aquifers and aquitards of the Clarence-Moreton bioregion. It helps to develop a more realistic understanding of the aquifer system behaviour, particularly if integrated with complementary data sources such as water level or hydrochemical data, and it will provide the geometric framework for the groundwater numerical model. The 3D geological model highlights the structural complexity of the Clarence-Moreton Basin, with significant vertical displacements of major basin units of several hundred meters registered along major regional fault systems, and abutments of stratigraphic units against basement ridges or pinching out of units observed in different parts of the basin. These observed structural features and the geometric characteristics of aquifers/aquitards can have a significant influence on potential connectivity pathways. For example, the thinning of the Gatton Sandstone against the underlying Woogaroo Subgroup at the basin margin in the Lockyer Valley results in upwards seepage of groundwater from the Gatton Sandstone into the alluvial aquifer, and this upwards discharge probably also feeds wetlands located along the northern margin of the Gatton Sandstone.

03EV-P10. INVERSION BASED UPSCALING OF GROUNDWATER MODELS FOR REGIONAL GROUNDWATER HEAD PREDICTION

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This study develops a methodology, which couples groundwater flow and transport models of different spatial and temporal scales. This method explicitly honours a range of different types of groundwater monitoring information, and therefore allows for more robust predictions of regional scale groundwater impacts.

A regional scale MODFLOW-based groundwater model was developed for a region in the Surat Basin, southeast Queensland. The regional scale model captures the large scale flow dynamics as established from the conceptual model and then constrained by the groundwater level data, piezometric contour, groundwater abstraction information, etc. Smaller local scale models were also constructed and calibrated. These include aquifer pumping test models, which were used to calibrate the hydraulic conductivity (K) distribution and storage (S) within the local scale model boundaries. Aquifer tracer test models were also constructed and used to calibrate porosity and dispersive characteristics, as well as further informing hydraulic conductivity and storage property value estimates. The respective grid sizes for the regional model and local models are 1.5 km × 1.5 km, 100 m × 100 m and 10 m x 10m. While the regional model has monthly time steps and is calibrated to regional groundwater head observations, the local scale pump test and tracer test models are calibrated to observations with time steps in minutes. Thus, these three models have different spatio-temporal scales and capture different information during the calibration process.

A subregional groundwater flow model was also developed with a lesser areal extent compared to the regional model. This model scale targets predictions at a scale pertinent for specific risk receptors chosen for this study. The groundwater flux obtained from the regional model was used to constrain the boundary fluxes of the predictive model. Therefore, while the regional and local scale aquifer test and tracer test models can be considered as input models, the subregional scale model serves as a predictive model which is informed by the three input models. Full coupling of all the models was achieved during the predictive simulations to ensure the information from different fine and course data was honoured. This coupling was achieved by integrating all models via matching to key coupling observations in the input models, which were defined at a range of spatial and temporal scales.

A suite of predictions was made with the subregional model including cumulative groundwater level changes resulting from re-injection scenarios. Movement and dilution of reinjected water was also simulated.

03EV-P11. REGIONAL GROUNDWATER MONITORING NETWORK FOR ASSESSMENT AND MANAGEMENT OF CUMULATIVE IMPACTS IN THE SURAT AND SOUTHERN BOWEN BASIN IN QUEENSLAND

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In the Surat Basin of southeast Queensland, there are multiple coal seam gas (CSG) operators developing CSG extraction activities adjacent to one another. The Queensland regulatory framework allowed a Cumulative Management Area (CMA) to be created in order to predict and manage impacts on groundwater pressure. An Underground Water Impact Report (UWIR) to assess the cumulative impacts of CSG extraction on groundwater was approved in December 2012. The UWIR was produced by the Office of Groundwater Impact Assessment and once approved became a statutory instrument under the Water Act 2000.

The UWIR establishes integrated management arrangements and identifies responsible tenure holders for the implementation of monitoring and mitigation activities. A key component of the UWIR is the Water Monitoring Strategy (WMS). The objective of the WMS is to monitor the impacts of water extraction by CSG activities on groundwater, and improve conceptual understanding of the groundwater system to support ongoing impact assessment through numerical groundwater modelling.

Amongst other things, the WMS comprises a regional monitoring network of 618 groundwater pressure and quality monitoring points, which are being installed in a staged approach by the CSG operators. The WMS network incorporates 102 existing water pressure-monitoring points and 28 existing water quality monitoring points. Some of these existing monitoring points contain 50 years of historical groundwater monitoring data.

Implementation of the network is gradually being rolled out. By mid-2014, 504 of the 618 monitoring points are scheduled to be installed. The remaining 114 monitoring points are scheduled to be installed by 2016.

Implementation is challenging due to a number of reasons including: areal extent of the CMA (160 985 km^2), aquifer monitoring depths down to 1500 m, gas environments, multiple monitoring points in single installations, adapting technology to monitoring fresh water and CSG aquifers, landholder agreements, and multiple tenure holders. The types of monitoring points vary across the CMA including: aquifer-monitoring bores, reservoir-type monitoring bores, and vibrating wire piezometers. The monitoring bores are typically installed with *in-situ* pressure transducers and loggers, and may be recording groundwater pressure from open screens, discrete screens with *in-situ* packer isolators, or pressure sensors from vibrating wire sensors. The monitoring bores may also contain multiple monitoring points within a single monitoring installation, which enables monitoring of discrete aquifers at the same time.

CSG development has not been commencing as early as was planned at the time the UWIR was prepared in 2011. The impacts will be smaller for the most part than previously predicted, and it is too early in the development of the industry to detect any water pressure impacts from CSG development in adjacent aquifers. However, the WMS has laid the foundation for an extensive, detailed and robust regional monitoring enabling capture of early time groundwater behaviour to inform hydrogeological conceptualisation and numerical modelling.

The UWIR is scheduled to be updated in 2015, which will include updated CSG development from CSG operators, hydrogeological reconceptualisation, rerunning of numerical modelling, and updating the groundwater monitoring network.

03EV-P12. OPTIMISATION OF OBSERVATION WELL NETWORKS TO BEST IDENTIFY CAUSES OF AQUIFER IMPACTS

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This paper describes two versions of a methodology underpinning the optimisation of observation well networks, such that they can be used to more reliably identify aquifer impacts from recent developments. When attempting to locate additional ‘sentinel’ observation wells to identify impacts from a specific development (such as coal seam gas extraction), groundwater regulators may face complications arising from complex aquifer geometry, including multiple hydrogeological units, or from the confounding effects of existing groundwater water development (such as irrigation abstractions). In this project we explore the efficacy of two methods of time series representation in the context of the identification of optimal sentinel well locations.

Optimisation methods are developed using synthetic data obtained from a 3-dimensional MODFLOW groundwater model. Our study considers groundwater drawdown time series collected at four locations: (i) close to an irrigator; (ii) close to a coal seam gas (CSG) development; (iii) distant to groundwater abstractions; and (iv) at a central location adjacent to (i) and (ii). Using these time series, we present a method, which we use to infer the relative contributions of extraction activities at locations (i) and (ii) to the drawdown dynamics at location (iv).

Series-based and wavelet-based methods were successfully used to represent drawdown time series observed at various locations. This enabled subsequent estimation of the relative contributions of a number of component series to a 'mixed' signal. Such analyses could be used to identify the contribution of stresses such as coal seam gas extraction to regional drawdown in highly developed aquifers. The uncertainty associated with modelled representations of drawdown time series was also quantified. This uncertainty was then used as a metric to successfully compare the relative merit of various potential sentinel observation well locations.

Consistent results were achieved using both the series-based and wavelet-based methods, using the optimisation metric of maximising the reliability of predictions of relative drawdown impact from a range of groundwater stresses and abstractors.

ENERGY

03EG-P02. THERMOCHRONOLOGICAL AND GEOCHRONOLOGICAL CONSTRAINTS ON THE ORIGIN AND EVOLUTION OF THE CRETACEOUS CEDUNA SUB-BASIN, GREAT AUSTRALIAN BIGHT

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The Ceduna Sub-basin is the main depocentre of the frontier Bight Basin, which formed as a result of the late Jurassic-Cenozoic separation of Australia and Antarctica. The sedimentary fill of the Ceduna Sub-basin is dominated by two structurally distinct deltaic lobes of Cenomanian and Santonian-Maastrichtian age with a combined thickness exceeding 12 km. These lobes are collectively known as the Ceduna Delta, which is likely the largest deltaic system to have existed in the geological history of the Australian continent. Understanding the origin and evolution the Ceduna Sub-basin is of profound importance for Mesozoic palaeogeographic reconstructions of Australia, and for models that seek to explain continental breakup between Australia and Antarctica. Furthermore, this region is the focus of growing exploration interest from the global petroleum industry, and thus improved knowledge of its origin and evolution is essential for reducing exploration uncertainty. However, because the Ceduna sub-basin is located completely offshore in water depths up to 5 km, to date there has been little exploratory drilling in this region, with only one well drilled in water depths >300 m. With primary data from the sub-basin itself lacking, we have collected a variety of new thermochronological (e.g. apatite fission track analysis (AFTA) and vitrinite reflectance (VR)) and geochronological (e.g. zircon U-Pb and fission track) datasets from the onshore margins and hinterland to the Ceduna sub-basin, which have a bearing on the evolution of the offshore region. These datasets include:

1. Zircon U-Pb ages from several samples of drillcore from the Lower Cretaceous Loongana Formation, which is preserved in the Denman Basin, a shallow depression that underlies the onshore Eucla Basin. Age populations within these data suggest that sediment input at this time was predominantly from the north and west.
2. Zircon U-Pb ages from several samples of drillcore from the Winton Formation, an Albian-Cenomanian-age fluvial-lacustrine sequence from the Eromanga Basin. This sequence has been proposed as an analogue for the Cenomanian deltaic lobe in the Ceduna sub-basin, which has yet to be penetrated by drilling.
3. AFTA and VR data from outcropping rocks in the Eyre Peninsula, and subsurface rocks retrieved by drilling in the Polda sub-basin, to the northeast of the Ceduna sub-basin. These data point to substantial exhumation of this region during the late Cretaceous.
4. Zircon U-Pb and fission track ages from the Turonian-Maastrichtian sequence penetrated by the offshore Gnarlyknots-1 well. Interpretation of these ages suggests that this sequence was largely sourced from recycled

Permian-Early Cretaceous cover and underlying basement rocks eroded from the proximal, northeastern basin margin.

The integration of these onshore and offshore datasets provides new valuable insights into the Cretaceous palaeogeography of the Ceduna sub-basin, the tectonic processes controlling the input of clastic sediments, and the prospectivity of this frontier exploration region.

03EG-P03. *IN-SITU* STRESS AND NATURAL NETWORKS IN THE CARNARVON BASIN, NORTH WEST SHELF, AUSTRALIA

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Hydrocarbon exploration in the Carnarvon Basin on the North West Shelf of Australia has proven significant reserves, making it Australiatralianatioent hydrocarbon province. However, there is little to no understanding of the naturally occurring fracture networks and their impact on the permeability of the basin, which is crucial to resource recovery and future basin development. This study has analysed resistivity image logs from ten petroleum wells in the offshore Carnarvon Basin in order to map the fracture networks and to determine the structural permeability of the basin.

A total of 508 naturally occurring fractures are identified on 10 resistivity image logs. There are a range of fracture orientations, with the mean fractures strike approximately NE–SW. The fractures can be divided in to two sets using image logs; electrically conductive fractures and electrically resistive fractures. There are 308 resistive fractures that are considered to be cemented with electrically resistive cements (such as quartz and calcite) and are thus, closed to fluid flow. These resistive fractures dominantly strike E–W. There are 200 conductive fractures that are considered to be uncemented and filled with drilling mud. Thus, the fractures are considered to be open for fluid flow. The conductive fractures have a mean strike of NE–SW.

The *in-situ* stress field is a major control on the ability for fractures to transmit fluid. Recent studies have indicated a strike-slip faulting stress regime in the Carnarvon Basin, with a mean maximum horizontal stress orientation of 107istive cements (such as quarorientations and magnitudes, we are able to predict the fracture sets that are open to fluid flow at present day. Using fracture susceptibility plots created using these calculated *in-situ* stress values, we show that the majority of NE–SW striking conductive fractures are optimally oriented within the *in-situ* stress field, demonstrating a high likelihood for fluid transmission. Additionally, several of these fractures demonstrate significant losses of drilling fluids at corresponding depths. Thus, it is likely that the identified conductive fractures are indeed open to fluid flow (and not filled with conductive cement), demonstrating that these fracture networks enhance the natural permeability of rocks in the Canarvon Basin.

03EG-P04. *IN-SITU* STRESSES OF THE CARNARVON BASIN, NORTHWEST SHELF, WESTERN AUSTRALIA

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The Carnarvon Basin in Western Australia is AustraliaX)ERN AUSTRALIAn. Additionally, several of th*in-situ* stress regime in this basin is poorly defined. In this study a large dataset of recent geophysical data from petroleum wells is analysed from the offshore Carnarvon Basin in order to remedy this deficiency. Borehole failure features are known to be caused as a result of the *in-situ* stress regime, and be used to reliably identify the orientation of principle stresses.

Present-day *in-situ* stress in the Carnarvon Basin has been inferred from wireline data, wellbore testing, and interpreted borehole failure features (borehole breakouts and drilling-induced tensile fractures) observed on image logs from 76 wells. Stress indicators from these wells give an approximately east–west maximum horizontal stress orientation of 107, consistent with previous studies of stress orientations in the Carnarvon Basin. This is in line with finite element modelling of the stress field in the Carnarvon Basin. It is demonstrated that the present day stress field of the Carnarvon Basin is a strike-slip (possibly transitional to reverse) faulting environment, with a vertical stress that ranges from 20 MPa/km to 22.4 MPa/km, a mean minimum horizontal stress of 18.1 MPa/km, and a mean maximum horizontal stress of 25.4 MPa/km. Horizontal stress values are derived using a new interpretation of leak-off tests, which assume shear reactivation of fractures during hydraulic fracturing rather than assuming the creation of new tensile fractures, and it is demonstrated that these values are a more accurate representation of present-day stress conditions than traditional interpretations of horizontal stress magnitudes.

03EG-P05. ASSESSING THE SYNGENEITY AND INDIGENEITY OF HYDROCARBONS IN THE ~1.4 GA VELKERRI FORMATION, MCARTHUR BASIN, USING SLICE EXPERIMENTS

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The usefulness of Precambrian hydrocarbons, in particular biomarkers, relies entirely upon both their syngeneity and indigeneity, or rather whether or not they are representative of the same time period and area as the host rock (Eigenbrode 2008). Due to both their age and typically low total organic carbon content, Precambrian basins are susceptible to hydrocarbon overprinting due to contamination. This study investigates the presence and nature of hydrocarbon signatures in core slices (from the exterior to the interior of the core) from the 1.4 Ga Velkerri Formation, McArthur Basin, North Australia, and assesses the likelihood of the hydrocarbon syngeneity and indigeneity. Each slice was crushed, solvent extracted, silica column fractionated and analysed using gas chromatography mass spectrometry (GC-MS).

The exterior flat (EF) and exterior curve (EC) of all three cores studied show contamination signatures in several compound groups, including *n*-alkanes, monomethylalkanes, bicyclic sesquiterpanes, alkylcyclohexanes, alkylnaphthalenes and alkylphenanthrenes. Although both the EF and EC slices were subjected to secondary organic matter input, the signatures were dissimilar and had differing origins (from sawing and drilling processes, respectively). This contamination overprinted and had the potential to completely obscure the indigenous hydrocarbon signal. Interior slices were found to have consistent hydrocarbon signals, providing strong evidence that the organic matter in the interior slices is indigenous. This study highlights the necessity for the removal of the exposed outside of the core prior to solvent extraction, not only in lean Precambrian rocks (as determined by Brocks 2011), but also in Precambrian rocks rich in organic matter. Despite the previous identification of sterane biomarkers in Velkerri Formation sediments (Jackson *et al.* 1986) and in Roper Group solvent extracted rocks (Summons *et al.* 1988), no steranes or aromatic steroids were detected in any cores analysed in this study, including the early oil window cores from Walton-2, despite using a highly sensitive magnetic sector GC-MS for this part of the study. This indicates that there was a very low eukaryotic input in the deep marine, low oxygen environment in which the Velkerri Formation was deposited, but does not exclude the possibility that shallower water facies may contain biomarker evidence for eukaryotes that are known from fossil evidence back to around 2.0 Ga (Hofmann 1976).

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03EG-P06. STRATIGRAPHY OF DEFORMED PERMIAN CARBONATES REEFS, THAILAND

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The Indosinian Orogeny brought together a number of allochthonous continental blocks and volcanic arcs during the Permian and Triassic periods. Prior to the orogeny, these blocks were dominated by carbonate platforms and minor clastic sediments. Subsequently the blocks were deformed into the Khao Khwang Fold Thrust Belt**.** It has been suggested that during the Early Triassic, the Khao Khwang Fold Thrust Belt developed as part of the Indosinian Orogeny along the southern margin of one of the continental fragments of the Indochina Block.

The sedimentology and stratigraphy of the Permian platform carbonates and basin complexes are poorly known. Three main carbonate platform dominated facies have been identified previously as the Phu Phe, Khao Khad and Khao Khwang formations. These platform facies are divided by clastic, mixed siliciclastic and carbonate sequences known as the Sap Bon, Pang Asok and Nong Pong formations.

In this presentation, we will build a stratigraphic model for the carbonate reefs and intervening clastic sediments using the exposed well developed sections in central Thailand. The model integrates fossil identification, biostratigraphic correlation, and paleoenvironmental analysis in accordance with field work in the Saraburi Province, central Thailand. Eight sections were logged encompassing units from the three thrust sheets. The stratigraphic logs suggest open shoal and platform margin to tidal environments for the Lower to Upper Permian sequences, dated previously using bryozoans, algae and fusulinids. These facies indicate a major transgressive to regressive succession of intertidal, lagoonal, shelf sea, platform sequences to pelagic environments. Multiple chert nodules and lenses, in addition to beds with scoured bases along with other characteristics of mass transport, are indicative of basinal facies receiving turbid debris flows. In comparison, several sections further north were highly bioturbated implying deposition in the offshore marine to transitional zone possibly low energy subtidal lagoonal environments. Furthermore, the sections taken from the north thrust sheet suggest lateral facies change from bivalve and fusulinid-rich grainstone, with lenses of coral that passes west into a reef mound. Directly below the thrust the carbonates contain grainstone lenses in the uppermost part of the section descending into wackestones that are separated by shales and occasional sill intrusions, suggesting variances in low energy environments with some bouts of volcanic activity. Further subdivisions between units have been identified in the past through fossil analysis using the abundance and diversity of fusuline and calcareous algal biota. The paleoenvironmental inferences and fossil identification will assist in correlating the sections with the pre-existing structural and stratigraphic notions of the region.

03EG-P07. REGIONAL VARIATION IN STRATIGRAPHIC ARCHITECTURE OF FORT COOPER AND EQUIVALENT COAL MEASURES, BOWEN BASIN

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The late Permian Fort Cooper and equivalent coal measures in the Bowen Basin hosts highly mature gassy coal seams, interestingly abundant in tuffaceous material though deprived of a consistent stratigraphic framework throughout the basin. The Fort Cooper Coal Measures are separated from the overlying Rangal Coal Measures through a marker Yarabee Tuff that is laterally consistent within the basin. Using 700 wells this study developed a regional stratigraphic framework that confirms the earlier published Fort Cooper stratigraphic variations within the basin, where continuous coal-bearing strata, 450 m (gross) thick, in the north thins and is equivalent to two formations in the south, namely the Burngrove and Fair Hill formations, split by the Black Alley Shale; their combined thickness (gross) is 300 m in southwest and >350 m in southeast.

The regional correlations assisted in making coal seam level correlations within the Fort Cooper Coal Measure sequence so as to trace the transitions in thickness, splitting characteristics and environment of deposition.

Internal architecture of the coal measures reveals that the Burngrove Formation in the south comprises five consistent seams equivalent to two seams (Lower Vermont and Girrah) of the northern Bowen Basin. Similarly, the Fair Hill Formation in the south comprises six seams equivalent to two seams (GF3 and Fair Hill) in the northern Bowen Basin.

The Black Alley Shale is better developed in the southwest (Denison Trough-Comet Ridge) and has minor influence in the southeast (northern Taroom Trough). It does not reach up to the northern Bowen Basin and is thus time equivalent to three seams that sit between the Burngrove and Fair Hill equivalent coal seams.

03EG-P08. ORIGINS AND CONTROLS UPON CALCITE AND SULFIDE MINERALISATION OF COAL FRACTURES IN A SURAT BASIN COAL MINE

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Faults, pervasive joints, coal cleats, and even the coal matrix within certain parts of a Surat Basin coal mine are heavily mineralised with calcite and/or sulfide minerals such as bornite and pyrite and associated sulfate minerals. The majority of the mined coal has low sulfur content, but sometimes heavily mineralised coal is unexpectedly encountered. Such mineralisation affects coal quality and can add to beneficiation costs and impacts coal utilisation. This study investigated the controls on the presence and distribution of the mineralisation. Fracture azimuth measurements showed that whilst most of the faults were north trending, the major coal fracture networks (with average joint spacing of 1.5 m to 2.0 m) were generally aligned diagonally relative to the faults with the exception of those immediately adjacent to faults. If faults were conduits for mineralising fluids, the alignment of coal fracture networks relative to them may have assisted migration of the fluids into the coal seams. Fluid inclusion analysis of several fault related calcite samples indicate elevated temperatures with three distinct modes at 130, 250 and 360°n the presence and distribution of the mineralisation. Fracture azimuth measurements showed that whilst most of the faults were north trending, the major coal frac sourced yet relatively short lived. The hot fault fluids also likely mixed with pre-existing cooler evolved meteoric water within the coal fracture networks. Some faults contained chimney-style calcite up to 20 cm in diameter and syntectonic bornite grown during fault activation, whilst bornite crystals and pyrite spherules and discs occurred both within calcite and on the walls of cleats and pervasive joints. This suggests that although faults may have been a primary source of this mineralisation, microbial sulfate reduction may also have occurred to produce pyrite discs/spherules. High precision ICP-MS analysis of the fault calcite found it to be more enriched in certain trace elements such as chromium, rubidium, and beryllium relative to the other coal fractures, and most of the calcite samples have the signature of hydrothermal veins in a plot of Yb/Ca against Yb/La. The calcites have a wide range of stable isotope compositions, i.e. $\delta^{13}C$ values from –17.8 to 18.9‰7.8 = 21) that are negatively correlated with $\delta^{18}O$ values ranging from 15.2 to 25.8‰ (R^2 = 0.9482). Interpretation of the REY, sulfur and strontium isotope analyses is ongoing; however, the work to date shows a strong fracture-network control on calcite and sulfur species mineralisation.

INFRASTRUCTURE, SERVICE & COMMUNITY

03ISC-P01. STATE-OF-THE-ART REVIEW OF EARTHQUAKE FORECASTING ALGORITHMS

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Earthquake forecasting and prediction has been one of the key struggles of modern geosciences for the last few decades. A large number of approaches for various time periods have been developed for different locations around the world. A categorisation and review of more than 20 of new and old methods was undertaken to develop a state-of-the-art catalogue in forecasting algorithms. The different methods have been categorised into time-independent, time-dependent and hybrid methods, from which the last group represents methods where additional data than just historical earthquake statistics is incorporated. The first category covers the most straight forward and simplest way to generate forecasts, which are robust and stable, but are in terms of accuracy and predictive abilities completely outdated. Even recent developments occur within the narrow boundaries of smoothed seismicity. Thus, in this study a simple toolbox has been developed which covers most of the core elements of time-independent forecasting algorithms. These elements have been collected using several time-independent methods, which were analytically disassembled and subdivided into different algorithm blocks. The advanced features were also characterised with smoothing, handling of Gutenberg-Richter parameters and probability calculation elements incorporated. In this way, the toolbox represents a summary and modular approach to time-independent forecasting algorithms. Time-dependent and hybrid methods cover many facets of computational approaches, with complex contributions from different statistical theories. Thus it was necessary to categorise between pure statistical approaches where historical earthquake data represents the only direct data source and also between algorithms, which incorporate further information e.g. spatial data of fault distributions, or which incorporate physical models like static triggering to indicate future earthquakes. All these different aspects have been reviewed and catalogued based on several parameters to provide another easy-to-use tool for the development of earthquake forecasting algorithms. Most of the methods cover well-known high-seismicity locations like Italy, Japan or California. After testing different time-independent algorithms in the greater regions of Turkey and Italy with up to 1000 years of historical data using the toolbox described above, it was clearly visible that the general choice of how to assemble a time-independent method has only a marginal influence on the general likelihood and accuracy of the results. The most important factor in generating appropriate forecasting maps is the right choice of smoothing parameters and the handling of the Gutenberg-Richter relation. Increasing complexity, like the introduction of spatially varied b-values, tends to destabilise the numerical results and leads to a general loss of likelihood. Thus time-independent methods are not considered to be used as forecasting tools, due to their stationary nature and minor complexity. In contrast, time-dependent methods can be considered as the real forecast generating algorithms. After testing this extensive number of approaches, numerical stability, likelihood and universal applicability are still issues, which have to be resolved. Additionally, the accuracy of such methods might lead to rather arbitrary results. Nevertheless, the development of time-dependent algorithms with the incorporation of additional data sources, e.g. virtual fault maps, is considered to be the most promising direction for future developments.

03ISC-P02. TAKING IT TO THE LIMIT: APPLICATIONS OF *IN-SITU* X-RAY POWDER DIFFRACTION TO GEOSCIENCES

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The Australian Synchrotron is powerful source of electromagnetic radiation that produces photon energies up to 3 GeV. The powder diffraction beamline exploits the unique properties of synchrotron radiation by offering tunable wavelengths (6 keV–30 keV) to minimise sample absorption, high flux and good S/N for increased detection limits, and high resolution to minimise peak overlap. The X-ray powder diffraction beamline produces bright, high collimated X-ray beams that, when combined with the state-of-the-art Mythen II microstrip detector, are ideal for time-resolved X-ray powder diffraction experiments requiring high resolution data collection. The beamline possesses a vast arsenal of sample stages and environments that enable a multitude of *in-situ* experiments where temperature, pressure or gaseous environment, to name a few, can be varied to observe structure change and/or formation in polycrystalline materials. Since beginning user operations in 2008, over 300 user experiments have been performed at the powder diffraction beamline.

This work demonstrates the capabilities offered by the beamline, particularly for earth sciences and energy applications, highlighting a range of unique *in-situ* experiments that have not only produced successful scientific outcomes, but have pushed the boundaries in many cases. The options for future developments at the powder diffraction beamline are also discussed and will enable the beamline to build on its strong *in-situ* foundations to offer more power and flexibility for its users.

03ISC-P03. THE TEACHER EARTH SCIENCE EDUCATION PROGRAMME: 2008–2014: WHERE TO FROM HERE?

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The Teacher Earth Science Education Programme (TESEP) was created in 2007–2008 by a collective of concerned educators and industry & university geoscientists in response to declining enrolments at pre-tertiary and tertiary levels and to a reduction in programs delivered by other organisations. The first series of eight professional development workshops, entitled *The Challenging Earth*, was developed after conducting a national survey of teachers. All workshops are mapped to the national curriculum and are designed to assist middle-school teachers improve their delivery of the Earth and Space content.

To facilitate delivery of workshops TESEP successfully sought funding partners from government and industry. TESEP has been able to pay for workshop development and for workshop delivery across the nation. From 2012 to 2014 TESEP has continued to deliver quality PD throughout eastern Australia in the face of declining financial support from industry due at least in part to the tighter fiscal environment Australian businesses now operate in.

TESEP has responded to teacher demand as the Australian Curriculum F-10: Science has rolled out across the nation by adding an additional PD on Plate Tectonics to the *Challenging Earth* series and by producing a Plate Tectonics poster that ties all aspects of the series into this over-arching big picture concept.

In addition, TESEP has embarked on the development of a suite of Case Studies to complement the teaching of senior Earth and Environmental Science, especially supporting the Earth and Environmental Science text book produced in Western Australia.

Here we report on the delivery of the program to date with feedback from participating teachers demonstrating that the primary goals of the *Challenging Earth* series have been met but that there remains a large disconnect between the number of teachers attending PD and those actively teaching middle school science who would benefit from the PD. We also discuss the way forward for TESEP in the current fiscal environment, including the increased delivery of training though use of on-line media, the on-going development of Case Studies and the possibility of future PD developments.

RESOURCES

03RE-P01. ON THE POSSIBILITY OF USING SEISMIC REFLECTION SURVEYS TO DETECT COPPER – GOLD DEPOSIT IN THE GAWLER CRATON

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Exploration and exploitation for orebodies such as iron oxide copper gold (IOCG) continue to poss serious challenges to mineral exlporers and mining industry. Since the discovery of the giant Olympic Dam deposits in 1975, the entire Gawler Craton has been subjected to intense research activities in search of similar deposits thereby leading to rapid depletion of surface and shallow subsurface within the entire craton. The IOCG deposit are consider to be metasomatic expression of large crustal-scale alteration events driven by intrusive activity and are associated with felsic igneous rocks in most cases. Traditionally, potential field and electrical geophysics have been the main techniques used to remotely sense and evaluate the deposit for drilling purpose. However, these traditional approach of detecting the major structures that lead to the location of prospective targets have poor resolution at depth and are limited to either directly detecting shallow targets or very large deposits with sufficient contrast in areas with significant cover, such as the Gawlar Craton. In this era of technological innovation as a result of increasing demand for copper and gold globally, exploration techniques such as seismic reflection, which can detect deep seated ore bodies up to a depth of 2500 m is hereby proposed. The application of seismic methods in hard rock environment has been piecemeal and relatively expensive with result not often encouraging due to the complex nature of the deposits, limited geological knowledge as well as the inability to develop a single model that best describe the deposit. However, recent research in this area provides greater promise in the ability to delineate ore-bodies and for mine planing especially in complex hard rock environment. Most of the recent work is at mine-scale; larger or regional scale 3D seismic surveys have not been articulated or proposed probably because there has not been a strong and convincing argument of economic benefit to proceed with such work. For the seismic reflection method to be used at these scales (100's to 1000's of square km covered), the cost of survey as well as the technical risk involved has to be reduced. Therefore, an important step for adoption in exploration package is to prove that IOCG deposits are "discoverable" with relatively sparse 3D seismic reflection techniques. Since IOCG deposits usually have "large footprints" due their association with large-scale metamorphism and intrusions we hypothesise that even relatively sparse 3D seismic surveys may be able to pin down the likely areas for exploration under 2 km of cover.

03RE-P02. REGIONAL AEM SURVEYING FOR UNCOVER MAPPING

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Geoscience Australia (GA) is a leading promoter of airborne electromagnetic (AEM) surveying for regional mapping of cover thickness, under-cover basement geology and sedimentary basin architecture. Geoscience Australia flew three regional AEM surveys during the 2006–2011 Onshore Energy Security Program (OESP): Paterson (Western Australia, 2007–2008); Pine Creek-Kombolgie (Northern Territory, 2009); and Frome (South Australia, 2010). Results from these surveys have produced a new understanding of the architecture of critical mineral system elements and mineral prospectivity (for a wide range of commodities) of these regions in the regolith, sedimentary basins and buried basement terrains.

The OESP AEM survey data were processed using the National Computational Infrastructure (NCI) at the Australian National University to produce GIS-ready interpretation products and GOCAD™ objects. The AEM data link scattered stratigraphic boreholes and seismic lines and allow the extrapolation of these 1D and 2D objects into 3D, often to explorable depths (~ 500 m). These data sets can then be combined with solid geology interpretations to allow researchers in government, industry and academia to build more reliable 3D models of basement geology,

unconformities, the depth of weathering, structures, sedimentary facies changes and basin architecture across a wide area. The AEM data can also be used to describe the depth of weathering on unconformity surfaces that affect the geophysical signatures of underlying rocks.

A number of 3D models developed at GA interpret the under-cover geology of cratons and mobile zones, the unconformity surfaces between these and the overlying sedimentary basins, and the architecture of those basins. These models are constructed primarily from AEM data using stratigraphic borehole control and show how AEM data can be used to map the cross-over area between surface geological mapping, stratigraphic drilling and seismic reflection mapping. These models can be used by minerals explorers to more confidently explore in areas of shallow to moderate sedimentary basin cover by providing more accurate cover thickness and depth to target information.

The impacts of the three OESP AEM surveys are now beginning to be recognised. The success of the Paterson AEM Survey has led to the Geological Survey of Western Australia announcing a series of OESP-style regional AEM surveys for the future, the first of which (the Capricorn Orogen AEM Survey) completed acquisition in January 2014. Several new discoveries have been attributed to the OESP AEM data sets including deposits at Yeneena (copper) and Beadell (copper–lead–zinc) in the Paterson region, Thunderball (uranium) in the Pine Creek region and Farina (copper) in the Frome region. New tenements for uranium, copper and gold have also been announced on the results of these surveys.

Regional AEM is now being applied in a joint State and Commonwealth Government initiative between GA, the Geological Survey of Queensland and the Geological Survey of New South Wales to assess the geology and prospectivity of the Southern Thomson Orogen around Hungerford and Eulo. These data will be used to map the depth of the unconformity between the Thomson Orogen rocks and overlying sedimentary basins, interpret the nature of covered basement rocks and provide more reliable cover thickness and depth to target information for explorers in this frontier area.

03RE-P05. TOWARDS AUSTRALIAN METALLOGENIC MAPS THROUGH SPACE AND TIME

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The rapid growth in digital spatial geo-data is a key driver of frontier research for resource exploration. Computing methodologies and technologies are growing in importance in combining and relating the numerous spatial datasets to each other, through space and time. As available data increases both in resolution and modality, the opportunity for unlocking knowledge by cutting-edge high-performance computational means increases. High-resolution geophysical datasets in Australia are creating new opportunities for extracting mineral and hydrocarbon targeting "proxies" at increasingly smaller scales, and provide additional sources of evidence for conceptual targeting models. These datasets, combined with other available spatial data such as geological maps, geochemistry and geochronology, represent new knowledge discovery pathways if paired with machine-learning approaches. We apply high-resolution data mining and statistical analysis across multiple datasets, extracting features and associations that tie into conceptual models or achieve good separability based on known ground-truth locations. In this way, metallogenic maps can be developed that incorporate estimated associations from a collection of datasets through 3-dimensional space and time for each spatial increment. We use iron-ore exploration in Western Australia as a case study, involving the joint assessment of 6 geophysical datasets, namely Gravity anomaly, Magnetic anomaly, Topography, and K-, Th- and U- Radiometrics at a resolution of ~150 m. Known iron-ore deposits are used to extract various statistical features from the geophysical datasets (e.g. textures, peaks, mean values). Once a suitable statistical model is trained using known and random locations, the next step involves the extraction of predefined statistical features from all 6 geophysical datasets at a resolution of 150 m. For the entire Australian continent (roughly 4100 x 3000 km), this would represent approximately 540 million calculations per required association; therefore cloud computing will offer new pathways for parallelising these computations. We illustrate the results of this approach for two large regions in Western Australia, the iron-ore rich Pilbara region, and the infertile Yeelirrie region to the South, as metallogenic map overlays. Our metallogenic maps demonstrate the power of this approach to simultaneously incorporate several associations across several datasets into a single map view trained for a specific metallogenic exploration aim, i.e. iron-ore exploration in this case. The next step will be a coupling of this approach to plate tectonic reconstructions to explore the regional kinematic and geodynamic environments associated with metallogenesis.

03RE-P06. THE ADVANTAGES OF A NATIONAL APPROACH TO MAPPING DEPTH BENEATH COVER FROM MAGNETIC FIELD INTERPRETATION

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Magnetic field interpretation is the most extensively used geophysical method for remotely investigating basement geology beneath cover. One important aspect of this interpretation is quantitative estimation of depth to magnetic sources (commonly referred to as 'depth to basement mapping'). Numerous methodologies are used to automatically recover depth estimates from magnetic field data, and it is very difficult for a non-specialist to utilise the outputs from these methods with any reasonable appreciation of the limitations involved. This problem currently leads to misuse and underuse of this most important resource for under-cover investigations.

Magnetic field interpretation is inherently non-unique, precluding the opportunity for associating true errors with estimated depths as an integral part of their generation. Self-consistency estimates produced by some automated depth estimation methods reveal some clearly inconsistent results, but often give misleading confidence in others. CSIRO has analysed the basis and methodologies for recovering estimates of source depth from magnetic field data, and has developed a novel method to supply high quality depth estimates, with associated meaningful sensitivity values (in place of unattainable error values) and additional source parameters such as thickness, strike, dip, and magnetisation. This ancillary information provides important discrimination in separating solutions from different geological sources. The method is based on two key recognised facts; that magnetic fields carry useful source information only in specific 'sweet spots' above and around suitable magnetic sources, and that model-based inversion of the data carefully clipped to those sweet spots provides the highest resolution recovery of depth information, with associated sensitivity values.

Geoscience Australia and CSIRO have investigated implementation of methodologies based on this analysis, as a documented and recommended process to recover source depth values from magnetic field data across Australia. The advantages are that the depth values would approximate to the best values that can be recovered from the data, that they would have associated sensitivity estimates, and that the methodology would be well documented and consistent from area to area, greatly assisting in the use of this data by a wide range of geoscientists. Application of a developed methodology to regional magnetic field data sets across Australia would be a considerable step in making available much more of the geological information that is latent in that data. We intend to apply this methodology to regional (GADDS) datasets, and, with sufficient resources, it should also be possible to make the methodology available via a web-based utility, for users to apply the same analysis to their more detailed prospect-scale data sets.

Provision of discrete high-quality, attributed depth values would be a considerable advance for national mapping of geological surfaces beneath cover. The next step of constructing continuous (and/or fault-disrupted) surfaces from these sample points is more interpretive, requires a more substantial geological input, and is site specific. However, we propose that it is also worthwhile to provide these interpretive surfaces, for geoscientists to either accept as a guide, or to modify according to their own interpretations.

03RE-P07. A GEOLOGICAL PERSPECTIVE ON AEM INTERPRETATION FOR MINERAL EXPLORATION IN A REGOLITH-DOMINATED TERRAIN: THE SE YILGARN CRATON MARGIN/ALBANY-FRASER OROGEN, WESTERN AUSTRALIA

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This study examines the implications of groundwater salinity variations on airborne electromagnetic (AEM) interpretation, for data acquired over a paleochannel network – in two areas of the Albany-Fraser Orogen (AFO), adjacent to the southeast Yilgarn.

Based on reverse circulation and diamond drill holes logged, we delineated the variability, thickness and characteristics of the regolith in two study areas: Study Area 1 in the northeast AFO and Study Area 2 in the west central part of the AFO, with groundwater salinities of <3,000 mg/L and >35 000 mg/L, respectively. This data was coupled with field observations of the transported cover thickness and mineralogy of the different stratigraphic units, which provided the context for interpretation of the two AEM surveys flown with Spectrem2000^{TM} in both study areas. These datasets were processed using a sample-by-sample 1D layered earth inversion algorithm (GA-LEI).

In Study Area 1, when comparing field observations with interpreted AEM inversion data we observed that the AEM suggested regolith thickness increases from ~5 m to a maximum value of ~60 m (from the AEM interpretation), compared with up to ~70 m from field observations. Consistent agreement between drilling information and interpreted EM data strongly supports the effectiveness of AEM in the area. The variability in these two depth figures is within a reasonable range of AEM interpretation, and uncertainties relating to the difficulties of defining transitional changes in the weathering profile. The transported cover varies from 2–25 m in thickness, and the *in-situ* saprolite ranges between 22 to 70 m.

The total thickness of the transported cover fits the AEM interpretation of the less conductive unit at the top of the profiles. This unit corresponds mainly with eolian sands at the surface, and cemented lateritic sands and gravels at depth. These materials are poor electrical conductors. The *in-situ* regolith is divided into three units from bottom to top: (1) lower saprolite (ferruginised parental rock); (2) silcrete unit (4–20 m thickness); and (3) sandy kaolinitic upper saprolite. Unit (2) has a very low conductivity and therefore mimics the EM response of the transported cover in the EM profiles. Drilling and field observations were essential to segregate and properly estimate the thickness of the transported cover. This underscores how interpretations based on single techniques can be deceiving. EM interpretation, without consideration of the regolith framework of the profiles, could lead to an error in estimating the thickness of the transported cover to being up to 45 m.

In Study Area 2 recorded groundwater salinity was interpreted to be associated with the confluence of large paleochannels. Stratigraphic detail relating to the regolith is masked by highly saline groundwater. In areas where saline groundwater conditions prevail, the depth of AEM penetration is limited, as is its ability to discriminate between individual regolith units and boundaries. However, the boundary between resistive basement and overlying regolith is still resolvable, and in Study Area 2, these packages of permeable sediment are well defined.

03RE-P08. RECEIVER-BASED PASSIVE SEISMIC PROBING OF THE AUSTRALASIAN LITHOSPHERE

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Tracing the interaction of seismic waves travelling through layers of Earth and thus, enhancing the understanding of unseen interior is a science older than a century. Though, the advancement in instrumentation, computational capabilities and development of new techniques calls for a constant improvement in handling these earth travellers.

The receiver-function technique (e.g. Langston 1979; Clitheroe *et al*. 2001) is a proven tool for extracting lithospheric shear-wave velocity profile beneath a receiver (seismic station) by source-equalisation. The lithospheric structural information was obtained from teleseismic receiver functions, firstly using linearised inversions (e.g. Ammon *et al*. 1990) and later by non-linear optimisation algorithms (e.g. Shibutani *et al*. 1996) within a Bayesian inference (e.g. Piana Agostinetti *et al*. 2010; Bodin *et al*. 2012), which could handle the non-unique nature of receiver functions.

The earthquake belts around Australia have served as reservoirs for seismic studies of the lithosphere using surface and body wave tomography and receiver function analysis. These studies have yielded a resourceful background about lithospheric structural patterns of most regions (e.g. Kennett *et al*. 2000). However, unlike in the previous studies on Australia, we carry out receiver function analysis with an attempt to include other compressional wave seismic phases, such as PP (e.g. Julia *et al*. 2008) and PKP. PP is a double-reflected P-wave, and complements the structural information derived from P-wave receiver function data. This grants us an opportunity to expand the azimuthal coverage by an increased number of events observed at a station and thus, increase our accuracy in deriving compressional and shear-wave velocity ratios and crustal thickness. With this aspect of work we look forward to outline a feasible procedure for receiver function analysis, particularly useful in noisy environments, such as coastal stations, and locations accessed through challenging temporary installations, such as the interior of Antarctica.

In addition, a recently developed hierarchical and transdimensional Bayesian inversion of receiver functions (Bodin *et al*. 2012) is used as a preferred inversion method. This represents a tool that is void of explicit parameterisation, damping and smoothing, and treats the noise in the data as a free parameter. In turn, although computationally expensive, this becomes particularly useful in noisy environments such as coastal areas and the interior of Antarctica. Here we present preliminary results of our imaging applied to different regions of Australasia, which will enhance our understanding of lithospheric composition and structure, and its lateral variation.

03RE-P09. IMAGING THE REGOLITH WITH FULL WAVEFORM REFRACTION SEISMOLOGY

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Traditional methods for processing near surface seismic refraction data have focussed almost exclusively on the use of scalar traveltimes. In recent decades, refraction data processing has employed model-based inversion, also known as refraction tomography. Automatic implementations of refraction tomography usually employ low-resolution 1D starting models. Usually, the resulting tomograms exhibit quite low resolution.

This study demonstrates that full waveform near surface seismic refraction methods are able to generate significantly higher resolution images. The images are similar to the more familiar seismic reflection images, routinely employed in the study of deeper targets. Accordingly, they are well suited to the application of the substantial range of seismic reflection processing and post-processing methods.

A major advantage of the full waveform refraction images is that exhibit events from below the base of the weathering. These events facilitate the generation of more useful structural models.

Furthermore, the full waveform images demonstrate the occurrence of multiples generated with the weathered layer. These multiples offer the possibility of more detailed delineation of layering within the weathering, especially for groundwater investigations, using seismic interferometry.

The usefulness of full waveform refraction seismology is demonstrated with a number of case studies.

03RE-P10. IMPROVED EARTHQUAKE MONITORING – ADELAIDE'S STORY

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During the last 7 years, densification of the earthquake monitoring network around Adelaide has made substantial improvements, not just in data quality and quantity, but also allowing research in other areas that were previously not possible. We now regularly collect data from stations operated by DMITRE, Geoscience Australia, private operators and schools.

Earthquake locations before 1909 were on the basis of newspaper reports. A single station from 1909 was in some cases able to confirm events, but newspaper reports usually provided better data. A network suitable for local earthquakes began in 1964. This allowed poor location calculations near Adelaide, but events were rare. A quiet monitoring site installed in 1988 improved detection, and marginally improved location accuracy.

In 2007, the completion of a network surrounding Adelaide made it possible to calculate depth with some accuracy. The Mt Barker earthquake, magnitude 3.8, in 2010 was sufficient for a focal mechanism to be produced.

From 2012, with the addition of some private seismographs and a school seismograph, we have taken a substantial step forward. We have accurate depths for many events, sometimes down to magnitude 0, with focal mechanisms possible at magnitude 2 and sometimes lower.

Questions that can now be considered for research now include:

- Are earthquakes aligning on any preferred planes near Adelaide?
- What is the depth distribution of hypocentres, and where is the transition to a ductile crust?
- How much variation is there between focal mechanisms?

When the current densification spreads over a wider area, research will include velocity modelling, tomography and b-value variation.

Critical components of this improvement are:

A few reliable high sensitivity stations that detect events have occurred, many stations for improved location, depth and first motions for focal mechanisms, accessible data, and meetings of private operators to maintain interest and running stations.

03RE-P11. FOURTH DIMENSIONAL MODELLING, A TOOL FOR 3D GEOLOGICAL MODEL VALIDATION

Hugh Anderson, Jenny Ellis & Alan Vaughan

Midland Valley Exploration

The successful exploitation of economic resources such as mineral, geothermal and hydrocarbon reserves depends on a number of well-established disciplines and techniques. However, exploration, appraisal and development of these resources, for example drill planning, reserve calculation and geotechnical simulations, are often reliant upon 3D geological models.

These 3D models are frequently based on incomplete data sets and the resulting interpretation is a hypothesis representing the interpreter's best estimate of reality. Any model should therefore be validated; i.e. is the configuration of horizons and faults structurally reasonable, and if not what are the implications on further analysis? Validation encompasses a range of techniques such as line-length and area balancing, but it is by implementing fourth dimensional modelling techniques, often referred to as kinematic modelling (sequential restoration and forward modelling), that the geologist can test and understand how structures have developed in an evolutionary sense.

Kinematic modelling guides the decision process between alternative interpretations and reduces the magnitude of uncertainty in the final model. This results in a validated geological model, which can provide detailed information on the structural history and gives a reliable framework for advanced analysis, including strain and fracture modelling, stress analysis and fluid migration studies.

03RE-P12. GUIDELINES AND STRATEGIES FOR MODEL BUILDING AND INTERPRETATION IN 3D SPACE

Hugh Anderson, Jenny Ellis, Alan Vaughan, Roddy Muir, Colin Dunlop & Peter Rourke

Midland Valley Exploration

Geologists routinely work with a wide range of geological and geophysical data in their attempts to build realistic 3D models of the subsurface. The approach taken to interpretation and model building can vary considerably depending on the worker's background and training as well as the techniques and technology that they have access to, have chosen to adopt or have been advised to use.

The traditional techniques, which are still taught in most universities and colleges, involve the production of 2D field maps and cross-sections using pen and paper. The map will illustrate the outcrop pattern (distribution of rock types/units) at the surface while the section will show how these rock units and associated structures extend into the subsurface. The intersection of the surface geology with topography can be used to project surfaces and structures at depth and combined with various geometric construction and stereographic projection techniques it is possible to build a robust 3D model of the subsurface geology. Working on paper, it often helps to visualise the 3D aspects of the geology in the form of a “fence diagram” or a “block diagram”. However it requires considerable artistic and technical skill to sketch a block diagram on paper in the correct orientation, which accurately demonstrates the 3D aspects of the geology and structural relation-ships in the area of interest.

The advent of 3D model building and validation software has dramatically improved our ability to construct and visualise often-complex geological scenarios. It is now possible to collect data, generate maps and cross-sections, build and test 3D models and visualise this information in an entirely digital environment. Furthermore, the same geological skills that have been traditionally taught on paper can now be easily demonstrated on tablet devices in the field; meaning the quality of a 3D model now depends on the knowledge and thinking skills of the geologist rather than their artistic ability.

Kinematic modelling tools, along with a range of other validation techniques, such as line-length and area balance, give predictive insight into the geometries and linkages of the fault framework through time with important implications for the relationships between the hydrocarbon or mineralisation systems and structure. This poster demonstrates how various structural modelling techniques and tools that can be used to help reduce the uncertainty and risk during interpretation. Together these form some of the key components in best practice 3D model building.

03DP-P02. THE FREQUENCY-DEPENDENT SEISMIC PROPERTIES OF CRACKED AND FLUID-SATURATED ROCKS: INSIGHTS FROM THE LABORATORY AND MODELLING

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The expected frequency dependence (dispersion) of seismic wavespeeds in cracked and fluid-saturated crustal rocks complicates the use of (mainly high-frequency) laboratory wavespeed measurements in seismological interpretation. The expected dispersion results from the relaxation of spatial gradients in pore-fluid pressure by fluid flow for appropriately low frequencies of wave propagation. The solution to this dilemma lies in laboratory measurements of elastic wavespeeds or corresponding moduli on cracked media over an appropriately wide range of frequencies. To this end, conventional measurements with ultrasonic (MHz) wave propagation methods are being complemented by subresonant forced-oscillation techniques that provide access to lower (mHz–Hz) frequencies. Ultrasonic and forced-oscillation measurements have been conducted on thermally cracked low-porosity specimens of natural quartzites and sintered aggregates of glass beads, tested dry or with argon or water saturants. The results show systematic increases in wave speeds/elastic moduli with increasing confining pressure or differential pressure (confining pressure minus pore pressure), and clear evidence of dispersion between Hz and MHz frequencies. The pressure-dependent elastic properties of the cracked media have been modelled with differential effective medium theory. In this way, a crack density is first inferred from the modulus deficit for the dry specimen at each pressure, and the pressure dependence of the inferred crack density provides information concerning the distribution of crack aspect ratios – broadly consistent with microstructural observations. Finally, the calculated influence of fluid saturation of the inferred crack microstructure supports the attribution of the dispersion, observed between Hz and MHz frequencies, to local 'squirt' fluid flow.

03DP-P03. TECTONIC SIGNIFICANCE OF PODIFORM CHROMITITES WITHIN THE MANATUTO DISTRICT, TIMOR LESTE

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Podiform chromitite is one of the modes of occurrence of chromite in ophiolites, fragments of oceanic crust obducted onto the continental margin as a result of tectonic processes. The environmental setting of formation of these chromite-rich rocks can be divided into two broad groups, mid-ocean ridges (MOR) and supra-subduction zone (SSZ), which can be inferred from either the geochemical fingerprint of the chromite forming the chromitite or their host peridotites. To achieve the formation of the chromitite the focalisation in mantle conduits of basaltic melts produced by high degrees of partial melting are required; these melts can be only produced in specific geodynamic settings. Hence the study of chromitites can provide strong evidence for discriminating former tectonic settings.

The Hili Manu peridotites, located on the north coast of Timor Leste, ~ 50 km east of the capital Dili, have been a topic of considerable debate as to their ophiolitic affinity over the last 30 years. This is the first detailed study on the geological setting, textures, mineralogy and geochemistry of the chromitites and their host peridotites.

Ultramafic rocks from Hili Manu, Manatuto District, were identified within two massifs (namely Be Heda and Kerogeol Hill in the east and Subao Highway in the west) separated by an amphibolite block of undefined origin. They range from fresh to completely serpentinised dunites, harzburgites and lherzolites associated with rare rodingites and gabbros. The difference between the two massifs is largely the degree of serpentinisation (lizardite and chrysotile), being more intensely developed in the eastern massif.

Chromitite pods at Hili Manu are found hosted in completely serpentinised dunites and harzburgites in the eastern massif (Be Heda and Kerogeol Hill) and in fresh olivine-rich harzburgite in the western massif (Subao Highway). The composition of chromite-forming the chromitite pods and from host peridotites are different. Thus, chromite-forming chromitites of Hili Manu are high-Cr (#Cr >0.6), indicating crystallisation from melt–rock interactions in a SSZ tectonic setting whereas chromite in peridotite hosting the chromitites are low-Cr (#Cr <0.6), suggesting a MORB environment.

Chromitites at Hili Manu have total PGE concentrations between 28 and 1071 ppb characterised by an enrichment in IPGE (Os, Ir, Ru) over PPGE (Rh, Pt, Pd) as is typical of an ophiolite setting. Consistently, frequent grains of Os-rich laurite are found as solid inclusions in primary chromite. Pentlandite is also found as inclusions in unaltered chromite as well as within fractures traversing the chromite grains; talnakhite, chalcopyrite and pyrite occur as inclusions in unaltered chromite only; and heazlewoodite, millerite and nickeline occur within the fractures.

03DP-P04. A MANTLE XENOLITH PERSPECTIVE ON KIMBERLITE PETROGENESIS

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Kimberlites are enigmatic, rare, small volume igneous rocks that are important because they are the primary host rock to diamonds and because kimberlite parental melts originate from deep within the Earth (>150 km, i.e. within the diamond stability field). In addition, kimberlite magmas have entrained abundant fragments of mantle and deep crust wall rocks en route to the surface, thus providing the major source of information about the petrology and geochemistry of the deep lithosphere in continental areas. Due to their hybrid and volatile-rich nature and widespread alteration by deuteric (i.e. late-stage magmatic), meteoric and hydrothermal fluids, the primary composition of kimberlites has proven difficult to constrain.

The study of melt inclusions in primary magmatic minerals of kimberlite rocks, such as olivine and spinel, has provided evidence that the composition of kimberlite magmas prior to late-stage modification might be close to carbonatitic. However, this interpretation contrasts with the broadly ultramafic composition of kimberlite rocks and has been widely criticised because the trapped melt inclusions may or may not be representative of the composition of primary kimberlite melts.

Given that not all pulses of kimberlite magmatism reach the surface, the investigation of reaction textures between mantle wall rock fragments (i.e. xenoliths) entrained by kimberlite magmas and primitive or precursor kimberlite melts may provide an alternative approach to gain constraints on the petrogenesis of kimberlite melts. Micro-textural, mineralogical, geochemical and melt/fluid inclusion analyses of these reaction zones can provide a wealth of information on the composition of kimberlite magmas at depth, i.e. before their composition is extensively modified by processes such as outgassing and crustal alteration.

This presentation will review existing studies of mantle xenoliths that preserve evidence of metasomatism coeval with kimberlite magmatism. These studies include detailed examinations of carbonate-rich metasomatic assemblages commonly occurring in veins and pools and overprinting pre-existing mantle minerals; and investigations of mantle polymict breccias, which are widely regarded as failed kimberlite intrusions that halted at lithospheric mantle depth. Where abundant data are available for both the entraining kimberlite magma and the metasomatic mantle agent, a direct comparison between the two melts can be drawn. We will show this is particularly significant for the Bultfontein kimberlite (Kimberley, South Africa), where an alkali–carbonate composition for the primary kimberlite magma has been deduced from our coupled investigation of kimberlite host rock and entrained mantle xenoliths. We conclude that the study of reaction textures in mantle xenoliths produced just prior to or during kimberlite entrainment represents a novel and exciting direction towards a new understanding of the petrogenesis of kimberlite melts.

03DP-P05. ^{40}AR/^{39}AR DATING OF PHLOGOPITE AND AMPHIBOLE IN METASOMATISED MANTLE XENOLITHS: THE “ROGUE” CHRONOMETER OF MANTLE EVENTS

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Precise dating of fluid processes in the Earth’s mantle remains a major challenge for geoscientists. The U/Pb and Ar/Ar dating techniques have both been used in an attempt to constrain the timing of mantle metasomatic events. U/Pb dating of zircon is widely considered the most robust dating method for mantle metasomatism. However, there is evidence that U/Pb ages of zircons from mantle xenoliths can be partially reset toward the emplacement age of the entraining kimberlite magma. In addition, zircon is uncommon in mantle rocks and only occurs in intensely metasomatised samples.

Phlogopite is a common mantle metasomatic phase and, together with amphibole, is widespread in mantle rocks enriched by hydrous fluids and melts. Therefore, the $^{40}Ar/^{39}Ar$ dating technique applied to phlogopite and amphibole has the potential to provide an additional and widely applicable tool to date mantle metasomatic events. However, the $^{40}Ar/^{39}Ar$ results for mantle phlogopite have proven contentious, given the common occurrence of excess ^{40}Ar (i.e. unrelated to *in-situ* decay of ^{40}K) in mantle fluids, as documented for fluid inclusions trapped in diamonds.

Here we compare the $^{40}Ar/^{39}Ar$ ages obtained for large phlogopite grains from 7 mantle xenoliths and for large K-richterite amphibole grains from 2 of these xenoliths with U/Pb ages of coeval metasomatic zircon and LIMA minerals (U–Pb-bearing titanates of the crichtonite group). The samples were retrieved from the *ca* 84 Ma Bultfontein kimberlite (Kimberley, South Africa) and include phlogopite-rich peridotites with variable amounts of clinopyroxene, LIMA and occasional zircon, zircon-bearing MARID (mica–amphibole–rutile–ilmenite–diopside) rocks and a mantle polymict breccia. $^{40}Ar/^{39}Ar$ step-heating analyses of phlogopite and K-richterite grains were conducted using a new generation ARGUSVI multi-collector mass spectrometer. Zircon U/Pb ages were obtained by SHRIMP and LIMA U/Pb ages by LA-ICP-MS.

All the phlogopite samples yielded much older $^{40}Ar/^{39}Ar$ ages (up to 780 Ma) than coexisting zircon (*ca* 80–130 Ma) and/or LIMA minerals (*ca* 180–190 Ma). The differences between phlogopite $^{40}Ar/^{39}Ar$ ages and zircon or LIMA U/Pb ages vary from sample to sample (between *ca* 30 and 700 Ma). Conversely, the two K-richterite samples provided ages younger and older, respectively, than the likely age of metasomatism given by zircon U/Pb systematics. We attribute the anomalously old $^{40}Ar/^{39}Ar$ ages of phlogopite and K-richterite to the presence of excess ^{40}Ar in the metasomatic fluid that crystallised these minerals. The younger $^{40}Ar/^{39}Ar$ age of one of the K-richterite samples may be due to subsolidus redistribution of excess ^{40}Ar into the phlogopite structure during mantle residence. We conclude that the $^{40}Ar/^{39}Ar$ technique applied to mantle phlogopite and K-richterite amphibole provides geologically meaningless ages and cannot be used to date mantle metasomatism.

03DP-P06. DIAMOND FLUIDS AT WORK – NANOSCALE INSIGHTS FROM POLYCRYSTALLINE DIAMOND AGGREGATES

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Polycrystalline diamond aggregates (diamondites) are produced by very rapid crystallisation caused by extreme carbon supersaturation in mantle fluids. They form episodically under variable chemical conditions, providing snapshots of diamond formation in the Earth's mantle. Diamondites represent an extreme end member of diamond formation mechanisms, but form by the same processes and from the same ingredients as gem-sized diamonds.

Modern microanalytical techniques allow *in-situ* analysis of diamonds and their inclusions spanning six orders of magnitude in spatial resolution, whereby information derived from inclusion suites at either end of the size range is complementary. Macro-inclusions give critical insight into the chemical environment as well as the pressure and temperature of diamond growth. Micro-inclusions at the lower end of the size distribution deliver direct information on the diamond growth medium represented by included minerals, quench phases and fluid, which cannot be derived from the macroinclusions alone.

In-situ sampling of diamond fluids reveals great heterogeneity in redox conditions and fluid chemical compositions at micro to nanoscale that is not reflected in the macro-inclusion suite. Perhaps surprisingly, fluids from polycrystalline diamonds from chemically different environments in the mantle and crust have compositions that conform to the fluid end-members established by studies on fibrous diamonds. This suggests a universally important role of a limited number of basic ingredients, namely carbon, silicon, halogens and water.

Strong redox gradients indicated by micro-inclusions in diamondites demonstrate diamond precipitation *via* small-scale, ephemeral redox processes driven by the contrasting oxidation states of fluids and their depositional environment. The presence of even small amounts of volatiles promotes melting simultaneous to diamond precipitation, further enhanced by changing fluid composition towards higher water activity during the redox reactions. This creates a chemically heterogeneous environment in which diamonds and their inclusions are precipitated by redox-freezing. Recent experimental work implies that the generation of ephemeral small-scale redox gradients may be further enhanced by the immiscibility of water and hydrogen at these pressures and temperatures.

The submicron inclusion suites in diamondites are therefore products of redox reactions and mixing of components from the influxing C–H–O fluid and those derived locally from the surrounding mantle rocks. Simple mass balance considerations predict that where partial melting of the host rock dominates, the fluid component is occluded in the resulting inclusion chemistry, so that the inclusion gives information only on the depositional environment rather than on the carbon-bearing medium.

Preliminary studies on the diamonds indicate that the crystals in diamondites may have grown by both octahedral (spiral/dislocation) and cuboid (rough, adhesive type) growth mechanisms. This suggests that other parameters in addition to extreme carbon supersaturation, play an intrinsic role in their growth. As both growth mechanisms occur in gem-sized diamonds, study of diamondites may tie these together in a new integrated model and help define the impurities, oxygen fugacity, and episodic nature of these deep mantle fluids. Their variability and rapid formation literally provides chemical snapshots of diamond formation and makes diamondite ideal for probing the C–H–O fluids and their evolution in the Earth's lithosphere.

03DP-P07. CARBONATE METASOMATISM COEVAL WITH KIMBERLITE MAGMATISM IN THE LITHOSPHERIC MANTLE BENEATH KIMBERLEY (SOUTH AFRICA)

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The presence and formation of carbonate melts within the lithospheric mantle has long been experimentally predicted, and such melts have been shown to be major metasomatising agents in many instances. Despite this, direct evidence of these melts is seldom preserved, with examples being restricted to carbonate-rich inclusions within metasomatic minerals, and rare trapped carbonate–silicate melt globules. Here we show textural, mineralogical, and geochemical data for a carbonate-dominated metasomatic vein assemblage, located within a sheared, garnet wehrlite from the Bultfontein kimberlite (South Africa). This sample exhibits well-preserved textural evidence indicating influx of carbonate rich melts, allowing for quantification of the fluid composition as well as their effects on mantle wall rock, and immiscibility between carbonate and silicate melts.

Carbonate-dominated vein assemblages traverse the sample, often forming large interstitial pools and spherical silicate–carbonate globules, the latter contained entirely within clinopyroxene and, rarely garnet. Vein assemblages are dominated by distinct carbonate phases (Ca-magnesite, dolomite, calcite, and minor strontianite), with subordinate sulfides (pentlandite and djerfisherite), spinel, ilmenite, Mg-magnetite and neoblastic olivine. Carbonates, neoblastic olivine, and ilmenite host abundant inclusions of alkali (Na, K, Ca, and Mg) carbonates, Na-rich apatite, and Na-titanate (probably freudenbergite). Carbonates are angularly intergrown, this in addition to the multiple generations of carbonate is interpreted to represent quenching. When in contact with the vein assemblages, clinopyroxene and garnet in the wehrlite host are intensely resorbed with formation of an alumino-silicate phase (probably a former glass), containing spongy accumulations of apatite. This silicate glass is interpreted to be the product of a reaction between clinopyroxene, garnet and a highly reactive carbonate melt. Within some pools and globules a thin film of Mg-magnetite separates carbonate and silicate components, with sulfides showing a direct spatial association with the Fe-oxides.

We propose that an incoming, alkali-rich dolomitic melt interacted with host clinopyroxene and garnet, generating a silicate rich component, observed as the glass reaction phase separating carbonate veins/pools and silicate minerals. Upon formation this silicate-rich component became immiscible to the incoming melt, separating into chemically distinct pockets, locally divided by a film of Mg-magnetite. This metasomatic event is interpreted to have occurred very close to, or during xenolith entrainment into the host kimberlite, based on the presence of quenched microstructures, preservation of immiscibility textures, and dis-equilibrium between wherlitic and vein assemblages. This provides a genetic link between carbonate metasomatism in the lithospheric mantle and kimberlite magmatism, but might also suggest metasomatism by carbonate-rich primitive or precursor kimberlite melts.

03DP-P08. HOW MANTLE HETEROGENEITIES CONTROL SUPRA-SUBDUCTION METASOMATISM: CONSTRAINTS FROM THE CABO ORTEGAL COMPLEX, SPAIN

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The origin of mantle heterogeneities and their fate in subduction zones are keys for understanding the core to crust exchanges and their application for exploration targeting. The Herbeira massif of the Cabo Ortegal complex has an unusually high volume of pyroxenites associated with dunites in a sheet-shaped body [2]. The igneous features of these peridotites and pyroxenites have been overprinted by prograde and retrograde metamorphism during a complex tectonothermal history involving a subduction event [1]. This study aims to provide a better understanding of the geodynamic context of such abundant pyroxenites.

The resolution of contentious issues resulting from inconsistent field relationships mapped in the Herbeira massif by different authors [1, 3] was a preliminary requirement. Our new mapping reveals that the contact between the pyroxenite-rich body and the mantle harzburgite is a smooth, non-tectonic transition, enclosed in a km-scale zone rich in late cross-cutting veins. Both harzburgitic and pyroxenitic lithologies are affected by a sheath-fold deformation (recently interpreted in the same complex as related to a deep-subduction setting [4]) and by amphibolite-facies retrograde metamorphism. These field observations suggest that the pyroxenite-rich body had already formed, in the mantle, when the massif intruded the subduction zone, and that its heterogeneities and subsequent deformation have controlled the development of a kilometre-scale metasomatic conduit.

In the Herbeira massif, chromites are locally concentrated in chromitite pods and bands, and are disseminated in peridotites and pyroxenites throughout the massif. A clear metamorphic overprint is recorded as an Fe^{3+}–Ti enrichment of the spinels from the most amphibolitised samples, and particularly of the spinels enclosed in hornblende. By re-examining the petrographic features previously described in platinum-group minerals (PGM) from the chromitites [3], we show that the fluid or melt circulation that occurred during amphibolite-facies metamorphism has resulted in high concentration of platinum-group elements (PGE) in the chromitites located near the metasomatic conduit. The combination, to our knowledge unique, of geological features related to mantle metasomatism and retrograde metamorphism provide the first constraints on the P–T conditions and the nature of fluids associated with the metasomatic remobilisation of PGE in supra-subduction chromitites. It constitutes an alternative view to the magmatic and post-magmatic processes usually invoked to account for the formation and evolution of PGM in ophiolitic chromitites.

In addition, our preliminary results suggest varying degrees of chromatographic re-equilibration between the percolating fluid or melt and the layered and massive pyroxenites and the host peridotites. By combining observations of these metasomatic features from the massif to the thin-section scale, and even to the grain scale, this work is ultimately expected to provide a geodynamic scenario for the magmatic processes that have led to formation of the abundant pyroxenites in the Herbeira massif of the Cabo Ortegal complex, despite their poly-metamorphic history.

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03DP-P09. LAWSONITE ACTS AS A TRACE ELEMENT SPONGE IN SUBDUCTION ZONES OF THE ALPINE-HIMALAYAN OROGENIC BELT: EVIDENCE FROM TAVŞANLI BLUESCHIST (TURKEY)

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Constraining the processes by which crust is recycled back through the mantle wedge and into volcanic arcs is one of the most challenging issues in modern geochemistry. Discussion is mostly centred on the dichotomy of fluid vs. melt transport and subsolidus dehydration vs. melting, in which the mobility of Th and the REE has particular significance.

The production of fluid or melt by breakdown of hydrous minerals such as lawsonite, and the consequences for trace element mobilisation remain largely unconstrained.

Here, we combine electron microprobe, Laser-ICP-MS, TIMS and confocal microRaman spectroscopy data of four samples of lawsonite and garnet bearing blueschists from the Tavşanlı Zone, Turkey; a melange metamorphosed under blueschist to lawsonite-eclogite facies conditions. Our aim is to monitor trace element redistribution during high-pressure–low-temperature metamorphism. Two lawsonite blueschists have low concentrations of Th, REE and K, unradiogenic Sr and radiogenic Nd isotopes, similar to normal MORB basalts, whereas the other two are enriched in K (up to 2.89% K_2O), Th and REE, and show radiogenic Sr and unradiogenic Nd isotopic composition, implying the presence of a continent-derived terrigenous component for the latter samples. These widely divergent isotopic features and trace element heterogeneities of lawsonite suggest complex geological processes in the source area, where metasomatic modification by percolating fluids is a likely process.

Equilibrium assemblages are lawsonite + glaucophane + chlorite + phengite + titanite + apatite ± garnet ± quartz and iron oxides. Garnet is the major host for HREE, phengite contains most LILE and titanite and zircon are the dominant carriers for Nb, Ta and Zr, Hf, respectively. Lawsonite and apatite carry almost all Sr and a significant proportion of the REE. In thorium-rich samples, lawsonite is extremely enriched in Th (up to 99.3 ppm), giving rise to high Th/La ratios up to 1.0, but has relatively low Sm/La (as low as 0.4), which defines a unique feature for subduction facies minerals worldwide. The high Th/La ratios observed in lawsonite are significantly higher than in average crust and normal arc volcanics, but similar to those in Mediterranean lamproites, rare ultrapotasic orogenic lavas occurring within Alpine-Himalayan belt.

Combining this fingerprint of lawsonite with previous studies of lamproites from the Alpine-Himalayan orogenic belt, we propose that lawsonite captured characteristically high Th/La and Sm/La ratios from continental sediments during HP–LT metamorphism and subsequent metasomatism, and then to convey them to subsequently produced magmas. The resulting lamproites were formed by low-degree melting triggered by post-collisional lithosphere delamination and thermal relaxation, during which lawsonite was consumed completely. The involvement of lawsonite blueschists is a characteristic of post-collisional melting in accretionary orogens, where shallow imbrication of sediments into the mantle formed new lithosphere that was re-melted without deep subduction processes ever having been involved. Similar geodynamic processes and melting mechanisms may apply wherever accretionary processes operate on the modern Earth. Furthermore, these geochemical characteristics may be widespread in the abundant mantle lithosphere newly formed in the late Archean, because the role of accretionary orogens may have been more important formed at that time.

03DP-P10. AUSTRALIAN MAFIC–ULTRAMAFIC MAGMATIC EVENTS: A GIS FRAMEWORK FOR SYSTEMS ANALYSIS

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Geoscience Australia has recently completed a multi-year compilation of Mafic–Ultramafic Magmatic Events for the Australian continent within a GIS framework. A detailed compilation of Phanerozoic mafic–ultramafic rock units and events has been appended to the previously published maps of Archean and Proterozoic mafic–ultramafic rocks and events. The full dataset has been released as a new GIS at a nominal scale of 1:5 000 000 for users to analyse and overlay other datasets.

The delineation of magmatic events in this GIS is based on several hundred published ages of mafic and ultramafic igneous rocks using different isotopic systems and minerals. The foundation for the spatial distribution of rock units in the GIS are regional solid geology compilations from the State and Northern Territory geological surveys (available mainly for the Archean and Proterozoic), and surface geology distributions elsewhere (mainly for the Phanerozoic). The solid geology extents of units provide insights into the extent of the magmatic systems under sedimentary cover.

Australian mafic–ultramafic magmatic events have been defined within resolvable bands of ± 10 million years. Nineteen newly formalised Phanerozoic mafic–ultramafic magmatic events range from the *ca* 530 Ma Truro Event, named for the Truro Volcanics in southeast Australia, to the near-continuum of mafic magmatism during the Cenozoic in eastern Australia. Together with the existing event series for the Archean and Proterozoic, the complete magmatic event record of the continent now comprises 74 defined mafic–ultramafic magmatic events. This detailed compilation in both space and time is now the most complete record of mafic–ultramafic magmatic events for any continent.

The GIS data are fully attributed to their sources. However, the geological datasets from the State and Northern Territory geological surveys use non-standardised attributes for rocks or solid geology, limiting the creation of a seamless nation-wide GIS dataset of mafic and ultramafic rocks. Nevertheless, the polygon attributes will allow the integration of the Mafic–Ultramafic Magmatic Events dataset with other national-scale datasets such as the national database of whole-rock geochemistry. Users may also link the new GIS data to the original attributed polygon data in State/Northern Territory GIS sources, because original map symbols were retained. Other attributes available for analysis include (but are not limited to) the presence or absence of ultramafic components within each defined magmatic event, Stratigraphic Units Database number, basic lithology, and the crustal domain within which each event is preserved (based on the Geoscience Australia Map of Australian Crustal Elements).

Relative to some other continents with comparable geology, Australia appears to be under-represented in known mafic–ultramafic intrusion-hosted nickel, PGE and chromium mineral deposits. The primary intention of the GIS of Mafic–Ultramafic Magmatic Events is the provision of information for those investigating under-explored and potentially mineralised environments in Australia that may lead to redressing the discovery imbalance. The events also provide an insight into the geodynamic development of the continent over time.

03DP-P11. LITHIUM ISOTOPIC COMPOSITION OF THE TONGA-KERMADEC ARC AND ITS CONSTRAINTS ON SUBDUCTION RECYCLING

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Understanding elemental transfer within subduction zones is integral to quantifying crust–mantle exchange and recycling. Lithium is water-soluble and potentially a useful tracer of subduction zone processes. We have analysed the lithium concentrations and isotopic compositions of a suite of lavas from the Tonga-Kermadec island arc, as well as a depth profile through forearc marine sediments from ODP hole 204, and lavas from the Fonualei back-arc spreading center in order to trace how lithium isotopes maneuver through an intra-oceanic subduction zone.

The δ^7Li of the entire suite of sediments and lavas vary from 0.3 to 14.4. The depth profile, along with published data from another nearby core sample (DSDP 595/596), shows a systematic increase in δ^7Li (1.2 to 14.4) with depth. This is in relation with the sediment type; lithium isotopic signatures for pelagic sediments are often lighter because of fractionation from weathering, while volcanogenic sediments can be lighter or heavier as a direct result of their alteration effects[1]. The δ^7Li of hole 204 pelagic sediments overlap that of the mantle, but range to lower values (1.2 to 5.2), while the δ^7Li of volcanogenic sediments are higher than the mantle (7.2 to 14.4). Thus, the Li isotope variation in the subducting sediments greatly exceeds that observed in the lavas. The fact that δ^7Li in some arc lavas (0.3–7.6) falls outside the range of MORB requires enrichments by fluid transfer of lithium from the sediments (which is reinforced with published B/Be data). Lavas from the back-arc spreading center (δ^7Li = 3.0–5.0) show no variation from the widely accepted lithium isotopic signature range of the MORB (1.5–5.5), suggesting that there is little Li transfer from the slab in the back-arc.

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COMPARISONS & CONTRASTS IN CIRCUM-PACIFIC OROGENS SYMPOSIUM

CPO-P01. GEODYNAMIC MODELS OF TETHYAN STYLE OPHIOLITE OBDUCTION

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Tethyan style ophiolite obduction is a conceptual ophiolite emplacement model involving the thrusting of overriding oceanic lithosphere on top of subducting continental lithosphere. Four-dimensional fully dynamic analogue models have been constructed to evaluate the mechanical feasibility of this ophiolite emplacement model. The role of continental crust thickness, passive margin width and subducting lithosphere thickness were investigated to determine the maximum horizontal obduction distance, passive margin depth, obduction velocity and ophiolite deformation.

The experimental setup includes (1) a sublithospheric upper mantle modelled using a low viscosity glucose syrup, (2) a negatively buoyant subducting plate modelled using a high viscosity silicone mixed with fine iron powder, (3) a positively buoyant continental crust located on the down going plate modelled using a mixture of two highly viscous silicone materials, (4) a neutrally buoyant overriding plate modelled using a highly viscous silicone mixed with fine iron powder, (5) a subduction interface lubricant (applied to the entire subducting plate) representing weak sediments and serpentinised oceanic crust. No external velocities or forces were applied to the system, rather the model was left to evolve on its own allowing the slab negative buoyancy force to be the primary driving force of obduction.

Experiments indicate that the Tethyan style ophiolite obduction model is a mechanically feasible ophiolite emplacement mechanism that can be driven purely by negative slab buoyancy. Results indicate that increasing the continental crust thickness decreases the maximum horizontal obduction distance, passive margin depth and obduction velocity, whereas increased passive margin width and subducting lithosphere thickness resulted in increased maximum passive margin depth, horizontal obduction distance and obduction velocity. Negligible trench perpendicular shortening was associated with the obduction process. Model obduction velocities and horizontal obduction distances were found to be comparable with natural examples in Oman and Papua New Guinea. Our geodynamic models illustrate that the conceptual geodynamic model of Tethyan style ophiolite obduction as proposed for ophiolites found in the Tethyan region, but also in the Southwest Pacific (e.g. New Caledonia, New Guinea, New Zealand), is mechanically feasible.

CPO-P02. STRUCTURES ALONG THE SOUTHERN BOUNDARY OF THE PAPUAN ULTRAMAFIC BELT, EASTERN PAPUA

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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. Recent geological mapping and low-level airborne geophysical survey of the Keveri and Ada'u Valleys, Mt Suckling district, has improved our understanding of bounding structures along the southern margin of the PUB. A well-developed sedimentary record in the area is unlike anything else in the PUB and has been important in elucidating tectonic events.

The WNW-trending Keveri Fault is straight for much of its length and is the southern margin of the PUB in eastern Papua. Aligned streams and broad valley floors mark the trace of the fault in the braided Ada'u River, Bonua River and Domara River Valleys. The fault's trace in the Ada'u Valley is marked by an abrupt step in elevation immediately north of the river. The land surface rises rapidly to the 3 676 m high Mt Suckling, the highest mountain in eastern Papua. The fault is contiguous with the Owen Stanley Fault to the WNW. The Keveri Fault has several splays including the Nonia fault and flanking faults in the Keveri Valley. Significant vertical and lateral motion is documented along the fault. Uplift estimated at 2.5 m/10^3 a during the past 5 Ma continues today resulting in the 3 676 m high Suckling Dome. High rates of erosion associated with the uplift of Mt Suckling are manifest by braided streams, alluvial terraces, ultramafic breccias and numerous landslide and scree deposits. Strike-slip rates are estimated from the offset of tributaries of the Ada'u River, indicating the Keveri Fault has slipped dextrally at a rate of 30 m/10^3 a during the Holocene.

There is no field evidence at any scale of structures associated with thrusting, with the exception of a low-angle thrust fault of local significance noted in the Du'ubo Valley to the north of the Ada'u Valley and well within the PUB sequence. Similar observations have recently been published from the Dayman Dome ESE of Mt Suckling. Surface traces of the Keveri Fault and the Nonia fault correspond with the boundaries of magnetic bodies identified at depth by inversion modelling of total magnetic intensity data, indicating these structures may be vertical to at least depths of 7 to 10 km.

Tremolite with yellowish serpentinite boulders in I'eve Creek at the western end of the Keveri Valley indicate localised high temperature and pressure conditions along the Keveri Fault. A 16 m wide serpentinite zone is exposed within the Nonia fault in Dimidi Creek. The zone consists of massive/blocky serpentinite with brittle fracture, sheared serpentinite and talc. Large blocks of weakly serpentinised pyroxenite are present in the fault zone and they are interpreted as tectonic inclusions. The serpentinite zone carries anomalous Ni, Cr and Pt contents.

Mt Suckling has experienced low levels of seismicity, but in the period 1964–1989 two shallow (0–39 km depth) M5.0–5.9 events originated within the area. Both events plot along the Keveri Fault suggesting the fault is active and may present a seismic hazard.

CPO-P03. FILLING THE GAP: THE TECTONIC SIGNIFICANCE OF THE AYR CONGLOMERATE IN THE NEW ENGLAND OROGEN

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The Carboniferous Ayr Conglomerate Member of the Isismurra Formation is located in the Rouchel Block of the southern New England Orogen, Australia. It is unusual for having well-rounded pebble to boulder-sized clasts (up to 80 cm) in a succession otherwise dominated by sandstone and siltstone, and for containing a wide variety of igneous lithology that is not observed locally, including pink granitic clasts. Possible explanations for the origin of these clasts are that they are derived from unknown basement, an exotic terrane, or the Carboniferous Currabubula Volcanic Arc located to the west of the Rouchel Block. Petrographic, geochemical, and geochronological analyses of the clasts show they are compositionally and temporally related to an evolving magmatic system.

Petrographic data reveal the Ayr Conglomerate clasts are derived from volcaniclastic rocks, granophyres, and coarse-grained plutonic rocks, reflecting derivation from across a shallow crustal profile. Geochemical data show that the clasts are transitional between andesites in the footwall, to overlying calc-alkaline and high-K rhyodacitic ignimbrites. The andesites are derived from melting of a mafic source, possibly subducted oceanic crust, with hornblende in the residuum. The ignimbrites represent a continental magmatic arc with high crustal input. LA-ICP-MS U–Pb zircon age dates of 355.3 ± 7.5 Ma and 350.3 ± 4.4 Ma for two Ayr Conglomerate clasts indicate derivation from penecontemporaneous volcanism, consistent with the inferred age from stratigraphy.

Thus, results of this study suggest that the Ayr Conglomerate represents basin in-fill of volcanic detritus eroded from an evolving volcanic arc, and of subvolcanic granitic and plutonic equivalents exposed through extensional faulting of the crust. The apparent hiatus in volcanism represented on regional stratigraphic charts at the level of the Ayr Conglomerate is, in fact, due to erosion beneath the Ayr Conglomerate rather than an actual cessation of deposition. An unresolved conundrum is that the Ayr Conglomerate thickens to the east, whereas the arc, and thus the supposed source for the detritus, is in the west.

CPO-P04. REVISION OF RELATIVE PACIFIC PLATE MOTIONS AND IMPLICATIONS FOR THE HAWAIIAN-EMPEROR BEND

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Understanding the relative motion of the Pacific, Farallon, and Vancouver plates in the Cenozoic has important consequences for deciphering the relationship between absolute and relative plate motions in the Pacific Ocean basin, the history of circum-Pacific subduction and the cause of the Hawaiian-Emperor Bend (HEB). Whilst the tectonic evolution of the north and central Pacific basin has been previously explored, published relative plate motion models lack formal uncertainties, making it impossible to assess the statistical significance of any given tectonic event. Further, published models rely on *ca* 7 m.y. stage intervals (e.g. 40.1 Ma, 47.9 Ma, 55.9 Ma) around the timing of the HEB (*ca* 47.5 Ma), therefore are unable to closely capture temporal variations in spreading direction and/or rate.

We investigate the Farallon-Pacific and Vancouver-Pacific seafloor spreading history during the Middle Paleocene to Eocene (i.e. 62 Ma–33 Ma). We use Hellinger's best-fitting criteria, extended by Chang and co-authors to include uncertainties, to compute half-stage rotations based on an extensive dataset of magnetic and fracture zone identifications on the Pacific Plate. Finite rotations cannot be directly computed in this case due to the subduction of the conjugate Farallon ridge flank.

We find a well-constrained increase in Farallon-Pacific half-spreading rates at 55.9 Ma (chron 25y) from 34 ± 1 to 53 ± 2 mm/yr, followed by a stepwise increase to 80 ± 5 mm/yr by 43.8 Ma (chron 20o). No statistically significant change in spreading direction accompanies the increases in Farallon-Pacific spreading rates. We propose the initial acceleration in Farallon-Pacific rates (i.e. at *ca* 55.9 Ma) resulted from subduction initiation in the western Pacific basin at *ca* 55 Ma, causing slab pull to replace ridge push forces along the western perimeter of the Pacific plate. Our kinematic model indicates the acceleration of Farallon-Pacific spreading rates took at least 12 m.y. after subduction initiation to complete. This agrees with modelled mantle slab sinking speeds (50 km/m.y.; Butterworth *et al.* J. Geodyn. 2014) and the time necessary for the slab to reach the transition zone (8 m.y.) and base (further 5 m.y.).

The generation of the HEB cannot be related to relative or absolute changes in Pacific plate motion, based on the lack of statistically significant change in Farallon-Pacific spreading direction. This allows us to reject a recent suggestion (Koivisto *et al.* JGR 2014) that a combination of true polar wander and absolute plate motion changes are responsible for the HEB and the associated mismatch in paleomagnetically and hotspot track-derived paleolatitudes for the Emperor chain dated from *ca* 82 to *ca* 50 Ma. We attribute the formation of the HEB to a combination of the westward acceleration of the Pacific Plate postdating 49 Ma, well resolved by our model, and the previously suggested slowdown of the southward motion of the Hawaii hotspot. Further, by embedding our revised regional model in a global relative plate model, we can compute convergence directions and rates to refine the implied convergence history along the North American. This is particularly relevant for understanding the evolution of the Coast and Cascade Ranges.

THURSDAY 10 JULY

ENVIRONMENT

04EV-P01. COASTAL WETLANDS REVEAL A NON-SYNCHRONOUS ISLAND RESPONSE TO SEA-LEVEL CHANGE AND A PALEOSTORM RECORD FROM 5.5 KYR TO PRESENT

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Here, we describe environmental change on Lord Howe Island (LHI; 31°30′S, 159°05′E) over the last 5500 cal. BP, derived from the analysis of the accumulating sediments in four coastal wetlands. Grain-size analyses, loss on ignition (LOI) and micrometre-resolution X-ray fluorescence (XRF) geochemical data were combined with 10 accelerator mass spectrometry (AMS) ^{14}C dates to determine a chronology of environmental change. Sedimentary coastal features were initiated on the drowned LHI basalt coastline after *ca* 4500 cal. BP, which was followed by gradual development of wetland environments from 4200 cal. BP to present. Within this period, a series of high-intensity storm events are recorded, perhaps related to low-pressure systems, including cyclones and East Coast Low (ECL) events. A lack of synchronicity between the studied sites resulted from their position in the landscape relative to the coast, features within the lagoon and greater sediment availability after 2800 cal. BP as sediment filled sinks in the lagoon floor. Increasing westerly wind strength from 600 cal. BP also combined with late-Holocene falling sea levels and lagoon infilling to facilitate the rapid growth of the coastal plain at *ca* 500 cal. BP. The coastal wetlands of LHI preserve a record of rapid changes superimposed over more gradual environmental change since the mid-Holocene. The findings of this study further the understanding of the development of this 'World Heritage Area', as well as provide an increased understanding of how small oceanic islands respond to rising sea levels.

04EV-P02. ASSESSING TOPOGRAPHIC CONTROL ON SEDIMENT DEPOSITION PATTERNS IN COASTAL DEPOSITS

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High-energy coastal events transport large amounts of sediment and leave important signatures in the landscape. The configuration of the coastline and topography has a significant impact on sediment transport processes and the form of preserved features, and inundation patterns are affected by surface roughness and elevation. The aims of this research are to assess the flow patterns during deposition of a suite of coastal deposits, most likely related to historical tsunami, and assess the role of topography and landscape configuration on depositional patterns.

A set of anomalous sand deposits intercalated between buried soils was identified in Okains Bay; an embayed coastal plain in Canterbury, New Zealand, where tsunami inundation was experienced in 1868 and 1960. The study area is located 1.3 km inland from the coast on an estuary margin and comprises a flat area adjacent to the estuary, backed by coast-parallel relict dune ridges. Two sand layers were analysed using a combination of stratigraphy, particle size analyses and measurements of Magnetic Fabric (MF). MF was used to investigate the orientation and degree of alignment of particles within the sand layers, in order to ascertain the hydrodynamic conditions and direction of water flow during deposition. A Digital Elevation Model was constructed from a high-resolution differential GPS survey of the study area for comparison with flow pattern data.

Results show sand layers were deposited during two separate washover events from the estuary, with deposition patterns controlled by local topography. Deposition is constrained to the flat area at the estuary margin and a swale between two relict dune ridges. Flow directions inferred from MF results suggest deposition of the sand material occurred primarily during backwash, as water flowed back out towards the estuary. Deposits become thinner with increasing distance inland from the estuary and particle size results show reverse grading in the sand layers at three out of four sites. This is consistent with MF results, which suggest flow velocity increased over the period of deposition. This can be explained by the configuration and gradient of the topography. No evidence of inundation directly from the coast was found, which highlights the importance of river channels as inundation conduits during tsunami or other high-energy coastal events in areas where coastal and fluvial systems interact.

04EV-P03. MORPHOLOGICAL CONTROLS ON RIP CURRENT ESCAPE STRATEGIES

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Rip currents are a significant global beach hazard, being responsible for an average of 21 drownings annually in Australia alone. Recent studies have begun to address relationships between physical flow characteristics of rip currents and different types of escape strategies for bathers caught in rip currents. Laboratory research has shown that morphological beach state is a key driver of rip current intensity, peaking for Rhythmic Bar and Beach (RBB) states and decreasing as beach state transitions up towards Dissipative or down through Transverse Bar and Rip (TBR) and Low Tide Terrace (LTT) states. It is hypothesised that this intensity trend will also produce maximised rip current escape effort for RBB beaches compared to lower energy morphological beach states. A two-day field experiment testing swimmer escape strategies (swim parallel to the beach, stay afloat) at Cronulla Beach, NSW is examined to assess the validity of this hypothesis. In total 100 individual escape actions were attempted, 42 in a rip current system identified as mixed LLT/TBR (RIP1), and 58 in an RBB/TBR environment (RIP2). Across all escape strategies, escapes typically lasted longer ($\bar{t}$ = 4.5 min, σ = 0.4 min) and covered more distance ($\bar{s}$ = 150m, σ = 167m) in RIP2 when compared to RIP1 ($\bar{t}$ = 0.75 min, σ = 0.4 min, $\bar{s}$ = 30m, σ = 16m). The significant variation is considered to be a function of increased distance to safe footing as the lack of shore-connected bars for RIP2 required swimmers to travel a greater distance to safety. These conditions also produced a higher fail rate for attempted escapes, with 21% of all actions in RIP2 failing, as opposed to a 100% success rate for RIP1. The two prevailing safety messages are compared: swim parallel and stay afloat. Active actions (swim parallel) had significantly lower durations (RIP1 $\bar{t}$ = 0.5 mins σ = 0.3 mins, RIP2 $\bar{t}$ = 2.4 mins σ = 1.3 mins) compared to passive actions (floating: RIP1 $\bar{t}$ = 1.2 mins σ = 0.1 mins, RIP2 $\bar{t}$ = 9.6 mins σ = 10 mins), at the expense of higher average exertion levels. The viability of the successful actions is also assessed for a theoretical weak swimmer. Of the successful escapes, 90% are considered beyond the capabilities of a poor swimmer, owing to the distance or duration required to reach safety. This has important implications for predicting the level of rip current hazard based on observations of antecedent morphology and future development of rip current education and awareness strategies.

04EV-P04. A RECORD OF HOLOCENE SEA LEVEL CHANGE FROM BEACH RIDGES AT RED BEACH, FAR NORTH QUEENSLAND, AUSTRALIA

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There is currently a lack of detail from the Gulf of Carpentaria (GoC) about the timing and elevation of sea level fluctuations during and following the culmination of the Holocene marine transgression, and how the marginal marine environment responded to these sea level fluctuations. Such information is critical since this time period corresponds with the known record of human occupation within the region. At Red Beach, on the northern shore of Albatross Bay on the northeast coast of the GoC, a sequence of eight beach ridges are being investigated to try to fill this gap. Fifteen pits and two auger holes were dug along a transect perpendicular to the shoreline to describe the stratigraphy and interpret the depositional history of the area. It is hypothesised that this beach ridge sequence formed during three time periods in the mid to late Holocene. The innermost ridges formed during the culmination of the last post-glacial marine transgression, at approximately 6500 yr BP. The middle set of ridges formed during a sea level highstand that lasted to around 3000 yr BP where, as sea level stabilised, increased terrestrial input resulted in a prograding shoreline. The regression of sea level from 3000 yr BP to present day resulted in the deposition of the proximal suite of ridges at Red Beach. Preliminary radiocarbon age determinations on shell and OSL age determinations on quartz sand support this model.

04EV-P05. PALYNOLOGICAL EVIDENCE FOR THE EXTENSION OF MARINE INFLUENCE IN THE SOUTHERN FLINDERS RANGES, SOUTH AUSTRALIA, DURING LATE MIOCENE–EARLY PLIOCENE TIME

Liliana Stoian

Geological Survey of South Australia, Department for Manufacturing, Innovation, Trade, Resources and Energy

Palynological analyses and dating of rock samples from both outcrops and drillholes, collected from various sites in the southern Flinders Ranges, South Australia, indicate widespread occurrence of upper Miocene–lower Pliocene marine to marginal-marine sediments. Samples are correlated with the *Monotocidites galeatus* Spore-Pollen Zone (Macphail 1999).

Marine dinoflagellate cysts are present in the sediments collected from drillholes in Myponga and Meadows basins in the Mount Lofty Ranges. They were identified also in outcrop samples nearby Chapel Hill and Echunga Creek, and in the southern Flinders Ranges, in the Willochra and Walloway intramontane basins.

There are similarities in vegetation and depositional environments on all investigated sites. Wet *Nothofagus* rainforest patches developed in the Meadows Basin, Chapel Hill and Echunga Creek areas.

The pollen spectra of samples from MYP-4 drillhole, Myponga Basin, show an increase in numbers of Restionaceae and spores, with rare dinoflagellate cysts towards the lower part of the drillhole. Casuarinaceae and Asteraceae are present towards the top sequence where more lacustrine environments prevailed.

Changes in vegetation from wet *Nothofagus* rainforest to sclerophyll forest and open woodland vegetation dominated by Casuarinaceae, *Eucalyptus*-type, Chenopodiaceae, Asteraceae, Restionaceae are well documented in the samples from Meadows Bore 1. Dinoflagellate cysts indicate a marine influence and a sea-level change, with water depths of 20–60 m. Evidence of cooling is suggested by the presence of *Operculodinium centrocarpum*, a dinoflagellate cyst, with its modern relative present in cold-temperate zones. Other taxa are cosmopolitan and found in coastal zones and brackish environments. Coastal swamps and bogs developed in Meadows Basin, while an estuarine depositional environment prevailed at Chapel Hill.

Further north in the Willochra Basin outcrop samples representing gypsiferous siltstone from the Fossil Hill area contain pollen grains belonging to Chenopodiaceae, Asteraceae and Casuarinaceae, with rare Myrtaceae, Euphorbiaceae and Poaceae. Here vegetation consists of open grassland and open woodland with rare dry rainforest patches. Cool climatic conditions prevailed and opening of the vegetation, compared to the Mt Lofty Ranges area, is interpreted as due to a reduction in precipitation. An estuarine environment developed with input of fresh water and lacustrine conditions.

Core samples from Orroroo 5 well, Walloway Basin, indicate the presence of marginal marine upper Miocene–lower Pliocene sediments at a depth of 96 m below surface. The deposition was contemporaneous with orogenic activity during Miocene–Pliocene time and was controlled by the fault along the southwestern margin of the Walloway Basin. Pollen spectra include Chenopodiaceae, Asteraceae, *Eucalyptus* sp, *Nothofagus* mainly Brassospora group, with rare marine dinoflagellate cysts.

The significance and widespread occurrence of marine transgressions in the late Miocene–early Pliocene indicates that some part of the Flinders Rangers were uplifted more recently, only during the last 5–10 Ma. The climate changed and glacial and interglacial cycles can be identified.

There is a continuous decline of *Nothofagus* rainforest that was replaced by woodland and grassland.

The recognition and timing of relative sea level changes is crucial for modelling the shoreline evolution along the southern part of Flinders Ranges and neotectonic activity during the last 5–10 million years.

04EV-P06. HIGH-PRECISION U-SERIES DATING OF STORM-TRANSPORTED CORAL BLOCKS ON FRANKLAND ISLANDS, NORTHERN GREAT BARRIER REEF, AUSTRALIA

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High-energy storm-transported coral blocks are widespread on the reef flats of the inshore Frankland Islands, northern Great Barrier Reef (GBR). In this study, 45 individual transported coral blocks were collected for high-precision MC-ICPMS U-series dating, and 6 of them were repeatedly dated with different cleaning procedures to determine the initial $^{230}Th/^{232}Th$ ratio for the northern GBR using an isochron approach (data will be presented). The weighted mean of $^{230}Th/^{232}Th$ activity ratio (0.64 ± 20%) was recommended as a more appropriate value for initial detrital ^{230}Th corrections for U-series dating of coral samples from Frankland Reefs. Using the specific correction ^{230}Th method for young coral samples from inshore coral reefs as well as the two-component equation correction for both hydrogenous and detrital ^{230}Th, the mortality ages of these storm blocks were determined. Their ages match well with known historical cyclone events, and 80% of them fell in the relatively stormy periods (1910–1915, 1945–1950, 1955–1960, 1975–1990, 1995–2000 AD) in the last century, confirming that transported coral blocks on inshore reefs can be identified as useful proxies for past storm occurrences. This study identified 17 storm events that occurred before European settlement in the mid-nineteenth century that are not recorded. It is the first time that three storm events (758.4 ± 3.7, 777.9 ± 4.9, 985.2 ± 4.8), before the last millennium, were determined by dating transported storm blocks. Our results demonstrate that the tropical cyclone activity in the past century has a close relationship with the El Niño-Southern Oscillation (ENSO) and interdecadal time scale Pacific Decadal Oscillation (PDO) Index. The high-frequent stormy periods are significantly correlated with the positive/warm PDO phases, and there is a general absence of coral mortality ages during the negative PDO phases. In addition, some stormy periods are consistent with the cooler SST anomalies, suggesting the regional Sea Surface Temperature (SST) plays either a negligible role for major storms or at least a secondary role for storm activities. Additionally, there is a clear trend towards each zone increasing in age with distance inland from 758.4 ± 3.7 AD to 1988.3 ± 1.6 AD, which may be attributed to the effect of sea-level change and coverage of beach and intertidal deposits.

04EV-P07. MAPPING SOIL SALINITY AND PH ACROSS AN ESTUARINE AND ALLUVIAL PLAIN

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Owing to increasing pressures from agriculture and urbanisation many floodplains along the southeast Australian coastline, which are underlain by sulfidic sediments, are drained to lower water tables and reduce soil salinity. Unfortunately, this leads to oxidation of the sulfidic sediments and a rapid decline in pH and ironically an increase in salinity. Accurately mapping soil salinity and pH in coastal acid sulfate soil (CASS) landscapes is therefore important. For example, mapping the extent of extremely acidic (i.e. pH <4.5) areas, is necessary because remediation with alkaline amendments (e.g. lime) to neutralise the acid produced can be specifically targeted where the variation in pH is known. One approach is the use of digital soil mapping (DSM) using ancillary information, such as an EM38, digital elevation models (DEM – elevation) and trend surface parameters (East and North). Herein we use an EM38 in the horizontal (EM38h) and vertical (EM38v) modes in combination with elevation data to first develop multiple linear regressions (MLR) to predict $EC_{1:5}$ and pH. For pH the best results are achieved when the EM38 EC_a data is first log transformed. By comparing MLR models using log likelihood analysis we found that using all covariates is optimal for mapping $EC_{1:5}$, whereas the best predictors for pH are North, logEM38v and elevation. Using residual maximum likelihood (REML), the final $EC_{1:5}$ and pH maps produced are consistent with previously defined soil landscape units and in particular CASS. The DSM approach used herein is amenable therefore for evaluation and in terms of mapping saline soil conditions and identifying areas requiring the application of lime to ameliorate and thereby manage acidic soil conditions in CASS landscape.

ENERGY

04EG-P02. HYPERSPECTRAL CORESCAN™ APPLICATIONS FOR COAL

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Corescan™ hyperspectral technology was applied to upper Permian coals from the Bowen Basin. Hyperspectral loggers can provide information on the mineralogy of coal and interburden using visible and near (VNIR), short wave (SWIR) and thermal (TIR) infra-red wavelengths. Corescan™ technology currently operates in VNIR and SWIR from 450 to 2500 nm and is used for automated virtual logging of core data from iron ore, copper–gold and other hard rock projects; but it can also be applied to coal geology. Corescan™ can perform profile and 30 mm swath scans at 0.5 mm intervals to produce high-resolution mineral maps. By comparison, Hylogger™ provides profile scans at 8 mm spacing that can be interpreted to produce mineralogy logs at meter scale resolution. Five upper Permian coal cores from the Bowen Basin were selected for their variability in rank and mineral matter and scanned with Corescan™ technology. The data was processed at the Coreshed™ virtual warehouse data storage facility. Coreshed™ provided a laser core profile, true and false colour spectral images, core photography, mineral class map, mineral abundance/purity maps for each mineral identified, organic matter abundance/purity map, and three organic slope maps for each core. Corescan™ effectively detected carbonates and clay minerals in coal cores, although it did not detect quartz and feldspar spectra that require TIR, nor trace minerals rutile, pyrite and apatite with grain size smaller than the 0.5 mm pixel resolution. The mineral content of the cores was confirmed by QEMSCAN, XRF, petrography and XRD. Additionally, the spectral organic abundance and organic slope maps potentially correlated with coal lithotypes and thermal maturity. Naturally coked coal was also identifiable. Hyperspectral core scan technologies can provide rapid, accurate, non-destructive, automated characterisation methods for mineral and organic matter in coal cores. In combination with other coal characterisation techniques, this information can assist in local to regional correlation; identifying zones of deleterious clays that can reduce borehole stability or generate fines, and properties that affect reservoir behaviour of coals and interburden, with potential application for in-stream processing and quality control.

04EG-P03. MAPPING BURIED STRUCTURES USING *IN-SITU* MEASUREMENTS OF SOIL HELIUM

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Elevated He is commonly associated with hydrocarbon and some U-bearing deposits. Being chemically inert, He tends not to be absorbed by mineral material and is highly mobile. Helium movement through sedimentary rocks and regolith is largely controlled by permeability but may be affected, at various time frames, by the amount of pore water or soil moisture and other climatic factors such as air pressure. Faults and fractures can act as preferential pathways for the migration of He.

The study area near Dalby in southern Queensland contains a series of hydrocarbon deposits (mainly coal bed methane) hosted in deformed sedimentary units. Most areas are overlain by alluvium with depths up to 50 m. The land is used for agricultural purposes and is regularly ploughed. *In-situ* measurement of He, using a (portable) Varian PHD-4 detector, were made on a 200 x 200 m grid and some higher density traverses at the soil surface and in subsoil (70–80 cm depth) using thin tubes hammered into the ground. The effect of other gases on the He response in the PHD-4 device has been tested, including CO_2, H_2S, SO_2, CH_4 and C_3H_8.

Helium values range from ~5 ppm to >500 ppm. The spatial patterns suggest He is leaking (vertically) through the alluvium along conjugate fault structures. There is high correlation but large differences between surface and subsoil values. Irrigation of the fields suppressed the He soil concentrations, but did not affect the general trends in the He patterns. The He values are exceptionally high when compared with previous soil-He studies conducted in Russia, the US and Australia and may in themselves constitute a resource.

04EG-P05. MULTISCALE GEOMODELLING IN THE COAL-BEARING GLOUCESTER BASIN, NSW

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CSIRO Earth Science and Resource Engineering

Sound modelling of subsurface geology is necessary to assess the potential interaction between Coal Seam Gas (CSG) reservoirs and aquifers. Evaluating the lateral variation of stratigraphy and of the impact of structures has the potential to significantly impact CSG exploration and production strategies. Several approaches classically applied to conventional hydrocarbon exploration/production have been incorporated to assess the subsurface architecture and the impact of faults on coal seam connectivity from basin- to prospect-scale in the coal-bearing Gloucester Basin, NSW.

Isopachs were used to define the basin-scale sequences' architecture in the absence of available seismic data or reliable geological cross-sections. This approach enabled uncertainties linked with the existing stratigraphic correlations to be overcome. Each isopach was calibrated using the well picks at the formation scale and constrained by trends observed within each interval. Definition of a reference horizon and the stacking of the isopachs resulted in an initial unfaulted geomodel. Multiple realisations of this workflow allowed calibrating the uncertainties on the formations thicknesses, structure and depth.

To test the validity of the interpretation of the larger faults in the basin and determine the potential impact of subseismic resolution faulting in the Stratford CSG Prospect area a fault population was derived from published fault populations. The population was used to constrain the fault interpretation in the basin-scale geomodel. A subseismic dataset conditioned by the fault population was used to test the potential impact faults could have on the connectivity of geobodies at the scale of a prospect.

Data from six recent wells near the Stratford Prospect were used to stochastically model potential stratigraphic facies of the Late Permian coal-bearing Wenham Formation. After faulting the facies model where applicable, the number, size, and connectivity of coal seams were investigated for various scenarios: (i) unfaulted; (ii) totally sealing faults (e.g. cemented faults); (iii) leaking faults (e.g. reactivated/permeable faults), and (iv) faults with a membrane seal capacity derived from the Shale Gouge Ratio. Initial results expectedly showed that the unfaulted scenario yielded the largest connected coal seam, however the totally sealing fault and membrane seal scenarios yielded the highest number of coal seams with volumes between 1000 m^3 and 1 000 000 m^3. The prospect-scale geomodel allowed assessing the lateral variation in the distribution of the coal seams, the distribution of channel system, and highlighted the risk of mis- or over-correlation of facies in a delta plain environment.

RESOURCES

04RE-P01. RE–OS AGE FOR ARCHEAN MOLYBDENITE AND ^{40}AR/^{39}AR DATING OF SERICITE FROM GOLD PROSPECTS IN THE YAMARNA TERRANE, FAR EASTERN PART OF YILGARN CRATON, WESTERN AUSTRALIA

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Gold deposits are numerous and well endowed in the Yilgarn Craton of Western Australia, forming as a result of orogenic events during the Archean. The new gold prospect is located on the eastern-most margin of the Yilgarn Craton, within the Yamarna Terrane. This is the first known gold prospect within the eastern edge of the craton, and its age would be critical in establishing the prospectivity of this terrane for further gold exploration.

The molybdenite samples in this study come from: (1) Central Bore gold prospect situated within the Yamarna-Mount Gill greenstone belt. Here, gold is closely associated with molybdenites, found as veins and inclusions inside this mineral. (2) Dorothy Hills greenstone belt, further east near the Ziggy Monzogranite. In this location, the molybdenite was found in a quartz vein within granitic gneiss and did not show any association with gold.

The ^{187}Re/^{187}Os ages were determined for molybdenites from both settings. The analytical work was performed in the John de Laeter Centre at Curtin University using the Carius tube digestion technique. Mass spectrometry for both Re and Os was performed using a TIMS Triton. The Re–Os ages for the Dorothy Hills molybdenites average 2820 Ma, in excellent agreement with a 2832 ± 4 Ma U–Pb zircon age for the monzogranite intrusion in the area.

In the Yamarna-Mount Gill greenstone belt, Re–Os molybdenite age is 2620 Ma. This age is close to the U–Pb zircon ages of felsic volcanics (2677 ± 7 Ma) and sandstones (2682 ± 5 Ma) from the Yamarna Terrane, and close to the peak gold deposition event (*ca* 2640 Ma) in the majority of gold deposits from the Yilgarn Craton.

The ^{40}Ar/^{39}Ar geochronometry in associated sericites was applied in order to provide an independent age constraint on the timing of hydrothermal gold mineralisation. One sericite sample from the Dorothy Hills greenstone belt yielded a ^{40}Ar/^{39}Ar plateau age of 2440 ± 38 Ma. The other three sericite samples (from both greenstone belts) show evidence for a disturbance event at *ca* 2100 Ma.

As a conclusion, the Re–Os age of molybdenite and associated gold mineralisation within the Central Bore gold prospect from the Yamarna Terrane, located on the eastern margin of Yilgarn Craton, may correspond to the peak gold mineralisation event observed in the rest of the Yilgarn greenstone belts. In turn, it implies that this part of

Yilgarn may contain highly prospective terrains for gold. Moreover, our study confirms the robust nature of the Re–Os geochronometer in molybdenite and its potential application for metamorphosed Archean terrains.

04RE-P02. PROSPECTIVITY ANALYSIS OF FELSIC VOLCANIC ROCKS FROM THE ARCHEAN YILGARN CRATON, WESTERN AUSTRALIA: IMPLICATIONS FOR VOLCANIC-HOSTED MASSIVE SULFIDE (VHMS) MINERALISATION

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Following the 1963 discovery of the giant Kidd Creek Cu–Zn deposit in Canada, significant VHMS exploration activity occurred in the Archean Yilgarn Craton of Western Australia during the 1960s and 1970s. One substantial find was made at Gossan Hill in 1971 and a smaller but higher grade deposit at Teutonic Bore in 1976. By the early 1980s, the lack of success and an increasing gold price saw a change in focus, and VHMS mineralisation effectively dropped off the exploration agenda in Western Australia for the next 25 years. To this day the total Yilgarn resource remains substantially less than similar Archean provinces of Canada (e.g. Superior) and, perhaps unsurprisingly, there has been much discussion about whether the Yilgarn is underexplored or intrinsically impoverished.

We have used a compilation of felsic whole-rock geochemical data (n = 642) to identify common associations to mineralisation and additional areas of interest for exploration. VHMS-bearing units in the Yilgarn Craton are similar to those of the VHMS-rich camps of the Abitibi greenstone belt and the Pilbara Craton of Western Australia. They are characterised by low Zr/Y, La/Yb_{CN} and Th/Yb ratios, high Sc/TiO_2, Sc/V, HFSE and HREE contents, and flat HREE profiles. Chondrite-normalised REE profiles for felsic rocks overlying 2.82–2.80 Ga plume-related basalts (= Greensleeves Formation) and large igneous complexes of the Youanmi Terrane (= Kantie Murdana Volcanics Member) are flat. Other VHMS-bearing felsic rocks are characterised by slight LREE enrichment (La/Sm_{CN} <3) and flattish HREE profiles. Felsic rocks of the Youanmi Terrane have higher Th/Yb values at given Zr/Y and La/Yb than felsic rocks from the Abitibi greenstone belt, consistent with the extended crustal recycling in the Youanmi Terrane, and its more evolved nature. In addition to areas associated with base-metal mineralisation (e.g. Golden Grove, Jaguar, Hollandaire, Dalgaranga), felsic rocks with VHMS prospective geochemical signatures have been identified across the Yilgarn Craton, including at Abbotts, Big Bell, Gullewa and Marda in the Youanmi Terrane, Bore Well in the Kurnalpi Terrane, and Mount Gill in the Yamarna Terrane. This data, coupled with the continued discovery of new deposits (e.g. Hollandaire, Austin, Bentley, The Cup), suggests the Yilgarn Craton is underexplored as opposed to intrinsically impoverished in VHMS mineralisation.

04RE-P02.01. Magmatic Ni-PGE Mineral Systems Framework for Australia: Magmatic Events and their prospectivity

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The search for world-class magmatic Ni-PGE resources requires a systems framework at the continental scale of the magmatic systems themselves, from the mantle to their intrusion in the explorable shallow crust. Geoscience Australia's new GIS of Australian Mafic-Ultramafic Magmatic Events, now completed from the Archean to the present-day, provides this framework. With the newly-completed Phanerozoic record added to the pre-existing Archean and Proterozoic products, this is now the most comprehensive digital magmatic event record available for any continent. The time-space-event distribution expresses the role of the mantle and mafic-ultramafic magmatism in the geodynamic development of the Australian continent, and is the basis for correlation with other continents. It also highlights the mineral system prospectivity of specific magmatic events by their extents, crustal locations, ultramafic components, known mineralisation, and co-location in space and time with other important indicators.

The chronology of Australian magmatism, ranging from the Eoarchean ~3730 Ma Manfred Event, confined within a domain of the Yilgarn Craton, to the widespread record of Cenozoic magmatism in eastern Australia, resolves into 74 magmatic events identified by coeval magmatism within ±10 million year bands. They range in magnitude from the giant volumes of magma in Large Igneous Provinces to events whose only known occurrence is a single dated rock. Explorers are encouraged to use the GIS to analyse specific events in context with other information, such as geochemistry, crustal architecture, lithosphere thickness, possibly reactive country rocks, the spatial distribution of erupted versus intruded magmatic components, geological setting, etc.

The Australian magmatic record draws attention to concentrations of mafic-ultramafic magmatism in three distinct periods: in the Archean from ~2820-2665 Ma; in the Proterozoic from ~1870-1590 Ma; and in the Palaeozoic from ~530-225 Ma. These three narrow periods contain 39 of the 74 magmatic events, 53% of the entire mafic-ultramafic magmatic event record of the continent. Relating these to crustal architecture narrows the intrusion focus of this activity to specific paleo-margins preserved within the continent which repeatedly focussed the passage of large volumes of magma through the lithosphere. A Proterozoic example of this is provided by the east margin of the Yilgarn Craton, host to the Proterozoic-age Nova magmatic Ni deposit recently discovered under shallow cover. Similar architecture focussed other major magmatic events through time. We draw attention to the time-space-event context of the Cambrian-age Kalkarindji Large Igneous Province, which provides insight into the continent-scale passage for gigantic volumes of magma through the shallow crust, offering a prospective focus for magmatic mineral system exploration.

The newly completed GIS of Australian Mafic-Ultramafic Magmatic Events is a fundamental framework within which to integrate other geological, geochemical and geophysical datasets, and to evaluate pointers to under-explored and potentially mineralised magmatic domains in the continent.

04RE-P04. SEAMLESS GEOLOGY OF NEW SOUTH WALES

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The vision of the Geological Survey of New South Wales (NSW) Statewide Seamless Geology Project is to compile the best available geological data into an internally consistent geodatabase. Historically, data capture by the Geological Survey of NSW has been restricted to regional mapping projects, which has resulted in the creation of regional datasets that are somewhat irreconcilable at a statewide level. Mapping also largely focussed on documenting the exposed geology, with little attempt made to project rock units or structural features under cover. Owing to this approach, interpretation of the NSW basement geology under cover is also limited.

The overarching aims of the Statewide Seamless Geology Project are to: (i) compile the different original scales, formats and rock unit naming conventions into a consistent, statewide format; (ii) edge-match the geology across existing map sheets; and (iii) interpret the basement geology under cover. The resulting geodatabase will comprise a series of layers, which will include: (i) solid basement geology; (ii) cover rocks (defined as undeformed and unmetamorphosed); (iii) Mesozoic igneous rocks; and (iv) Cenozoic sedimentary and igneous rocks. The basement geology layer will be further subdivided into: (i) rock units; (ii) metamorphic grade; and (iii) finite strain record.

Critical to our approach is the development of an accurate solid basement geology layer that will provide a single point of truth. This will involve compiling best available maps for integration with new geophysical interpretations and field mapping. Compilation of mapping data will have three main challenges, namely: (i) edge matching of geological features across pre-existing map sheet boundaries; (ii) integrating mapping data that has been captured at different scales, and; (iii) harmonising stratigraphic units across NSW. Once completed, the resulting geodatabase will provide an important reference tool in the form of a dynamic database (as opposed to a static map) that can be interrogated at a range of scales. The solid geology will also provide a powerful tool for mineral explorers, allowing exploration companies to ‘peek’ under cover to assess the possibility of basement mineralisation. In the past, undercover parts of the state have remained as basement ‘blank spots’, thus rendering them potentially underexplored.

A further dimension to the project is the internally consistent nature of the database, where data layers will be stitched to the basement layer. This will allow geological boundaries to be interrogated at several levels (i.e. the nature of a geological boundary with respect to lithology, structure, metamorphism and time). This will be done by capturing vector data from the basement geology database and integrating it into another data layer. For example, if a metamorphic facies boundary is defined by a fault or a lithological contact, then vector data will be copied from the basement layer and pasted into the metamorphic layer. As a result, data layers will be spatially consistent across the statewide seamless database.

The databases will be rolled out on a zone by zone basis, with work commenced on zone 56 early in 2014.

04RE-P05. THE AUSTRALIAN STRATIGRAPHIC UNITS DATABASE – MAINTAINING QUALITY DATA BEHIND THE SCENES

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The Australian Stratigraphic Units Database (ASUD) is a publicly available database maintained by Geoscience Australia staff in co-operation with the Australian Stratigraphy Commission and the State and Territory Geological Surveys. The ASUD provides an authoritative source of information on Australian stratigraphy, and underpins a variety of geoscience products including the Seamless 1:1 M Surface Geology of Australia map and the recently-released Geological Provinces dataset. Checks against ASUD are required prior to release of national and regional datasets from Geoscience Australia, and State and Territory Surveys also review their usage against this national database.

The ASUD aims to provide information on the stratigraphic units used in Australia: which ones are current; their age; how they relate to each other; how one unit is distinguished from another, which references discuss which units, etc. We do this by indexing publications, maps and datasets. We apply a QA process of reviewing, data entry and final checking before data is made available to the public. The quality and quantity of information in ASUD is limited by the quality of the material we index. Maps are appropriate for briefly introducing new units, but they need to be followed up with broader descriptions, usually done in Explanatory Notes. Specialist studies may provide age or other data that help to explain units or regional settings, but it is important for these papers to use the current stratigraphic unit names, and it is always important to spell the names correctly.

In 2013 there were 88 names reserved, 93 reserved names published, 197 current informal names added and 352 misspellings or probable misspellings added to the database. We try not to add misspellings if it is clearly a one-off typo, but a frustrating number of publications are inconsistent, or consistently wrong, so they are indexed to try to avoid perpetuating errors. Inconsistencies in naming units within an article (even within a paragraph!) are common. Once a mistake is published, it has the potential to persist in the literature. Such errors cause confusion and give rise to doubts about the science quality.

Complications occur when a unit has its rank changed (eg Suite to Supersuite; Member to Formation). The ASUD will always lag behind publication, despite a priority system that expedites processing of new names and redefinitions. There is a substantial backlog of items awaiting indexing, including the pre-digital card file system, which is not fully entered into ASUD.

Every author has the primary responsibility for the accuracy of his/her published work. Stratigraphic names can be checked individually against ASUD or, depending on the number of names, against easily-downloadable State lists. Downstream QA checks by peer reviewers and editors should also include the minutiae of checking stratigraphic nomenclature for accuracy and consistency.

We welcome feedback and notification of new maps, reports and publications that include stratigraphic definitions.

04RE-P06. GUIDING FIELD MAPPING WITH INTERGRATED DIGITAL MAPPING AND MODEL BUILDING

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Midland Valley Exploration

The collection of field data in a geo-referenced digital environment allows the user to integrate multiple data types, which can then be quickly referred to in the field. Digital field collection can be advantageous over paper collection by facilitating rapid digital communication with off-site researchers (i.e. digital reports and e-mails compiled while in the field), as well as preserving the thought processes in more detail. For example, the seemingly simple practice of copying and annotating a field sketch can improve the clarity of field notes by showing multiple stages of an interpretation that has been refined and tested. Providing a more complete picture of the thought process used to develop an interpretation may also allow researchers to target areas of uncertainty or incompletely tested hypotheses.

This poster will examine the use of new digital smartphone and tablet devices for the collection of geological field data and model building. Apps such as Midland Valley Exploration's *FieldMove Clino* enable the geologist to use their smartphone as a measuring device rather than a traditional compass-clinometer. A further advantage is that the field notebook and camera – essential components of the geologist's tool kit – are now an integral part of this new technology. The time saved by the geologist by collecting data digitally can be spent on model building and analysis, reducing risk and highlighting areas of uncertainty with the dataset. This iterative process, where maps, sections and 3D models are worked on together helps to guide the fieldwork effort.

04RE-P08. BIOGEOCHEMICAL CYCLING OF IRON IN CANGA ECOSYSTEMS

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Giant supergene iron ore deposits result from the protracted weathering of banded iron-formations (BIFs). An indurated and goethite-cemented duricrust (also known as canga) covers lateritic profiles overlying BIFs (Dorr 1964). In the Quadrilátero Ferrífero and Carajás Mineral Provinces, Brazil, elevated plateaus are blanketed by canga that varies from 1 to more than 30 m in thickness (Dorr 1964). While the canga layer is extremely resistant to erosion, the weathered BIF underneath is friable and easily eroded. Goethite and hematite cementation is the main process leading to canga formation. Dorr (1964) first suggested that the biogeochemical cycling of iron was important to the formation of canga. Monteiro *et al.* (2014) showed that the recurrent goethite dissolution and recrystallisation in cangas is mainly driven by the only freely available source of reducing agents at the Earth's surface, the biota. Therefore, identifying iron-reducing and iron-oxidising organisms and understanding the biological factors involved in this process is crucial to constrain the biological parameters controlling canga formation.

Our research suggests both past and present biological cycling of iron within canga. Electron microscopic analysis reveals canga structures that are likely to have been formed by iron oxidising bacteria. Metal analysis of perched water pockets above canga revealed low concentrations of dissolved Fe (up to 20 ppm) that quickly drops out of solution at the canga surface. Cultivation-based approaches readily yield both iron reducing and iron oxidising bacteria from canga suggesting that an active biogeochemical cycle of Fe exists within canga. Our current work focuses on harnessing this natural microbial potential to promote formation of canga in a laboratory setting. Long term, we expect that restoration of mined iron ore sites should be achievable through promotion of the natural biogeochemical processes occurring in canga.

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04RE-P09. THE BIOGEOCHEMICAL CYCLING OF GOLD: IMPLICATIONS FOR SUPERGENE PROCESSES

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The examination of field samples and samples from aqueous laboratory-based experimental systems demonstrate that bacteria can have a profound effect on gold solubilisation, immobilisation and accumulation. Bacteria initiate the cycling of gold by promoting the biogeochemical weathering of gold-bearing metal sulfide minerals. Acidophilic iron- and sulfur-oxidising bacteria produce thiosulfate ligands as an intermediate oxidative product that is important in gold complexation producing gold(I)-thiosulfate. While this aurous complex is generally stable under S-oxidising conditions, gold thiosulfate in highly reactive in the presence of iron-oxidising bacteria and results in the formation of nanometre-size colloidal gold. Similarly, gold(III)-chloride can be also be produced under oxidative weathering conditions. However, destabilisation of this auric complex by 'organic compounds' such as iron- and sulfur oxidising bacteria, cyanobacteria and sulfate-reducing bacteria results in the bioprecipitation / immobilisation of gold as elemental, nanophase to micrometre-size, colloidal and crystalline octahedral gold platelets. It should be noted that because of the extremely small sizes of these materials, they could still be mobile under surface and near-surface environmental conditions. Within natural and experimental systems, the formation or occurrence of soluble gold complexes should be viewed as a dynamic albeit a transient phenomenon. Under surface and near-surface environmental conditions, gold will predominantly occur as secondary gold. When bacteria develop as a structurally cohesive biofilm, reduction and enrichment of gold can occur and produce macroscopic gold structures including foils and grains, and presumably nuggets. Therefore, bacteria can have profound effects on the occurrence of gold in natural environments as long as nutrients necessary for microbial metabolism are sustained and gold is in the system. Our studies suggest that the direct and indirect biogenic effects on gold biogeochemistry will persist over geological time forming observed anomalous gold-enriched concentrations such as supergene gold deposits. High-resolution scanning electron microscopy analysis of gold grains, obtained from Kilkivan, Australia, demonstrates the occurrence of nanophase gold particles embedded in detrital material on the surface of grains. Gold particles include colloidal gold, octahedral platelets and 'bacteriomorphic' structures. Collectively, these secondary structures represent dissolution and reprecipitation processes occurring at the interface between the grain surface and detrital material. Characterising these secondary gold structures, in association with understanding how biogeochemical conditions, contribute to gold dispersion are critical for improving gold exploration as it has practical application in vectoring towards potential ore deposits.

04RE-P10. DID BACTERIA IN AN ANOXIC BRINE BASIN FORM PALEOPROTEROZOIC COBALT-PYRITE DEPOSITS NEAR BROKEN HILL?

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Cobalt-pyrite deposits near Broken Hill occur as disseminated, banded and semi-massive sulfide horizons within widespread quartz–feldspar gneiss of the Himalaya Formation, an upper unit of the Thackaringa Group. This largely quartzo-felspathic package of Paleoproterozoic gneisses, pelites and schists underlie the host rocks of the giant Broken Hill Ag–Pb–Zn deposit. The sulfide deposits form a deformed stratabound unit with outcrops spanning more than 10 km in the study area, centred 25 km southwest of Broken Hill township.

Cobalt content of pyrite throughout the deposits is relatively uniform and is mostly between 0.45–0.55% Co. Cobalt-pyrite typically comprises between 10–30% of the pyritic gneiss. Base metal sulfides and other cobalt-bearing minerals are usually very rare, and quartz and albite (Na-feldspar) are the predominant silicates in much of the mineralised rock.

A syngenetic model is proposed where a precursor sulfide accumulated in fine-grained sediments on a sea floor beneath saline anoxic waters of a Paleoproterozoic basin. Subsequent metamorphism and tectonic disruption failed to destroy the stratabound nature of the deposits, significantly alter their chemistry or destroy some of their sedimentary textures.

Present day analogues of the Broken Hill deposits occur as deep basinal brine-lake depressions near the middle of the Mediterranean Sea (e.g. Urania and Medee basins) where anoxic brines host a prolific community of halophilic microbes that live in the extreme methane-enriched and oxygen-poor water. Within the anoxic water column of many deep hypersaline anoxic basins species of magnetotactic bacteria have been identified. These bacteria reduce sulfate to form minute elongated chains of magnetic greigite (Fe_3S_4) crystals. Greigite crystals are embedded within each magnetotactic bacterium (spirillum) and allow each microbe to rotate and reposition using the magnetic properties of the sulfide.

The bacteria make use of the Earth's magnetic field, which provides each spirillum the movement to maintain its preferred habitat relative to the oxic–anoxic transition and to accommodate chemical variability within the Urania seawater column. Given optimum conditions and suitable nutrition the bacteria rapidly multiply to form microbial blooms. Post-bloom dead bacteria cells, still with contained greigite, settle to form a considerable proportion of the sulfide on the Urania sea-floor where greigite forms microscopic isometric hexoctahedral crystals and minute sooty masses. Greigite, similar in appearance to pyrite, transforms to the more stable sulfide as diagenesis proceeds.

Cobalt is used to produce strong magnets and when incorporated into the greigite crystals in each spirillum it may have provided a more powerful engine for the Paleoproterozoic bacteria to manoeuvre. During relatively ice-free periods, influx of BIF iron and volcanic sulfur into the ancient sea could have provided a nutrient mix, which encouraged vigorous reproduction and growth of microbe blooms to enable the accumulation of considerable thicknesses of cobalt-rich sulfidic detritus.

Quartz–albite gneiss with disseminated and layered cobaltiferous pyrite formed after diagenetic and metamorphic alteration of the sodium and silica-rich sulfidic sediments.

DYNAMIC PLANET

04DP-P01. ZIRCON U–PB–HF–O ISOTOPE EVIDENCE SUGGESTS THAT MESOARCHEAN CRUST FORMATION DOMINATED EARLY GROWTH OF THE NORTH AUSTRALIAN CRATON

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The North Australian Craton is one of three large Precambrian Australian cratonic blocks, the others being the West Australian and the South Australian cratons. The Archean crustal evolution of the North Australian Craton is little known, owing to limited age and isotopic studies of both its Neoarchean basement and, to a lesser extent, of its younger, Paleoproterozoic orogens and basins. The O isotope character of zircon can be used to distinguish those that crystallised from mantle-derived sources from those derived from reworked sedimentary sources. Coupled with U–Pb and Hf isotopes, this allows an assessment of the timing of formation of crust by separation from the mantle. We investigated the Archean evolution of the North Australian Craton using zircon U–Pb–Hf and O isotopes from samples of the few known exposed areas of Archean crust. The Archean basement comprises *ca* 2670 Ma, 2640 Ma and 2550–2510 Ma monzogranite and granodiorite, exposed as inliers in the Pine Creek Orogen (Rum Jungle Complex, Nanambu Complex, Kukakak Gneiss, Arrarra Gneiss, Woolner Granite, Njibinjibinj Gneiss) and the Tanami Region (Billabong Complex). These inliers may represent parts of a contiguous Neoarchean crust under cover of younger metasedimentary successions, or perhaps more likely, they may be rifted fragments of a common Neoarchean craton that re-amalgamated during Paleoproterozoic orogeneses in the period *ca* 1870–1840 Ma.

The 2674 Ma Woolner Granite and 2671 Ma Njibinjibinj Gneiss are characterised by dominantly mantle-like zircon δ^{18}O (δ^{18}O = 5.1–7.4‰), but have distinct Hf zircon isotope signatures. The Woolner Granite has radiogenic Hf zircon (εHf_t = +8.5 to +4.3) consistent with a Neoarchean (*ca* 2.75 Ga) mantle-derived source, whereas the Njibinjibinj Gneiss shows a broad vertical unradiogenic zircon Hf array (εHf_t = –2.5 to –9.0), consistent with mixing between Eoarchean and Mesoarchean or younger sources. The 2640 Ma Arrarra Gneiss has mantle-like zircon δ^{18}O (5.0–6.5‰) and dominantly radiogenic zircon Hf (εHf_t = +3.3 to +1.8) consistent with derivation from Mesoarchean (*ca* 3.2–2.9 Ga) mantle-derived sources. The 2510 Ma Billabong Complex again has mainly mantle-like zircon δ^{18}O (2.0–6.5‰) and dominantly unradiogenic Hf (εHf_t = +2.1 to –5.1), consistent with derivation from a range of mainly Mesoarchean (*ca* 3.3–2.9 Ga) mantle-derived sources. In contrast magmatic zircon from the 2535 Ma Waterhouse Complex and 2530 Ma Kukalak Gneiss have comparatively higher δ^{18}O (6.0–8.9‰) and dominantly unradiogenic Hf (εHf_t = +0.1 to –6.6), consistent with magmatic reworking of older crust with a significant sedimentary component. These data indicate heterogeneity in the sources to Neoarchean basement to the North Australian Craton. However, there is consistency in Mesoarchean Hf crustal residence ages for most of the zircon with mantle-like δ^{18}O from the three recognised phases of Neoarchean magmatism. These data indicate that Mesoarchean crust formation is likely to have been an important era in the growth of the North Australian Craton.

04DP-P02. ZIRCONS FROM YAKUTIAN KIMBERLITES REVEAL ARCHEAN CRUST UNDER THE EASTERN SIBERIAN CRATON

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Kimberlite magmatism is widespread across the Siberian Craton. The Yakutian kimberlite province has both diamond-bearing and non-diamondiferous fields. Kimberlite pipes are not only economically important, but also provide samples of the lower crust and underlying subcontinental lithospheric mantle (SCLM) across the craton. Previous reports indicate a general decrease in the age of the crust from SW to NE: Archean crust is recognised in the Tunguss province in the western part of the Siberian Platform (3.3–2.6 Ga; Smelov & Timofeev 2007) while the E. Olenek province consists of Proterozoic crust (Birekta, Khapchan terranes, 2.4–1.8 Ga; Griffin *et al.* 1999; Rosen *et al.* 1991). The Anabar and Aldan provinces in the central part of the craton yield both Archean and Proterozoic ages. However, the available age information mainly represents the upper crust, while several studies of lower-crustal xenoliths from volcanic rocks have demonstrated that parts of the deep crust may be significantly older than the exposed upper crust, and that the lowermost crust may have been formed still later through underplating of mantle-derived magmas, accompanied by heating and remelting of older lower crust (Griffin *et al.* 1999).

Zircons were extracted from heavy mineral concentrates obtained by panning of detrital material from creeks draining kimberlitic pipes. More than 400 zircons from different kimberlitic fields of the Siberian Craton have been described, mounted, imaged and analysed for U–Pb age, Hf-isotope and trace-element composition. Integration of different techniques provides information not only on the timing of magmatic/metamorphic events, but also gives model ages for the protolith(s) and the possible type of host rock reflected in the trace-element composition o each zircon. U–Pb age results for the western part of the Siberian Craton show good agreement with previously available data. On the other hand, the ages from the eastern part of the Craton are up to 600 Ma older than previously reported. Thus, whereas the oldest reported age for Birekta terrane of 2.4 Ga is a Sm–Nd model age (Rosen *et al.* 1991), zircons from two eastern kimberlitic fields (Kuoika and Merchemdenskoe) show Archean ages (2.5–2.8 Ga and up to 3.0 Ga, respectively). These new results imply that Archean crust might extend further to the northeast than previously suggested for the Siberian Craton.

Hf-isotope information on the dated zircons as well as Re–Os isotope data on sulfides (inclusions in silicate minerals and diamonds) from the Siberian kimberlites will provide an ultimate test for this suggestion. If proven, this finding will extend the exploration potential for diamonds to the eastern part of the Craton.

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04DP-P03. K–AR DATING OF FAULT GOUGE AND SLICKENSIDES TO RESOLVE THE PRECISE AGES OF LOW-GRADE BASIN INVERSION AND COAXIAL EVENTS DEFORMING PROTEROZOIC METASEDIMENTARY ROCKS.

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The K–Ar dating method has been used to date fault gouges and slickenlines from faults in the 1620–1070 Ma Edmund and Collier groups of the Capricorn Orogen, Western Australia. Fault gouge from two separate exposed faults yielded similar ages of *ca* 1171 Ma and *ca* 1157 Ma, both of which are consistent with the lower age limit of the 1385–1170 Ma Mutherbukin Tectonic Event, which deforms the Edmund Group. The Edmund and Collier basins contain 4–10 km of fine-grained siliciclastic and carbonate metasedimentary rocks, intruded by several suites of dolerite sills and dykes and have been deformed by subsequent compressional events. The Edmund Basin formed during a north–south oriented extensional event, which was accommodated by the reactivation (in a normal sense of movement) of older, and largely compressional, major faults and shear zones in the underlying basement rocks. Previous U–Pb dating of monazite, xenotime, zircon and baddeleyite has constrained the age of basin deposition, dolerite intrusion and hydrothermal activity, but not the precise age of low-grade basin inversion and subsequent faulting by compressional events of the Mutherbukin Tectonic Event and the younger 1030–955 Ma Edmundian Orogeny. Differentiating between the structures produced by these two events is difficult because they are coaxial. Most of the faults are characterised by offset ridges of steeply dipping meta-sandstones separated by valleys filled with regolith, or as linear outcrops of massive vein quartz or quartz–ironstone breccias. The applied K–Ar method assumes that new authigenic clay mineral growth occurs with each successive faulting event, and overprints clay minerals grown during earlier phases of deformation. Poorly preserved and weathered faulted rocks often preclude direct dating of fault gouge. Fault plane exposure is not common, and these rarely contain fault gouge or show well developed slickenlines. Nonetheless, clay was recovered from suitable fault gouge samples, and characterised by SEM, TEM and XRD methods to confirm that the clay minerals were the only K-bearing phase, and that they are authigenic synkinetic rather than pre-existing in the metasedimentary rocks. K–Ar dating of the clays determined K content in duplicate by atomic absorption and the isotope composition measured with high-sensitivity mass spectrometry. Fault gouge from drill core also located in the Edmund Group yielded dates of *ca* 1017 Ma and *ca* 972 Ma consistent with the Edmundian Orogeny, and dates between *ca* 914 and *ca* 794 Ma consistent with a later 900–800 Ma deformational event recognised in basement rocks farther west. Further study of the Collier Group and these younger ages will hopefully provide more information about these later events as well as why mineralisation is concentrated in the Edmund Group.

04DP-P04. GEOCHEMICAL CHARACTERISATION OF GRANITIC ROCKS IN THE GRANITES-TANAMI OROGEN

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The Granites-Tanami Orogen (GTO) forms a long NW–SE-trending belt spanning the Western Australia (WA) and Northern Territory (NT) border in the North Australian Craton (NAC). The orogen comprises tightly to isoclinally folded *ca* 1864 Ma metasedimentary and rare volcanic rocks assigned to the Tanami Group in the Tanami Basin. These rocks are intruded by *ca* 1825–1795 Ma granitic rocks and mafic dykes. Although contacts are not exposed, the Tanami Group is inferred to unconformably overlie *ca* 2515 Ma and older banded orthogneiss in the Billabong Complex, which represents the oldest rocks known in the southern part of the NAC.

It is estimated that granites form ~60% of the GTO. The granites are generally not deformed, but locally have a ductile foliation indicating they were emplaced late during the *ca* 1795 Ma Tanami Orogeny (D_{GTO2}). Most granitic rocks in the orogen have U–Pb zircon ages of between 1844 and 1790 Ma. These ages do not show any consistent variation either spatially along the orogen or between the three granitic suites (Coomarie, Frederick and Winnecke) recognised in the Northern Territory.

The suites are broadly contemporaneous and distinguished by their aeromagnetic signatures and by their geochemical features. The Coomarie and Frederick suites are interpreted as a post-tectonic intrusive phase of magmatism, whereas the Winnecke Suite is interpreted in terms of caldera-type volcanism in the northern part of the orogen.

In this study the granitic rocks of the GTO in WA have been studied and Nd isotopic compositions for those samples have been reported. The samples are interpreted as late syn-collisional granites and the geochemical data indicate a crustal source and continental margin affinities. The granites have inherited zircons suggesting a > *ca* 2.6 Ga lower crustal component. The available Nd whole-rock isotope analyses of granites show a wide range of Epsilon Nd(t) values, from –0.3 to –6.4. The negative values suggest incorporation of old crust, with Nd model ages of 2.5 and 2.3 Ga, but the large variation in values could suggest a mixing of different sources. This mixing signature of the sources of the granitic rocks in the GTO has not yet been constrained.

This project represents the basis for the understanding of the processes involved in the genesis and differentiation of primary magma in the GTO. In turn, this can help reveal the nature of the litho-sphere and upper mantle at the time of their formation, and the fundamental genesis of mineralisation.

04DP-P05. EVOLUTION OF 3-D SUBDUCTION-INDUCED MANTLE FLOW AROUND THE LATERAL SLAB EDGES: INSIGHTS FROM ANALOGUE MODELS

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We present the results from analogue models of free subduction in which we investigate the three-dimensional (3-D) subduction-induced mantle flow focusing particularly around the slab edges. We use a stereoscopic Particle Image Velocimetry (sPIV) technique to map the 3-D mantle flow on 4 vertical cross sections for one experiment and on 3 horizontal depth-sections for the other experiment. On each section the in-plane components are mapped as well as the out-of-plane component for several experimental times. The results indicate that four types of maximum upwelling are produced by the subduction-induced mantle flow. The first two are associated with the poloidal circulation occurring in the mantle wedge and in the subslab domain. A third type is produced by horizontal motion and deformation of the frontal part of the slab lying on the 660 km discontinuity. The fourth type results from quasi-toroidal return flow around the lateral slab edges, which produces a maximum upwelling located slightly laterally away from the subslab domain and can have another maximum upwelling located laterally away from the mantle wedge. The zones of upwelling located laterally away from the subslab domain and the mantle wedge occur during the whole subduction process. In contrast, the poloidal circulation in the mantle wedge produces a zone of upwelling that is vigorous during the free falling phase of the slab sinking but that decreases in intensity after (steady-state phase). The position of the maximum upward component and horizontal components of the mantle flow velocity field has been tracked through time. Their time-evolving magnitude is well correlated to the trench retreat rate. The maximum upwelling velocity located laterally away from the subducting plate is ~18–24% of the trench retreat rate during the steady-state subduction phase. They occur in the mid upper mantle but upwellings are produced throughout the whole upper mantle thickness, promoting decompression melting and, thereby, potentially providing a source for intraplate volcanism, such as Mount Etna in the Mediterranean, the Chiveluch group of volcanoes in Kamchatka and the Samoan hotspot near Tonga.

04DP-P06. OVERRIDING PLATE DEFORMATION IN DYNAMIC LABORATORY MODELS OF SUBDUCTION WITH VARIABLE FAR-FIELD KINEMATIC BOUNDARY CONDITIONS

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Subduction zones are thought to be the main driver of plate tectonics and the comprehension of their dynamics and kinematics is of fundamental interest to our understanding of geodynamics. Subduction zones are bordered by subducting plates and overriding plates, which are generally trailed by larger plates that may impose a far-field kinematical boundary condition to the subduction zone. It is expected that such boundary condition would have potential effects on the deformation of overriding plate. In this work, we present three-dimensional dynamic models of subduction, in which far-field boundary conditions are varied (i.e., free or fixed at trailing edges of plates), namely, Free model (with both subducting and overriding plate free at their trailing edges), SP-Fixed model (with a subducting plate fixed at its trailing edge and a free overriding plate), OP-Fixed model (with a fixed overriding plate and free subducting plate), and SP-OP-Fixed model (with both subducting and overriding plates fixed). We investigate the impact of such variation on the kinematics and dynamics of subduction, particularly on the overriding plate deformation. When the subducting plate is fixed subduction is partitioned almost entirely into slab rollback, while in the cases in which the overriding plate is fixed trench retreat is partitioned entirely into overriding plate deformation. Our models show that in the steady slab-rollback stage subduction partitioning ratio ($v_{SP\perp}/v_{S\perp}$) is approximately constant for Free and SP-Fixed models but decreases for OP-Fixed and SP-OP-Fixed models, which is attributed to the decrease in the strength of the overriding plate due to higher extension. The trench retreat partitioning ratio ($v_{OPD\perp}/v_{T\perp}$) remains constant for Free and SP-Fixed models, indicating that it partitions into 10–18% of overriding plate deformation and 82–90% of overriding plate translation. Our models further confirm that the overriding plate deformation is primarily caused by the toroidal component of subduction-induced mantle return flow, irrespective of plates' far-field boundary conditions.

04DP-P07. GEOCHEMICAL CONSTRAINTS ON THE SEAFLOOR SPREADING HISTORY BETWEEN AUSTRALIA AND INDIA

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The Perth Abyssal Plain (PAP), offshore southwest Australia, is a region of relatively unexplored seafloor generated during the Cretaceous separation of India and Australia. Geophysical and bathymetric surveys of the PAP reveal a number of submarine features, whose origins remain enigmatic. The PAP formed in the context of the larger-scale breakup of East Gondwana, and during a time of widespread volcanism thought to be associated with the Kerguelen Plume.

In 2011, the Southern Surveyor dredged igneous and metamorphic samples from seven locations in the PAP. The Batavia and Gulden Draak Knolls, located at the western boundary of the PAP, were found to be microcontinents, composed of granites, sandstones and intermediate to high-grade metamorphic rocks. A suite of mafic igneous samples were dredged from the flanks of the Dirck Hartog Ridge (DHR), a linear NNE–SSW trending bathymetric feature, located roughly midway between the western Australian margin and newly discovered microcontinents. Geochemical analyses of the mafic igneous samples provide new insights into the geodynamic processes associated with the early stages of India's separation from Australia.

Extrusive mafic samples dredged from three distinct sites display a range of geochemical characteristics from highly enriched alkaline basalts to normal mid-ocean ridge basalts (NMORB). Basaltic samples show variable degrees of hydrothermal alteration, and in some cases low-grade metamorphism-spilitisation. All basalts are fined grained with the majority of the igneous texture altered by recrystallisation and the presence of secondary minerals: epidote, chlorite, smectite and hydrated iron oxides. Intrusive mafic samples were dredged only from the southern most dredge site on the Dirck Hartog Ridge. The comparative absence of secondary minerals is indicative of a cumulate origin below the zone of sea-floor hydrothermal processes, typically corresponding to the lower oceanic crust (~7 km depth).

Our results help to constrain the extent of Kerguelen Plume influence in the region, the events associated with the separation of East Gondwana and the final stages of seafloor spreading in the Perth Abyssal Plain. Magnetic anomalies correspond to M9 (130 Ma) in the east PAP adjacent to the continent, and young to M0 (120.6 Ma) towards to the west. In the western PAP, the conjugate magnetic anomalies young to the east, suggesting the presence of one or more extinct spreading centres in the PAP. However, because much of the PAP was formed during the Cretaceous Quiet Zone, there are large uncertainties associated with estimates of the spreading centre locations as derived from magnetic anomaly data. The combination of new geochemical data and swath bathymetry suggests that the DHR represents the paleospreading ridge responsible for the formation of the PAP. The distinctive geochemistry of basaltic samples, the presence of lower crustal rocks on the surface and the irregular bathymetry of the DHR itself are characteristic features of slowing seafloor spreading leading to an eventual extinction of a spreading ridge.

04DP-P08. TECTONIC EVOLUTION OF THE WESTERN TETHYS FROM JURASSIC TO PRESENT DAY COUPLING GEOLOGICAL AND GEOPHYSICAL DATA WITH MANTLE CONVECTION MODELS AND TOMOGRAPHY

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The geodynamic evolution of the Western Tethys is characterised by multiple phases of rifting, seafloor spreading, subduction and collisional events. These episodes of tectonic evolution occurred within a region bounded to the west by the opening of Central and North Atlantic Ocean, and to the east by Paleo- and NeoTethyan subduction. Reconstructions of the Western Tethys are highly dependent on the kinematic history of the major plates bounding the Atlantic and Tethyan tectonic domains. Fragmentation of northern Gondwana, involving numerous rifting events in Jurassic and Early Cretaceous time and opening of Tethyan back-arc basins, led to the formation of small microplates between Eurasia and Africa. The motion and deformation between these plates are important in the tectonic history of this region.

The complexity of tectonic events in this area leads to major discrepancies between competing models about the nature and location of active plate boundaries in general and timing, location and polarity of subduction zones in particular. Significant points of uncertainty include whether the Neotethys was divided into separate northern and southern branches: the existence of one single or two separate Vardar and Pindos Seas east of Adria, which leads to ambiguity about the possibile existence of two separate subduction zones and ophiolite belts; the relationship between the initiation of subduction in Alpine Tethys and the timing and direction of thrusting in the Eo-Alpine; and the history of subduction associated with the closure of the Valais Sea north of Iberia and Ligurian Ocean on the eastern margins of this microplate.

To shed some light on these ongoing debates, we first constructed new kinematic models for the Early Jurassic–Late Cretaceous opening of the Central and North Atlantic, and use these as boundary conditions on our kinematic reconstructions of the Tethyan realm. The motion of Iberia relative to Europe and Africa been revised to fit in the refined plate configuration of Central-North Atlantic. We built alternative reconstructions to investigate the history of Neotethys subduction and closure of the Vardar Ocean. Tectonic elements in western and eastern Alpine and Pyrenean domains were also reconsidered and altered in the light of new geological evidence, to derive a self-consistent model for the entire time period of 200 Ma. The second stage of our workflow is to build geodynamic models that link the surface plate kinematics with global mantle flow, from the Triassic to present day. We create synthetic isochrons and age grids for extinct oceanic basins and build evolving topological plate boundaries based on our new rigid plate models in the software GPlates. These models examine the consistency of subduction histories implied by different kinematic reconstructions and allow us to test the consequences of these different subduction histories by comparing predicted mantle structure with seismic tomography data.

04DP-P09. SUPERCYCLES, WILSON CYCLES AND THE FUTURE OF EARTH’S OCEANS

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At the dawn of the 20th Century Alfred Wegener proposed the existence of a supercontinent – Pangea – gathering all the continental masses on Earth. Five decades later, while seeding the theory of plate tectonics, Tuzo Wilson introduced a new concept that would become known as Wilson cycles, which describes the evolution of oceans: 1) opening and spreading, 2) foundering of the passive margins and development of new subduction zones, and 3) consumption and closure. Later on, in the 70's evidences for the existence of a number of other supercontinents and ancient oceans on Earth´s history started to emerge. Today, concepts like supercycles, supercontinents, superoceans and Wilson cycles are loosely used. However, several important questions remain. How do subduction zones initiate in pristine oceans? Which major ocean on Earth will close to form the next supercontinent? The Atlantic (introversion), the Pacific (extroversion), or both? Are Wilson cycles of lower order than Supercycles? Are we in an abnormally long supercycle? Is there any cyclicity at all? These are some of the questions that we will tentatively address together with the proposal of several future scenarios for the evolution of Earth's oceans and continents.

04DP-P10. A PALEOMAGNETIC TEST OF THE COLUMBIA SUPERCONTINENT AT 1.88 GA; CONSTRAINTS FROM RADIATING MAFIC DYKE SWARMS IN THE DHARWAR CRATON, INDIA

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Recent advances in paleotectonics and detrital geochronology indicate that Earth's history was punctuated by numerous supercontinental configurations. The geometry of the most recent supercontinent, Pangea, is well constrained from seafloor magnetic anomaly data, paleomagnetism, geology, and faunal evidence, although there are still vigorous debates regarding the exact configuration. In attempts to reconstruct previous Proterozoic supercontinents, geologists use geologic similarities and the alignment of features such as orogenic belts, dyke swarms, or rapakivi pulses in order to establish contiguity; however, paleomagnetic techniques remain the only quantitative test of such reconstructions. As an example, the geologic record present in Precambrian terranes suggests a major global rifting event from 2.2 to 2.0 Ga followed 100 million years later by global widespread orogenesis from 1.9 to 1.7 Ga. The orogenic belts that formed during this event were used to generate a plausible supercontinental assemblage named Columbia. Here we report results from 4 separate magmatic events during the Paleoproterozoic, including a ~85 000 km^2 radiating dyke swarm with a fanning angle of 65 degrees at 1.88 Ga. The Grand Mean dual polarity paleomagnetic pole falls at 36.5 N and 333.5 E (D = 129.1, I = 4.2, $\alpha95$ = 4.5, λ = 2.1) for 29 sites from the present study combined with previously published sites. Using our continental reconstruction for India at *ca* 1.9 Ga and the database of well-dated paleomagnetic poles for this time period, we test the geometry of the archetypal Columbia model. Our conclusion is that either Columbia did not exist as a coherent supercontinent, or it was not assembled by 1.88 Ga as evidenced in the geologic record. Finally, we provide an Apparent Polar Wander Path (APWP) for Peninsular India from 2.37–1.88 Ga and analyse potential cratonic relationships for each magmatic interval.

04DP-P12. THE CARSON VOLCANICS: EVIDENCE FOR A BROAD, SHALLOW MARGINAL MARINE SETTING FOR A PALEOPROTEROZOIC LARGE IGNEOUS PROVINCE, NORTH WESTERN AUSTRALIA

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The Carson Volcanics are the only volcanic unit within the Kimberley Basin of northern Western Australia. Together with their intrusive equivalent, the Hart Dolerite, they form a little studied Large Igneous Province (LIP) of ~300 000 km^3, slightly larger than the Columbia River Basalts in the western USA. Zircon age data suggests that the Carson Volcanics formed around 1800 Ma. In 2012 and 2013, new work focussing on this LIP included helicopter-supported traverses and sampling of the Carson Volcanics in remote areas of the far north Kimberley Basin.

Across the central and northern part of the Kimberley Basin, the succession is flat lying to gently dipping. Three to six basalt units are intercalated with sandstone and siltstone and locally with stromatolitic rocks. Each basalt is 20–40 m thick with up to 60 km strike-length. Most commonly, the basalt is either massive or amygdaloidal with polygonal, subhorizontal jointing and occasional vertical columnar joints. Ropy tops and bases, basal pipe vesicles and some lava toes are consistent with pahoehoe flows.

The intercalated sedimentary units vary in thickness, but can be up to 40 m thick. Individual beds rarely exceed 1 m thick. Some can be followed for 40 km along strike. The interaction between wet, unconsolidated sediment and basalt lava is marked by peperite.

Many of the siltstone beds preserve mud cracks. The mud cracks and locally abundant stromatolites suggest a tidal flat environment, which was intermittently emergent. The volcanics were extruded onto a broad marginal marine setting subject to flooding events. Thickening of the volcanic succession toward the south and paleocurrent indicators consistent with flow from the north in the underlying King Leopold Sandstone and the overlying Warton Sandstone suggest that the shelf sloped to the south. The type of basalt and the basalt morphology indicate a low slope gradient of about 1°.

04DP-P13. THE GRANITES-TANAMI OROGEN SUBSURFACE GEOMETRY AS REVEALED BY AN INTEGRATED POTENTIAL FIELD GEOPHYSICAL AND GEOLOGICAL STUDY

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The Granites-Tanami Orogen (GTO) is a Paleoproterozoic terrane located on the southern margin of the North Australian Craton. The interpretation of crustal-scale reflection seismic data combined with stratigraphic and geochemical studies has revealed that the architecture of the orogen is that of a basin that has been subsequently inverted, deformed and intruded during a series of collisional events coincident with: a) the amalgamation of the Kimberley and Tanami basins along the Halls Creek Orogen to form the North Australian Craton; and b) the amalgamation of the North Australian Craton with the Central Australia Craton at *ca* 1800 Ma. These continent–continent collisions have left the GTO with a complex poly-deformed structural history riddled with overprinting relationships, re-activated structures and puzzling geometries. As with much of continental Australia, the GTO is poorly exposed and deeply weathered. A series of younger cover sequences further add to the difficulties of deciphering the complete structural history of the orogen. In this paper we use combined potential field (gravity and magnetic) interpretation together with structural outcrop mapping to reveal mechanisms and structural complexities, which could not be sufficiently identified without this combined geology and geophysical approach.

The regional D_{GTO1} event resulted in north to northeast trending isoclinal fold trains (F_1) of the Tanami Group with wavelengths of ~10 km or greater. On a regional scale, F_1 folds are recognised through the interpretation of joint gravity and magnetic anomalies. In outcrop, D_{GTO1} is recognised as isoclinal folds (F_1) with a strong axial planar fabric (S_1), which has generally resulted in bedding (S_0) transposition subparallel to this foliation. D_{GTO2} is recognised in regional aeromagnetic data as poly-phase deformational interference figures caused by the refolding of F_1 folds around axes trending E to ESE. On the outcrop scale, F_2 is recognised as two end members being: a) a strongly developed ESE-trending axial planar fabric resulting in the transposition of S_1 into S_2; and b) an ESE-trending axial planar cleavage crosscutting S_1 at various angles depending on the orientation of the F_1 folds. Both D_{GTO1} and D_{GTO2} occurred at greenschist facies. D_{GTO1} precedes the emplacement of granitic plutons, whereas D_{GTO2} was broadly coeval with granitic emplacement. Both of these deformation events represent thin-skinned folding of the Tanami Basin stratigraphy accompanying: (1) the collision with the Kimberley Craton along the Halls Creek Orogen to the NW during *ca* 1850 Ma to form the North Australian Craton (NAC), and (2) collision of NAC with the Arunta Orogen in the Central Australian Craton to the south during the *ca* 1800 Ma D_{GTO2}.

04DP-P15. DATING MICROSTRUCTURES IN THE GREATER HIMALAYA, NW INDIA

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Here we employ microstructurally-focused $^{40}Ar/^{39}Ar$ geochronology across key tectonic contacts and terranes of the Greater Himalaya to constrain the timing and temperature evolution of individual deformation and metamorphic events. The Himalaya is an orogenic welt within the Alpine-Tethyan mountain chain. Current tectonic models entail continuous post-collisional convergence and persistent heating during burial and subsequent exhumation. An alternative hypothesis to this “continuous evolution” scenario involves episodic tectonic mode switching, a concept that has been documented in other orogens along the Alpine-Tethyan belt. We test the possible occurrence of episodic mode switching in respect to the evolution of the Greater Himalaya in its topographically high crystalline core, in Himachal Pradesh, NW India.

Webb *et al.* (2007, 2011) depict the Miocene-age South Tibetan Detachment System (STDS) as being recumbently folded around a 15 km amplitude giant recumbent fold referred to as the Phojal nappe. The upper levels of the shear zone outcrop in the adjacent Lahaul area, where the shear zone can be shown to have been statically overprinted by upper greenschist garnet-grade Barrovian metamorphism at *ca* 35 Ma. This cannot be the STDS.

The lower limb of the Phojal fold was therefore examined at a location above the structure that has been mapped as the Main Central Thrust (MCT). Shear bands associated with a fault ramp were dated, and shown to have been statically overprinted by a second upper greenschist garnet-grade Barrovian event at <*ca* 24 Ma. The microstructural sequence implies metamorphism in the hanging wall of a larger extensional shear zone. This microstructural sequence is not compatible with a structural location in the hanging wall close to a thrust. The MCT in this area is thus an unrelated thrust.

Age spectra from rocks deeper down in the structure of the Rohtang Antiform show that the second static Barrovian event continued until *ca* 21 Ma.

Argon diffusion modelling supports the conclusion based on microstructures that the M1 and M2 metamorphic events cannot have occurred as part of a single protracted heating event, and that there must have been cooling (and possible exhumation) in between. Our data shows that the tectonic evolution of the Greater Himalaya is consistent with multiple episodes of crustal shortening followed by regional extension events. The timing of the tectonic mode switches is broadly compatible with mode switches as observed in orogens elsewhere along the Alpine-Tethyan chain.

04DP-P16. A SHALE DETACHMENT IN THAILAND: EVIDENCE OF BRITTLE DEFORMATION FROM STRUCTURAL OBSERVATIONS AND LABORATORY ANALYSIS

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Shale detachments have been previously described as largely ductile in their mechanism of deformation, however, increasing resolution of seismic imaging and understanding of these zones suggest brittle deformation may have a significant role in their behaviour and the deformation of overlying fold and thrust belts. Dependence on seismic imaging and other indirect and low-resolution study methods has resulted from the lack of outcropping shale detachment zones, both active and ancient, for detailed study. However, recent investigation of the structural style and deformational mechanisms of a newly described shale detachment zone in the Khao Khwang Fold and Thrust Belt in Central Thailand demonstrate an exceptionally well-exposed example of a shale detachment. We use detailed structural analysis to investigate the deformational mechanisms of this ancient, exhumed detachment zone, as an analogue to active modern-day examples. Through detailed field mapping we were able to construct multiple cross sections through the detachment zone and characterise the deformational style and brittle nature of deformation. The cross sections were subdivided into structural domains displaying and increase in deformational intensity and complexity toward the thrust at the base of the detachment zone. Increase in deformational intensity is also associated with finer-grained packages within the shales. Sample throughout the cross section were used for x-ray diffraction analysis, total organic carbon analysis, carbon and oxygen stable isotopes analysis, and vitrinite reflectance analysis. A suite of data from these analyses has given insight into variation of key properties within the detachment and supports our conclusion that the detachment zone is this study (analogous to those in modern-day fold and thrust belts) displays a predominantly brittle accommodation of shortening, characterised by a complex, three-dimensional, fault-dominated deformational style.

04DP-P17. LATE MESOZOIC AND CENOZOIC WRENCH TECTONICS IN EASTERN AUSTRALIA: INSIGHTS FROM THE NORTH PINE FAULT SYSTEM (SOUTHEAST QUEENSLAND)

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The North Pine Fault System (NPFS) in southeast Queensland belongs to a series of NNW-striking sinistral faults that displaced Paleozoic to Cenozoic rock units in eastern Australia. We have studied the geometry and kinematics of the NPFS by utilising gridded aeromagnetic data, digital elevation models and field observations. The results indicate that all segments of the NPFS were subjected to sinistral reverse strike-slip faulting. Restorations of displaced magnetic anomalies indicate sinistral offsets ranging from ~3.4 to ~8.2 km. A ~11 km long granophyre dyke with possible Late Triassic age located immediately parallel to one of the fault segments and the contribution of parallel NNW-striking steeply dipping strike-slip and normal faults in the development of the Late Triassic–Early Cretaceous Maryborough Basin, indicate that the NPFS has likely been active during the Mesozoic. We propose that from Late Cretaceous to Early Eocene, NNW-striking faults in eastern Australia, including the NPFS, were reactivated with oblique sinistral-normal kinematics in response to regional oblique extension associated with the opening of the Tasman and Coral seas. This is supported by modeled dominant NNE- to NNW-directed horizontal tensional stress in the Eocene. The latest movements along the NPFS involved sinistral transpressional kinematics, interpreted to be related to far-field contractional stresses from collisional tectonics at the eastern and northern boundaries of the Australian plate in the Cenozoic. The sinistral-reverse oblique kinematics of the NPFS in the Cenozoic is in line with ESE to ENE directions of modelled maximum horizontal stress in SE Queensland.

04DP-P18. LATE CENOZOIC DEFORMATION IN THE EASTERN GONDWANA PASSIVE MARGIN: EVIDENCE FROM DEFORMED VOLCANIC ROCKS IN EASTERN AUSTRALIA

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We showed that Cenozoic volcanic rocks in southeast Queensland have been deformed by numerous faults. Using gridded aeromagnetic data, digital elevation models, field observations and published $^{40}Ar/^{39}Ar$ geochronological data, we mapped faults in eastern Australia, which have displaced Cenozoic volcanic rocks dated *ca* 31–23 Ma. Faults have been mapped in several areas in southeast Queensland, mainly as reverse and strike-slip high-angle faults. We found a series of reverse and strike-slip brittle faults in the Maleny area, which displaced Cenozoic basalts with the age of *ca* 31 Ma. Farther south, reactivation of the West Ipswich Fault resulted in the development of some subsidiary faults such as the Redbank Plains Fault (RPF), which displaced late Oligocene trachyte dextrally in the south of Redbank Plains. Same brittle faults were also observed in the Tweed and Main Range volcanoes as well. Considering these maximum ages, we postulate that faulting must have occurred since the late Oligocene. Compressional deformation was possibly associated with far-field stress fields transmitted from the collisional zones at the eastern boundaries of the Australian plate during the late Oligocene–early Miocene and the late Miocene–Pliocene. The late Oligocene–early Miocene collisional events occurred at the northeast and southeast boundaries of the Australian plate and included the initiation of oblique convergence between the Melanesian arc system and the Ontong Java Plateau (OJP), arc–continent collision at the northern margin of New Guinea, and ophiolite obduction and collision in New Zealand. A younger phase of deformation may have occurred in response to sinistral oblique collisional events in New Guinea and OJP, and kinematic reorganisation from strike-slip to a transpression regime in New Zealand from the late Miocene to Pliocene. These events have resulted in the hitherto unrecognised reactivation of NNW-striking sinistral and NE-striking dextral fault systems in eastern Australia.

04DP-P19. BRITTLE *VS* DUCTILE DEFORMATION IN SALT DETACHMENTS: A STUDY FROM THE SALT RANGE, PAKISTAN

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Shortening of the Earth’s crust is commonly accommodated by fold-thrust belts (FTBs) that are mechanically decoupled from the underlying rocks by a detachment zone. Salt typically form these detachments due to its intrinsically weak nature under stress. The Potwar Plateau, Pakistan, is an example of an active foreland FTB

detaching over a thick salt layer, the Salt Range Formation, being driven by a combination of far-field stresses (continent–continent collision) and near-field stresses (gravity gliding) and represents the southernmost expression of the Himalayan orogenic deformation. Our recent fieldwork carried out in the area of Khewra, Salt Range, Pakistan has focused on the structures within the Salt Range detachment. Two cross sections constructed from detailed scaled sketches combined with microstructural analysis of samples taken along these section displayed both brittle and ductile characteristics. Both show an overall NNW moderately dipping bedding trend that mirrors the larger Himalayan deformation. The Billianwala Salt Member, the primary detachment indicates a brittle component of deformation with boudins of halite within potash rich layers. The Sahwal Marl Member stratigraphically above is distinctly rheologically different having accommodated deformation with the formation of both gypsum cataclasites and mylonites with evidence of imbrication. Considered the same unit within large-scale models, these clearly behave differently from one another under stress. Microfabrics observed using optical and EBSD techniques within the halite are parallel to bedding orientations adding further consistency to the results. A novel analytical technique involving gamma-irradiated halite with optical microscopy has exposed previously unobservable microstructures. Our findings differ with the current understanding that salt detachments behave as entirely ductile horizons, akin to a fluid over geological time scales. Although, the large scale deformation styles portrayed by FTBs is established and the microstructures associated with the mechanical deformation of halite well documented, this work shows that the meso-scale structures are significantly different and require further characterisation, including analysis at the micro-scale.

04DP-P21. 3D CRUSTAL STRUCTURE IN NORTH TIBET FROM AMBIENT NOISE TOMOGRAPHY: IMPLICATIONS FOR THE GROWTH OF THE TIBETAN PLATEAU

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Based on the analysis of continuous ambient noise data collected from ~280 stations during 2008 and 2010 in north Tibet, Rayleigh phase velocity maps at 10–60 sec periods are generated using ambient noise tomography. A 3D Vsv model with a resolution of ~60 km is constructed based on calculated surface wave dispersion curves using a Bayesian Monte Carlo method. The new 3D image helps to reveal more detailed distribution of mid-crustal low velocity zones (LVZs) in north Tibet than our previous model (**Yang *et al.* 2010, 2012**), thus providing more direct evidence on answering how the enormously thick crust and high topography of this plateau is being achieved and maintained in the deep.

Our 3D model reveals strong LVZs at the middle crust between 20 and 40 km across northern Tibet showing significant west–east variations of LVZs along the Kunlun Fault. In the western part, LVZs are confined to regions of the Kunlun Fault and the eastern Kunlun Mountain but do not appear beneath the Qaidam Basin; while in the eastern part, LVZs are observed to extend and penetrate northward into the East Kunlun and Qinling Orogens over ~100 km beyond the eastern boundary of the Qaidam Basin. The strong contrast of the distribution of LVZs in the west and east of the study region mainly results from the distinct tectonic units neighbouring northern Tibet with the strong crust of the Qaidam Basin in the west blocking the penetration of LVZs, but a probably weak crust in the Qinling Mountains allowing the extrusion of LVZs. The distribution of LVZs is consistent with the crustal channel flow model, which predicts a north-eastward flow of mid-crustal materials. Our 3D Vsv model helps delineate the north extent of the mid-crustal channel flow if it does exist.

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04DP-P22. MULTI-ARRAY, MULTI-FREQUENCY PROBING OF THE EARTH'S HETEROGENEITY

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Variations in elastic properties of the Earth's crust and mantle, such as those induced by changes in local chemistry, scatter seismic energy. Many of the seismic phases that need to be observed in order to infer small-scale heterogeneity, particularly at great depth, are commonly so attenuated that it is difficult to identify them on a single seismogram. In addition, small-scale seismic structures cannot be directly imaged by seismic tomography. The use of seismic arrays allows signals with small amplitudes to be enhanced by exploiting the coherency of waveforms at adjacent stations. The benefits of array techniques have been recognised in many fields that analyse wavelike disturbances. The combination of results from many sensors allows the enhancement of coherent signals and the suppression of incoherent 'noise'.

Australia has a long history of hosting seismic arrays since Warramunga array was established in 1965. Although the main purpose of this array is long-distance detection of nuclear explosions, its existence proved invaluable for exploration of deep Earth. Since the establishment of the Warramunga array many similar experiments have been carried across Australia (for example SKIPPY or SEAL) but all of them focused on using single array methods. Building upon foundations of excellent detection capabilities of weak seismic phases across Australia, we plan to extend array techniques from single to multiple. Data from several simultaneously operating networks of seismic instruments will provide finer control on the nature of structure within the Earth. The backbone of this experiment consists of two temporary arrays; one in Queensland and another in Western Australia, both deployed in November 2013. In addition, we will exploit the fixed seismic arrays in Australia (Warramuga – WRA and Alice Springs – ASAR in the Northern Territory, and the new PSAR array in the Pilbara) linked to nearby deployments of broad-band stations. This will provide a new style of seismological experiment with multiple arrays in reasonable proximity being used to study the same events and exploit Australia's unique geology and location relative to major seismogenic zones.

In the first stage of the project we focus on utilising well-established array processing methods such as beam forming, velocity-spectral analysis (VESPA) and frequency-wave number method (fk analysis) in order to map energy coming from deep interfaces such as core–mantle boundary. This step helps to map energy coming from well-known deep interfaces *via* the seismic phases such as PcP and ScP. Next step will be to utilise advanced array processing methods such as sliding window fk analysis and migration in order to map energy scattered from unknown sources. We will use data from a seismic event recorded on multiple arrays to 'triangulate' on the source of the anomalies and refine understanding of the nature of heterogeneities. By looking at the various phases in the seismic records we can achieve multiple coverage of the mantle and hence provide additional sources of information. By utilising data from multiple arrays we hope to push the resolution limit of seismic tomography.

04DP-P23. 3D NUMERICAL MODELLING OF THE STEADY-STATE TEMPERATURE DISTRIBUTION IN VICTORIAN CRUST, CONSTRAINED BY SURFACE HEAT FLOW DATA

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A considerable body of surface heat flow data has been gathered over Victoria in the last decade. While geophysical techniques such as magnetotelluric and seismic surveys can provide indirect means to constrain temperature in the crust, heat flow data is directly related to temperature. The collection of 175 heat flow calculations in Victoria offers the highest resolution dataset of any state in Australia. An interpolation of this data reveals the heterogeneous nature of heat flow. We extrapolated the temperature at the Moho from surface heat flow data, using our knowledge of the thermal properties of the crust, and uncovered a zone of impossibly high temperatures exceeding 900°C at the base of the crust. This zone is broadly situated between Bendigo and Ballarat and correlates with a region of low teleseismic velocity and high electrical conductivity that intrudes into the mid-crust. 3D modelling using the finite element code, Underworld, was utilised to examine the effect of adding geological structure in a thermal model to account for lateral heat flow variation, and to validate the anomalously hot zone west of Melbourne. Our results indicate that a steady-state approach to crustal heat flow modelling breaks down in this zone, and remnant heat from the Newer Volcanics Province eruptions has contributed to the surface heat flow budget. Finite difference models of thermal diffusion show multiple pulses of magma migration injected at shallow depth are required to reproduce the heat flow signature observed at the surface. Forward modelling our 3D models against surface heat flow data some distance away from the Newer Volcanics Province has enabled us to evaluate the 'residual' heat flow across the state. This work demonstrates the value of heat flow data to constrain the transient thermal effects of volcanism. Further work will examine the dynamics of magma migration through preferred fault pathways.

04DP-P24. HIGH-LEVEL LITHOSTRATIGRAPHIC SCHEME FOR NEW ZEALAND ROCKS

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Fifteen new high-level stratigraphic names are proposed to collectively describe New Zealand's onland and offshore Cambrian to Holocene rocks and unconsolidated deposits. The two topmost-level units are Austral Superprovince (new) and Zealandia Supersuccession (new). These encompass the lithostratigraphic units of the country's Cambrian to Lower Cretaceous basement rocks and Upper Cretaceous–Holocene cover rocks, respectively.

Most high-level divisions of the Austral Superprovince are in current and common usage: Eastern and Western Provinces are subdivided into 12 tectonostratigraphic terranes, ten igneous suites, five batholiths and Haast Schist.

We divide the Zealandia Supersuccession into five diachronous, predominantly sedimentary, partly unconformity-bounded units. The rift to passive margin (marine transgressive) rocks comprise Kawatiri, Kahurangi and Waitomo Supergroups (new), and are collectively termed Waka Succession (new). The overlying subduction margin (marine regressive) rocks comprise Maui and Aoraki Supergroups (new), and are collectively termed Aotearoa Succession (new). Ruaumoko Volcanic Province (new) is used to optionally describe all igneous rocks of the Zealandia Supersuccession and is geochemically divided into Whakaari, Horomaka and Maungataniwha Supersuites (new).

The new scheme, termed Litho2014, provides a complete, convenient, comprehensive, bottom-up, high-level stratigraphic classification for all of onland and offshore New Zealand. We hope it will help explain and demystify New Zealand geology for both New Zealand and non-New Zealand geoscientists alike.

04DP-P25. A DIGITAL WORKBENCH FOR UNDERSTANDING THE STRATIGRAPHIC EVOLUTION OF RIFT BASINS AND CONTINENTAL MARGINS

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Passive margins and rift basins supply the major fraction of global hydrocarbon resources. While our society is massively reliant on them, reserves are waning and new discoveries in conventional sedimentary systems remain limited forcing exploration into deeper and more remote territories. In order to secure new resources in frontier basins, it is vital to improve the understanding of the forces that drive basin formation and the internal sedimentary structures within them.

The evolution of sedimentary systems is primarily controlled by the feedback interaction of surface processes and tectonics. Lithospheric deformation creates high topography from which material is eroded, and accommodation space in which sediments are deposited; while climate controls the supply and mass transport from source to sink of sediments, which in turn impacts *via* denudation and burial on temperature and stress fields.

Despite the recognition of these interactions, decoding the sedimentary signals recorded in rift basins of the relative impact of surface *vs* tectonic forcing remains a significant challenge. This problem is due, in part, to a lack of tools capable of simulating small-scale surface processes (soil creep, sediment yielding and dispersion, stratigraphy) within the large-scale (spatial and temporal) tectonic setting of continental rifting.

To overcome these limitations we introduce a new "digital workbench". The workbench simulates the evolution of a virtual landscape on an actively deforming lithosphere with realistic thermal and mechanical properties. At the heart of the workbench are two forward modelling codes: *Underworld*, capable of simulating 3D self-consistent thermo-mechanical processes, and *LECODE*, a stratigraphic and geomorphic modelling framework dedicated to simulating highly detailed surface dynamics. Through the intermeshing of both codes, the workbench allows us to investigate the thermal, mechanical, and stratigraphic evolution of sedimentary rift basins in a robust physical framework, in 3-dimensions and through time.

We demonstrate the capabilities of the workbench through a number of experiments, including normal and oblique continental rifting. Within each experiment, various parameters such as extension rate, lithospheric rheologies, or climate conditions are explored to test the relative importance of each in continental rift evolution, and help constrain whether the signals of these changes can be resolved within basin stratigraphy.

We show from these experiments that climate forcing plays a fundamental role in the lithospheric dynamics of continental rifting, and basin development. Strong climatic forcing (effective erosion and transport) delays the timing of continental lithospheric break-up, increases the depth and size of rift basins, and increases the longevity and absolute offset of rift bounding faults.

04DP-P26. FERRUGINOUS PISOLITHS IN THE EXTENSIVE PALEOCHANNELS OF THE YILGARN CRATON, AUSTRALIA: IMPLICATIONS FOR THE PALEOENVIRONMENT

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The paleochannel system preserved in the Yilgarn Craton of Western Australia had a combined catchment aerial extent of 1.2 x 10^6 km^2. Ferruginous pisoliths are a common component within this system and are found in kaolinitic clays deposited in fluvio-lacustrine environments. The pisoliths are composed predominantly of goethite and hematite with minor quartz and clays, hematite is mostly present in the nucleus and inner laminations. Pisoliths analysed from paleochannels over 300 km apart are divided into simple, compound and fragmented types. Simple pisoliths are composed of up to 200 continuous regular iron-oxide laminations surrounding a nucleus of ferruginised wood or clay. Compound pisoliths contain multiple smaller ferruginous ooliths within the nucleus. Fragmented pisoliths are fractured, broken and possess multiple micro-unconformities as successive laminations are developed in discordance with preceding layers. Nodules (≥8 cm across) are also present at most locations. The mean bulk chemical compositions show pisoliths are composed of 57 wt% Fe_2O_3, 15 wt% SiO_2 and 12 wt% Al_2O_3, and the surrounding clays are composed of 55 wt% SiO_2, 26 wt% Al_2O_3 and 3 wt% Fe_2O_3. The trace elements Ba, U, V and Ga are enriched in the pisoliths compared to the surrounding clays.

The pisoliths are interpreted to have formed entirely within the paleochannel system. A cyclic process of repeated floods and exposure produces ferruginised clays. During flood events, rip-up clasts are formed and become the nucleus for goethite precipitation. The interface between river water and sediment is a redox boundary between reduced slightly acidic sediments and oxidised river water. Pisoliths formed on the surface of the sediment by redox reactions likely mediated by micro-organisms. Occasional movement along the river bed led to removal of some laminations and the development of unconformities as goethite precipitation continued. Hematite is formed by the dehydration of goethite during extended periods of exposure. Many pisoliths have undergone a number of phases of exposure, growth and movement linked to variation in paleoenvironmental conditions producing a complex series of textural features.

04DP-P27. DEPOSITIONAL ENVIRONMENTS AND STRATIGRAPHY OF AN EXTENSIONAL SETTING: MYALL TROUGH, SOUTH-EASTERN AUSTRALIA

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The Carboniferous depositional succession of the Myall Trough, southeast Australia, provides a superb record how a forearc basin may fill. Sedimentary rocks within the southern edge of the late Paleozoic active continental margin of eastern Australia have been described utilising methods of facies analysis to elucidate the different depositional environments and subenvironments and to unravel the regional stratigraphic evolution. Lithological units are described in terms of colour, texture, thickness, grain size and sedimentary structures. Five main depositional environments have been identified demonstrating a regional deepening-upward trend. In particular, the stratigraphy initiates with the deposition of fluvial sediments and progressively evolves through tidal and shoreface environments to shelf and submarine fan deposits. Fluvial deposits can be further subdivided into fluvial channels and overbank deposits. Channel fill is typified by thick-bedded and amalgamated sandstones. Channel-fill sediments are typified by erosional basal contacts overlain by planar and trough cross-bedded sandstone. Overbank deposits are characterised by thin- to medium-bedded sandstones interbedded with mudstone. Crevasse and chute sands contain planar bedding. Tidal facies consist of alternations of fine- to medium-bedded sandstone and mudstone with flaser, wavy and lenticular bedding. The shoreface environment is represented by a sandstone-dominated unit consisting of thin- to thick-bedded sandstones with hummocky and swaley cross stratification. Shelf facies are distinguishable as thin bedded to very thick-bedded laminated mudstones that have undergone large-scale soft sediment deformation. The submarine fan deposits correspond to the proximal parts of the turbidity system (inner fan). They are characterised by very thin to very thick-bedded sandstone and conglomerate interbedded with mudstone. Sandstone beds have sharp bases, which are commonly erosive. They are laterally discontinuous and have accumulated in packages, which exhibit distinct fining and thinning upward trends. Sandstones display both complete and incomplete Bouma sequences. Paleodirection data obtained by measuring directional structures, such as foreset laminae, flute and groove casts exhibit a general eastward trend indicating a westward source rock location.

04DP-P28. A THERMOBAROMETRICAL AND PETROLOGICAL STUDY OF A CUMULATE XENOLITH SUITE FROM AN OXIDISED, VOLATILE-RICH ARC VOLCANO

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Sangeang Api (Eastern Sunda Arc, Indonesia) is an active, rear-arc volcano, sitting on a major cross-arc structure. Its primary magmatic products are highly oxidised, volatile-rich, silica-undersaturated, shoshonitic lavas. These entrain a suite of mafic and ultramafic cumulate xenoliths, including clinopyroxenite, olivine-clinopyroxenite, gabbro and amphibole-gabbro. Amphibole (Mg-hastingsite) can make up to ~30% of the phenocryst populations within the studied cumulates, implying a high H_2O content at crystallisation depths.

Major element chemistries of cumulate mineral populations were analysed on the Cameca SX5 and Cameca SX51 microprobes at Adelaide Microscopy, University of Adelaide. A variety of suitable thermobarometers were then applied to the results to calculate the temperatures, pressures and water contents under which the Sangeang Api cumulates crystallised. Calculated temperatures of amphibole crystallisation are in the range of ~980°C (± 20°C) to ~1070°C (± 20°C), whilst pressures range from ~0.4 GPa to ~0.75 GPa. Calculated water content in the melt (H_2O_{melt}) at the time of amphibole crystallisation is in the range of 3.5–5.8 wt%. Clinopyroxenites seem to show a positive correlation between H_2O_{melt} and both temperature and pressure, whereas no correlation is observable in gabbros. Calculated temperatures fall into the range of those suggested by Turner *et al.* (2003) (1000–1100°C), whilst calculated pressures are at the lower end of the range that Turner *et al.* (2003) propose (~0.5–1 GPa). However, average water content (4.6 wt%) is significantly higher, and in some cases almost double than that suggested by Turner *et al.* (2003) (~3 wt%). These results suggest that water contents in Sangeang Api magmas are, in some instances, higher than previously thought. Evidence is provided that the parental mantle melts of Sangeang Api magmas are volatile rich and hydrous. Oxygen fugacities (fO_2) of amphibole-bearing xenoliths are calculated to be up to 1.2 log units above the NNO buffer. As a function of temperature, calculated fO_2 seems to show complex, unbuffered behaviour with some suggestion of an early oxidation trend. This trend is interesting given the observation by Lee *et al.* (2010) that arc magmas may become oxidised after their extraction from the mantle. The Mg# of the amphiboles shows a large range (0.45–0.6), falling towards lower pressures (<550 MPa) and suggesting fractionation occurs at shallow depths. We interpret the Sangeang Api cumulate suite to represent crystallisation from shoshonite melts in a succession of small, stacked crustal magma chambers.

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04DP-P29. UNVEILING IGNEOUS ACTIVITY ALONG AUSTRALIA'S SOUTHEASTERN CONTINENTAL MARGIN

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The Australian southeastern continental margin is a classic example of intraplate volcanism and its origin and emplacement has confounded geologists for decades. To date, almost all investigations of this intraplate basaltic province have focused on the preserved, onshore record of magmatism. However, this review shows that an extensive and largely undescribed record of Cenozoic magmatic activity is preserved within the sedimentary successions of the Bight, Otway, Bass and Gippsland rift basins.

While continental breakup initiated at 83 Ma in the Bight Basin, seismic reflection surveys show that magmatic activity in the central Ceduna Sub-basin mainly occurred during Middle Eocene times, coinciding with accelerated seafloor spreading and major changes in global tectonics[1]. This activity is expressed as volcanoes and lava flows at the base of the Dugong Supersequence, and is fed by underlying dykes and sills[1]. The Otway Basin on the other hand, has seen breakup at 67 Ma and near continuous volcanic activity with large volumetric peaks at 57–42 Ma and 5–0 Ma[2]. Onshore, this activity is recognised as the various volcanic features of the Older and Newer Volcanic Provinces. Offshore features comprise latest Maastrichtian–Middle Eocene lava aprons, small sills and hydrothermal vents and extrusives of Newer Volcanic age[3]. The Torquay Sub-basin, although part of the Otway Basin but stratigraphically more similar to the Bass Basin, hosts a mid-Oligocene shallow marine volcanic complex, consistent with the onshore Eastern View and Airey's Inlet lavas and plugs. In contrast to the Bight, Otway and Gippsland basins, the Bass Basin has not undergone breakup. Within the Bass Basin, several volcanic phases have been identified, which correlate with observed volcanic activity onshore in Tasmania. A first Mid-Cretaceous phase caused by rifting, consists of lava flows, mounds and cones, followed by a latest Maastrichtian–Paleocene phase of extrusive flows and intrusive sills[3]. A third and more extensive phase occurred during the Oligocene to Miocene, comprising volcanic mounds, vents, lava flows, sills and dykes[3], which correlates strikingly to an extensive phase of magmatism onshore Tasmania, with a volumetric peak at 20–30 Ma. Breakup of the Gippsland Basin initiated at 80 Ma by a failed rift arm of the Tasman Sea and volcanism consists of offshore Campanian flows and sills along the major northern fault system and mid-Eocene sills near the Bream Field, and a late Oligocene suite onshore[3].

This review signals that the distribution of igneous activity cannot be solely explained by the classic plume model proposed for Cenozoic magmatism in eastern Australia. Unravelling the magmatic signal remains a key challenge and calls for an amalgamation of lithospheric processes, such as stretching and edge convection.

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LIVING EARTH

04LE-P02. THE RISE AND FALL OF LIFE IN THE CA 3.5GA DRESSER FORMATION, NORTH POLE DOME, PILBARA CRATON, WESTERN AUSTRALIA

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Extensive mapping, petrological data and geochemical analyses are presented that shed new light on the environment of cherty sedimentary rocks that contain Earth's oldest convincing evidence of life in the *ca* 3.5Ga Dresser Formation, North Pole Dome, Western Australia.

Some researchers have interpreted a quiet shallow water evaporitic setting whilst others have suggested stromatolites grew within a tidal flat. However, recent stratigraphic correlation and petrographic data supports alternative models that the Dresser Formation was deposited within a developing volcanic caldera setting flushed by voluminous hydrothermal fluids.

A series of stratigraphic profiles measured on either side of the Dresser Mine over a distance of seven kilometres display true sediment thickness variations (estimated by extracting the thicknesses of intrusive hydrothermal barite and chert) across active growth faults, as previously noted, thereby supporting a volcanic caldera setting. In addition, we report here the first occurrence of geyserite from the Dresser Formation, which is proximal to demonstrably biogenic stromatolites and thus provides evidence for microbial communities living adjacent to hot spring vents. Petrographic data from an occurrence of domical stromatolites shows termination of stromatolite growth with appearance of felsic volcanic glass shards, confirming the setting of early life within a low-eruptive felsic volcanic caldera. Signs of life in the sedimentary units are restricted to shallow water environments, formed immediately prior to widespread crustal rupture and onset of voluminous hydrothermal fluid circulation. This is inferred to have developed as a response to inflation and uplift of the surface during emplacement of a subvolcanic magma system that drove geysers and erupted ash. Subsequent caldera collapse formed deeper basins accompanied by coarse clastic sedimentary rocks in which there are no apparent signs of life. Therefore we present stratigraphic evidence and petrographic analyses, which support the deposition of sediments, hydrothermal precipitates and putative fossils during the episodic stages of uplift and subsidence controlled by the cyclic nature of a volcanic caldera, and outline the stages of a developing hydrothermal system, features of which depict the rise and fall of this ancient volcanic environment and the life contained therein.

04LE-P03. K(C)ALAMINA GORGE ODDITIES REVISITED

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Features in the Brockman Iron Formation of K(C)alamina Gorge, Karijini National Park, WA, were offered for comment in *Nomen nudum* ***32,*** p. 10–12 (2012). Remarks received and further study has suggested particular interpretations.

Three types of features occur – all bed-wide features associated with microbial mats showing Trendall microbands. Two – *Alpha* and *Beta* – generally modify the depositional interface microbial mat. The third – *Gamma* – are localised subcircular zones within which several subjacent microbands have been destroyed; radial elements – *spokes* – when present lend a pseudo-medusoid appearance.

Alpha displays randomly-oriented gentle 3–5 mm-wide interfering and meandering ridges of variable length. *Kinneyia* is used for such wrinkled microbial mat. However, diverse origins are indicated since examples with ridges ranging from subparallel to randomly oriented have been grouped in *Kinneyia*.

Beta are *shadow structures* (*inverted flutes* or *setulf*): subparallel drumlin-shaped ridges (up to 5 mm x 50 mm) on the depositional interface. These result from currents emphasising any raised irregularities on the depositional interface by encouraging thicker mat growth on the sheltered lee-side of irregularities.

Gamma are subcircular to elliptical bedding plane depressions, many with *spokes* emerging from their edges; several occur on one bedding plane, with localised concentration up to ~400 /m^2. Their size ranges from 17 mm x 15 mm up to 52 mm x 38 mm. Alignment of long axes has a spread of only 42^o, suggesting possible current control. One photograph provides a vertical cross section; here about 40 microbands are sharply interrupted by a central body of amorphous massive material, which is biconcave with a mound beneath (possibly diagenetic concretionary inflation) and the depression above (with microbands draped into the depression). The traces of microbands above and below suggests that about 75% of sedimentary material has been removed within the depression. The combination of the depression surrounded by *spokes* gives *Gamma* a ‘medusoid’ appearance; the *spokes* of closely located depressions merge into each other.

‘Medusoid’ appearance is a feature of ‘*Astropolithon*’ (*s.l.*) – a gas/fluid escape feature in microbial mats involving upward entrainment of sediment. No features suggesting this entrainment are seen in the cross section of *Gamma*. Also other factors do not agree with this interpretation.

Gisela Gerdes (Fig. 2-1-4H *in* Schieber 2007) illustrated modern features with geometry comparable to *Gamma*; her caption reads: “Individual knots protruding out of the leathery surface mat. Major species involved in both mat and knots is cyanobacterium *Lyngbya aestaurii*.” Gerdes’s figure shows lines/strands (?*spokes*) connecting neighbouring knots. No description or discussion of cross sections of knots was presented.

Regardless of modern analogies, *Gamma* either destroyed or inhibited development of the microbe-bound microbands. Timing of this is uncertain; however, the *spokes* suggest completion when the topmost layer was still the depositional interface, with *spokes* representing surface tension tears in the microbial mat around *Gamma*’s depressions. The relationship between *Gamma* and the microbands could be seen as competition between bacteria each influencing the sedimentary record differently.

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