

Temperature and hydrological change in central Australia through the last glacial cycle: Insights from clumped isotope analysis of lacustrine molluscs

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ABSTRACT

Quantitative records of past temperature are crucial for understanding the full range of variability experienced on Earth's surface, and associated drivers. However, Quaternary temperature reconstructions for arid regions are rare, particularly in the Southern Hemisphere, including Australia. Here we utilise the clumped isotope (Δ_{47}) thermometer to estimate carbonate precipitation temperatures for fossil mollusc (*Coxiella* sp. and *Corbicula australis*) shells deposited within Quaternary shoreline sediments of three large ephemeral lakes – Kati Thanda-Lake Eyre, Lake Frome, and Lake Callabonna as a way of investigating past climatic conditions in Australia's arid interior throughout the last glacial-interglacial cycle. This study constitutes the longest and most detailed record of past temperature variability to date in central Australia, with estimated mean annual air temperatures (MAAT) inferred to be $\sim 4\text{--}6\text{ }^{\circ}\text{C}$ cooler than modern-day conditions between ~ 51 and 33 ka and air temperatures comparable to present interpreted for 196 ± 12 ka and $\sim 75\text{--}57$ ka. Calculated MAAT estimates are supported by Δ_{47} measurements for modern mollusc shells, collected in salt lakes in southern Western Australia, which give accurate modern air temperature estimates within the bounds of uncertainty. Additionally, calculated water temperatures and carbonate $\delta^{18}\text{O}$ are used to infer past lake hydrology. Carbonate $\delta^{18}\text{O}$ was driven predominantly by changes in lake water $\delta^{18}\text{O}$, rather than by environmental temperature, depicting changes in the evaporative state of the palaeo-lakes. While these findings are limited by the inability to confirm the absence of potential disequilibrium effects and uncertainties regarding the organisms' life cycles, our results demonstrate the value of clumped isotopes for reconstructing palaeoclimate in arid environments and indicate significant temperature variability in Australia's arid interior during the last glacial-interglacial cycle.

1. Introduction

Quantifying past climates is essential for understanding the full range of climate variability on Earth's surface. Palaeoclimate records have important ramifications for better understanding climate system mechanisms and for predicting future changes in climate under various warming scenarios (Tierney et al., 2020b). Unfortunately, there are few direct quantitative records of past climate – especially temperature – across all climatic zones. Palaeoclimatology instead relies heavily on indirect “proxy” surrogates for climate variables, mainly from past ecological assemblages or geochemical data such as elemental and

stable isotope ratios from a range of minerals, fossils, and organic materials (Tierney et al., 2020a).

Estimating past temperature has proven particularly difficult in semi-arid and arid terrestrial environments, such as the Australian continental interior. The need for palaeotemperature records from Australian deserts is mirrored in other desert regions worldwide, notably in the arid subtropics of Africa and South America, where Quaternary temperature records are also scarce (e.g. Klinge and Sauer, 2019; Fietz et al., 2023). Consequently, developing new temperature records for arid Australia is of hemispheric and global significance, both for understanding the sensitivity of arid regions to global change and to better constrain

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changes in equator-pole thermal gradients (e.g. Shakun et al., 2012; Tierney et al., 2020a; Seltzer et al., 2021).

Various proxies have been used to reconstruct late Quaternary temperature changes in the temperate and humid subtropics of Australia, such as stable oxygen isotope ratios in mollusc shells ($\delta^{18}\text{O}$) (Tynan et al., 2017), pollen (Fletcher and Thomas, 2010), and both branched and isoprenoidal glycerol dialkyl glycerol tetraether biomarkers (GDGTs) (Woltering et al., 2014; Li et al., 2023). For arid central Australia, the only estimates of past temperature to date were made from emu eggshell fragments using amino acid racemisation, deposited over the last 45 kyr (Miller et al., 1997). The temperature-dependent rate changes in amino acid racemisation have been used to infer cooling of millennial-scale average annual air temperatures by at least 9 °C from 45 to 16 ka, relative to those after 16 ka, reflecting global-scale cooling processes during this period (Miller et al., 1997). Estimates from Lake McKenzie, K'gari (Fraser Island) (Woltering et al., 2014), and marine sediments near the Cape Range Peninsula, Western Australia (van der Kaars and De Deckker, 2002, 2003; van der Kaars et al., 2006) suggest only ~4 °C of warming occurred between the LGM and Holocene. This raises the question of whether the magnitude of warming was either magnified in the arid regions or muted in more temperate zones.

Good progress has been made in understanding the hydrological and ecological changes in central Australia through the mapping and dating of geomorphic archives, including ancient lake shorelines (Magee et al., 1995; Magee and Miller, 1998; Nanson et al., 1998; Cohen et al., 2011, 2012, 2017, 2022), dune fields (Chen et al., 1991; Hesse et al., 2004; Maroulis et al., 2007; Bourne et al., 2019), alluvial and fluvial deposits (Croke et al., 1996; Nanson et al., 2008; Williams, 2015), and groundwater-fed carbonates (Priestley et al., 2018). Geochemical data from soil carbonates, eggshells, pollen, microbial lipids, and plant phytoliths (Pearson et al., 2001; Miller et al., 2005, 2016; Bray et al., 2012; Fitzsimmons et al., 2013) have also been used to quantify past hydrological and ecological changes. While these records are extremely valuable, there remains a lack of quantitative temperature reconstructions which are vital for further understanding past and future climatic changes in arid Australia.

Palaeoshorelines of central Australian playa lakes are iconic archives of the central Australian hydrological record, providing the only direct proxy for previous water depths (Cohen et al., 2012; Fitzsimmons et al., 2013). The ephemeral Kati Thanda-Lake Eyre (KT-LE) is primarily fed by rainfall from the Indo-Australian Summer Monsoon (IASM; Fig. 1), with ancient shoreline and lacustrine deposits interpreted to reflect of changes in the IASM over the last glacial-interglacial cycle (Bowler, 1986; Magee and Miller, 1998; Croke et al., 1999; Hesse et al., 2004). In contrast, Lake Callabonna and Lake Frome, located south of KT-LE, are fed by runoff associated with both summer (northerly) and winter (south-westerly) precipitation (Cohen et al., 2012). However, whilst the shorelines can be directly interpreted in the context of lake volume and hence total effective moisture (Nanson et al., 1998; Magee et al., 2004; Cohen et al., 2011, 2012, 2015, 2022), uncertainties remain regarding the nature of the lakes' hydrology, such as the residence time of water within the lakes, and hence the extent to which the lakes were terminal or throughflow systems. These processes can be interpreted from oxygen isotope analyses of lake carbonates, although such interpretations are typically hindered by a lack of constraint over the relative effect of temperature and the $\delta^{18}\text{O}$ of water on carbonate $\delta^{18}\text{O}$ values (Fritz et al., 1975; Talbot, 1990; Sampei et al., 2005; Yang et al., 2005; Kieniewicz and Smith, 2007; Liu et al., 2009).

Lake hydrology and air temperature variability during the last glacial cycle is important for the ongoing debate around the extinction of the Australian megafauna, with evidence for abundant megafauna prior to ~40 ka (Hocknull et al., 2020) implying hydrological and ecological conditions that were significantly different to modern conditions (Nanson et al., 1998, 2008; Magee et al., 2004; Maroulis et al., 2007; Cohen et al., 2015, 2022; Miller et al., 2016). While much of the current

understanding of central Australian palaeoecology is derived from megafaunal remains (Wells and Callen, 1986; Wells and Tedford, 1995; Nanson et al., 2008), the climatological context for their habitation and disappearance from Australia's interior remains poorly understood. The debate around the extinction of the Australian megafauna has previously focused on the arrival of humans into Sahul (e.g. Roberts et al., 2001; Gillespie et al., 2008; Clarkson et al., 2017; Hiscock, 2017), with the possibility of a relatively long period of coexistence between people and megafauna from ~65 ka (Clarkson et al., 2017) to 40.1 ± 1.7 ka (Hocknull et al., 2020). More detailed assessment of the climate during the period of megafauna extinction is required to further increase our understanding of the drivers of this ecological catastrophe.

'Clumped isotope' carbonate thermometry presents a potential solution to the need for quantitative palaeotemperature estimates in central Australia. The clumped isotope carbonate palaeothermometer exploits the correlation between mineralisation temperature and the frequency of bonding between ^{13}C and ^{18}O (quantified as Δ_{47}), due to the greater thermodynamic stability of the ^{13}C - ^{18}O bond at lower temperatures (Ghosh et al., 2006; Eiler, 2007). Unlike palaeotemperature inferences using single element isotope geochemistry (e.g. $\delta^{18}\text{O}$), clumped isotope estimations of mineralisation temperature are independent of environmental water oxygen isotope compositions, which are often unknown in terrestrial settings (Eiler, 2007; Spencer and Kim, 2015). Clumped isotope analysis also enables inference of environmental water $\delta^{18}\text{O}$, which is valuable for reconstructing palaeohydrology (Eiler, 2007).

In this paper we present mollusc Δ_{47} estimates for lake water and air temperature, representing the longest and most detailed record to date of past temperature variability for the iconic central Australian ephemeral lakes (Callabonna, Frome, and KT-LE). The relationships between inferred temperature and $\delta^{18}\text{O}$ for source water and bulk carbonate are also used to investigate the environments in which the molluscs lived. Due to the global dearth of quantitative palaeotemperature data from arid and semi-arid zones, this investigation provides an important case study towards increasing our understanding of the magnitude and impact of climate change in desert regions worldwide.

2. Regional setting

Kati Thanda-Lake Eyre (KT-LE) is Australia's largest playa lake, situated at the southern end of the continent's largest endorheic drainage system (~ 1.2×10^6 km²; Fig. 1). The modern lake consists of the Lake Eyre North and Lake Eyre South basins, which have a combined area of ~9700 km² and are connected by the Goyder Channel. KT-LE is mainly fed by the Georgina-Diamantina River and Cooper Creek to the north-east, with more intermittent contributions from the Macumba and Neales rivers to the west (Fig. 1). The lake floor sits as low as -15.2 m AHD (Australian Height Datum), representing the lowest point on the Australian continent (Leon and Cohen, 2012). Presently, KT-LE only fills at times of monsoon intensification, with the largest recorded event in historical times filling to a depth of approximately 5 m (-10 m AHD) in 1974 (Magee and Miller, 1998). Ancient shorelines indicate the lake filled to a maximum depth of ~25 m (+10 m AHD) during Marine Isotope Stage (MIS) 5, with geomorphological evidence and digital elevation modelling suggesting KT-LE was joined with nearby playas of Callabonna and Frome to form a mega-lake system with a combined area roughly 10 times that of modern KT-LE and a combined volume of 388 km³ (Nanson et al., 1998; Cohen et al., 2011, 2012, 2015, 2022; Leon and Cohen, 2012).

The Lake Mega-Frome system (the combination of the ephemeral lakes Blanche, Callabonna, Frome, and Gregory – see Fig. 1) form an arc around the northern Flinders Ranges. The playas are fed by runoff from the Flinders Ranges and by Strzelecki Creek, a distributary of Cooper Creek. While the Lake Mega-Frome playas have relatively small catchment areas (compared to the KT-LE basin), sporadic large flooding



Fig. 1. Map of southern central Australia, with Kati Thanda-Lake Eyre and the playa lakes Gregory, Blanche, Callabonna, and Frome. Major ephemeral waterways are also shown. Palaeoshoreline excavation sites where the mollusc shells used in this study were collected are denoted by dark grey circles.

events on Cooper Creek enable Strzelecki Creek to carry discharge into lakes Blanche and Callabonna from an upstream catchment area that could be larger than 360,000 km² (May et al., 2015; Treble et al., 2017). During previous filling events, water also flowed from Lake Callabonna into Lake Frome via Salt Creek, which is a channel that connects the two lakes (Fig. 1). Lake floor elevations of the Mega-Frome system range from −5.42 to +1 m AHD, with the four playas combining to form Lake Mega-Frome when filled to ~4–8 m AHD. Filling to ~15 m AHD is required before Lake Mega-Frome flows into Lake Mega-Eyre via the Warrawoocara Channel (Nanson et al., 1998; Cohen et al., 2012).

The catchment area of the Lake Eyre Basin (LEB) extends into the IASM rainfall zone (Bowler, 1986) with the headwaters at ~17–19°S latitude. Transmission of floodwaters to the terminal playas is very inefficient, with only the largest floods resulting in lake filling under the modern regime, implying the palaeohydrology of the two mega-lakes was dominated by extreme monsoonal precipitation events, changes in flood frequency (Bowler, 1986; Magee and Miller, 1998; Croke et al., 1999; Hesse et al., 2004; Cohen et al., 2015) in addition to the impacts of changed evaporative conditions. The lakes are also situated on the western margin of the Great Artesian Basin and receive artesian groundwater inflow from this very large (~1,700,000 km²) series of aquifers. However, absolute and relative groundwater contributions to the lakes cannot be reliably constrained and may have varied in the past (Habermehl, 1980; Bowler et al., 1986; De Deckker et al., 2011; Evans et al., 2024).

The central Australian playas experience hot and dry modern climatic conditions, with summer and winter mean monthly maximum temperatures of ~37 °C and ~20.1 °C, respectively, as recorded by the nearest Bureau of Meteorology weather station in Marree (<http://www.bom.gov.au>). Averaged temperature data from several nearby weather stations can be found in Table S1. Annual potential evaporation rates for the region are estimated to be > 3000 mm/yr but with specific years with limited measurements showing annual values of 1960 mm/yr (Penman, 1955), with a mean average annual rainfall of 168 ± 31 mm/yr from 2000 to 2023 (<http://www.bom.gov.au>).

3. Methods

3.1. Sample collection

A suite of mollusc shells excavated from ancient shorelines from lakes Callabonna, Frome, and KT-LE were selected for this study. Samples were also collected from a palaeoshoreline at the northern extent of Salt Creek, where water would have previously entered from Lake Callabonna (Fig. 1). Shoreline elevations range from near the modern playa to 25 m above the playa floor. Sample information, including locations, elevation, and the number of individual shells used, can be found in Table S2. Mollusc samples are predominantly *Coxiella*, with the bivalve *Corbicula australis* also studied. Most shell samples are from stratified shoreline sediments that were dated using single grain optically stimulated luminescence (OSL) and thermoluminescence (TL) (Cohen et al., 2012, 2017, 2022). A new single-grain quartz thermally transferred optically stimulated luminescence (TT-OSL) age is also presented in this study for the +20.8 m AHD shoreline sediments at Lake Callabonna that host *Corbicula australis* shell samples. Direct dating of shells is based on previously published radiocarbon determinations by Cohen et al. (2012, 2017), along with new additional radiocarbon analyses where possible for comparison.

No modern *Coxiella* were available from the studied central Australian playas, so modern samples were collected from lakes near Esperance and Green Head, Western Australia, from 2018 to 2021 to validate the assumption that the clumped isotope composition of *Coxiella* shells reflects lake water and air temperature. These modern *Coxiella* shells had previously been collected from 2018 to 2021 and subsequently archived by the Murdoch University Centre for Sustainable Aquatic Ecosystems. All shells had been collected during August to October months, with all

samples collected as living specimens. Unfortunately, no samples outside of these months could be obtained, as they were originally collected for a previous *Coxiella* phylogenetics study at the Murdoch University (Lawrie et al., 2023). Annual water temperature data was also not collected for the lakes that the modern Western Australian molluscs grew in. These modern shells were prepared using identical methods to the central Australian samples and sample information is included in Tables S2 and S3 in the Supplementary Material section of this paper.

3.2. Shell sample preparation

Whole shell pieces were used for each sample, except for the four *Coxiella* samples indicated in Table S2, for which the most complete remains of broken individuals were prepared. Mollusc shells were selected and manually cleaned with a fine brush and reverse osmosis (RO) water to ensure any adhering sediment had been removed before treatment with pH 8 buffered 18% H₂O₂ solution for 30 min to remove any organic matter (Fig. 2) (Falster et al., 2018; Roberts et al., 2018; Zhang et al., 2020). Treated shells were then rinsed four times with ultrapure 18 MΩ Milli-Q water and oven-dried overnight at 40 °C. Cleaned shells were finely ground into a homogenous powder with an agate mortar and pestle. Multiple individuals of a single taxon (up to 20 for *Coxiella* samples and 1–2 for *Corbicula australis*) were combined to obtain sufficient powder for clumped isotope analysis, with the homogenous powders representing the average isotopic compositions for the shells within a sampled sediment layer.

Where possible, mollusc shell mineralogy was determined by X-ray diffraction (XRD) analysis, which was conducted at the Mawson Analytical Spectroscopy Services (MASS) facilities, University of Adelaide, Australia. XRD analysis was performed using a Bruker D8 ADVANCE Powder X-ray Diffractometer with a Cu-radiation source operating at 40 kV and 40 A, scanning 2 θ from 5° to 65° with sample rotation of 30 rotations per minute. Sample powders were sprinkled onto silicone wafers in a fine dusting over the centre of the wafer and loaded into an XRD sample holder with vibration to minimise orientation. Data were processed using Bruker DIFFRAC.EVA software and Crystallography Open Database reference patterns for identifying mineral phases, with mineral relative abundances semi-quantitatively calculated using TOPAS 4.2 software.

3.3. Radiocarbon dating

Shells from the same palaeoshorelines as those used for XRD and clumped isotope analyses were ultrasonically cleaned in ultrapure 18 MΩ Milli-Q water for 1 h, with undamaged shells selected where possible. Shell samples were reacted with ~2 mL of 85% phosphoric acid (H₃PO₄) at 90 °C. CO₂ gas evolved from the outer portion of each sample in the first 3 min of the hydrolysis reaction was evacuated from the reaction vessel and not used for ¹⁴C analysis. On average ~25% of mass for each sample was removed by this acid etch. The reaction was then maintained for another 1 h. The liberated CO₂ from the remaining carbonate of each sample was cryogenically purified and reduced to graphite over an Fe catalyst at 600 °C in excess of H₂ (Hua et al., 2001). Approximately 1.5–2.0 mg of Fe catalyst was used, with a H₂ to CO₂ ratio of ~2.5:1. Water vapour produced by the graphitisation reaction was removed using a two-stage Peltier chiller at −39 °C.

Graphite was pressed into an aluminium cathode for accelerator mass spectrometry (AMS) analysis using the VEGA accelerator at the Australian Nuclear Science and Technology Organisation (ANSTO) in Lucas Heights, New South Wales (Fink et al., 2004; Wilcken et al., 2015). A portion of graphite was used for the determination of δ¹³C for isotopic fractionation correction using an Elemental vario ISOTOPE Select Elemental Analyser coupled with an Elementar EcovisION Continuous Flow Isotope Ratio Mass Spectrometer (EA-IRMS). Oxalic acid I (HOxI) was used as a primary standard for the calculation of ¹⁴C ages for the

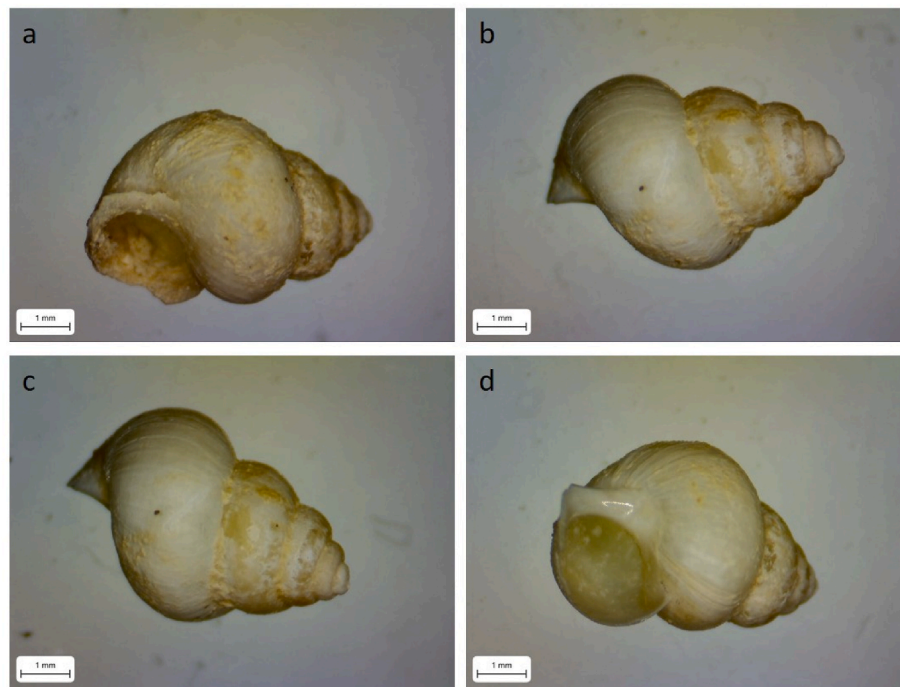


Fig. 2. Effects of sample preparation process on individual lake shells after a) no treatment; b) manual cleaning; c) H_2O_2 treatment for 15 min; and d) H_2O_2 treatment for 30 min.

shell samples. IAEA-C2 travertine and IAEA-C1 marble (Rozanski et al., 1992) were used as reference material and blank, respectively. Radiocarbon results are reported in percent modern carbon (pMC) and as conventional radiocarbon ages (Stuiver and Polach, 1977). All radiocarbon ages have been calibrated using the Southern Hemisphere calibration curve SHCal20 (Hogg et al., 2020) and the OxCal program v.4.4 (Bronk Ramsey, 2009).

3.4. Single-grain TT-OSL dating

An optical dating sediment sample (LE19-10) was collected from the uppermost shell-rich gravel layers of the +20.8m AHD shoreline at Lake Callabonna to provide an estimate of when the host deposits were last exposed to light prior to burial. We have focussed on using single-grain quartz TT-OSL dating (Arnold et al., 2013, 2014) to determine when the +20.8m AHD shoreline sediments accumulated as this ‘extended-range’ optical dating signal exhibits considerably higher dose saturation properties than the conventional quartz OSL dating signal (e.g., Arnold et al., 2015) and has been shown to provide reliable finite depositional chronologies over both Late and Middle Pleistocene timescales at a range of independently dated sites (Arnold and Demuro, 2015; Méndez-Quintas et al., 2018; Arnold et al., 2019, 2022, 2024; Demuro et al., 2019, 2020; Duval et al., 2020, 2022).

Purified coarse grain quartz extracts were processed under safe light conditions (630 nm LEDs, $<0.15 \mu\text{W}/\text{cm}^2$ power density at sample position) at the University of Adelaide using standard preparation procedures (e.g. Demuro et al., 2013). These procedures included a 48% hydrofluoric acid etch (40 min) to remove the alpha-irradiated outer layers of the quartz extracts. Single-grain TT-OSL measurements were made using the experimental apparatus, single-aliquot regenerative-dose (SAR) procedures, and quality assurance criteria published previously by Arnold et al. (2019, 2024), which are further detailed in the Supplementary Note 1. For equivalent dose (D_e) evaluation, 90–125 μm diameter quartz grains were manually loaded onto aluminium discs drilled with an array of $300 \times 300 \mu\text{m}$ holes. One thousand six hundred D_e measurements were made using the SAR procedure shown in Supplementary Note 1, which yielded suitable dose recovery test results for

sample LC19-10.

Environmental dose rates were estimated using a combination of *in situ* field gamma spectrometry and low-level beta counting, taking into account cosmic ray contributions (Prescott and Hutton, 1994), an assumed minor internal alpha dose rate (Bowler et al., 2003), beta-dose attenuation (Mejdahl, 1979; Brennan, 2003) and long-term sediment water contents (Aitken, 1985; Readhead, 1987). Gamma dose rates were calculated from *in situ* measurements made at each sample position with a NaI:Tl detector (using the ‘energy windows’ approach; Arnold et al., 2012; Duval and Arnold, 2013), while beta dose rates were calculated on dried and powdered sediment collected from within a 1 cm radius of the TT-OSL sample position using a Risø GM-25-5 low-level beta counter (Bøtter-Jensen and Mejdahl, 1988). Further details of the TT-OSL dating procedures are provided in the Supplementary Note 1.

3.5. Water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotope analysis

Three water samples were obtained from Belt Bay, on the southwestern margin of KT-LE (S28°49′58.8″, E136°54′58.2″) in July 2022. Stable oxygen and hydrogen isotope ratios were analysed at Flinders University, South Australia, using a Picarro L2130-i cavity ring-down analyser, calibrated against three internal standards, with an analytical precision of 0.49‰ for $\delta^2\text{H}$ and 0.07‰ for $\delta^{18}\text{O}$.

3.6. Clumped isotope analysis

Detailed methods for clumped isotope analysis are provided in Supplementary Note 2. To summarise, clumped isotope analysis was performed at the University of Adelaide using a Nu Instruments Perspective-IS stable isotope ratio mass spectrometer, interfaced with a Nu Carb carbonate sample preparation system to measure Δ_{47} , $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ for purified sample gas, relative to a working gas of known isotope composition. Sample aliquots of 350–400 μg of the prepared carbonate powder were digested with anhydrous phosphoric acid at 70 °C, with the resulting carbon dioxide purified by a combination of cryogenic and adsorptive means to remove possible contaminants.

Raw sample Δ_{47} values were calculated using Equation (1), with R_i

values derived from the measured δ^i values for each isotopologue in the sample gas, relative to the working gas:

$$\delta^i = \left[\frac{R_{i(\text{sample gas})}}{R_{i(\text{working gas})}} - 1 \right] \times 1000 \quad (\text{Eq.1})$$

Uncertainty is reported as standard error:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \quad (\text{Eq.2})$$

where n is the number of replicates and σ is the standard deviation of the 10 sample replicates for a given unknown powder.

Following analysis, data were screened for unrealistic raw Δ_{47} measurements, with any potentially contaminated data points excluded from further analysis. Conversion into the I-CDES reference frame was achieved through calibration of raw Δ_{47} measurements against measurements of ETH standards to allow inter-laboratory comparison of results (Dennis et al., 2011; Meckler et al., 2014; Bernasconi et al., 2018, 2021; Daëron, 2021). An internal standard (ANU P3) and the New Carrara Marble (NCM) standard were used for calibration of sample $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ measurements.

ETH standards 1–3 were used to correct data for pressure baseline effects (Bernasconi et al., 2013; Meckler et al., 2014; Petersen et al., 2019) and to project raw Δ_{47} measurements into the I-CDES standardisation scheme (Anderson et al., 2021; Bernasconi et al., 2021; Daëron, 2021). ETH-4 was excluded in favour of additional ETH-3 standards to increase sample Δ_{47} precision (Kocken et al., 2019). The “IUPAC” (International Union of Pure and Applied Chemistry) parameters for the abundance of heavy carbon and oxygen isotopes in the Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW) universal standards, as summarised by Brand et al. (2010), were used for the calculation of Δ_{47} values (Daëron et al., 2016; Schauer et al., 2016; Kelson et al., 2017; Petersen et al., 2019).

Ten aliquots were prepared and analysed for each sample, with Δ_{47} , $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ values calculated as the arithmetic mean average of these 10 aliquots, after excluding any potentially contaminated aliquots. Carbonate $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are reported relative to the VPDB standard. Once converted to the I-CDES reference frame, sample formation temperatures, $T(\Delta_{47})$, were calculated using the calibration of Anderson et al. (2021):

$$\Delta_{47} = (0.0391 \pm 0.0004) \times \frac{10^6}{T(\Delta_{47})^2} + (0.154 \pm 0.004) \quad (\text{Eq.3})$$

where $T(\Delta_{47})$ is temperature in Kelvin ($R^2 = 0.97$).

The transfer function of Hren and Sheldon (2012) was used to convert mollusc carbonate precipitation temperatures to mean annual air temperature (MAAT) values, with this function being independent of latitude, elevation, the size of the water body, and annual climatic conditions:

$$\text{MAAT} = -0.0318 \times T_{\text{water}}^2 + 2.195 \times T_{\text{water}} - 12.607 \quad (\text{Eq.4})$$

where T_{water} is the mean annual water temperature and both MAAT and T_{water} are in $^{\circ}\text{C}$ ($R^2 = 0.96$).

Environmental water oxygen isotope compositions were calculated using the equation of Grossman and Ku (1986) for biogenic aragonite, as modified by Dettman et al. (1999):

$$1000 \ln(\alpha_{\text{aragonite-water}}) = 2.599 \times \frac{10^6}{T^2} + 0.715 \quad (\text{Eq.5})$$

where T is degrees Kelvin ($R^2 = 0.94$). Environmental water $\delta^{18}\text{O}$ values were then calculated using the following equation:

$$\alpha_{\text{aragonite-water}} = \frac{(1000 + \delta^{18}\text{O}_{\text{aragonite(VSMOW)})}}{(1000 + \delta^{18}\text{O}_{\text{water(VSMOW)})}} \quad (\text{Eq.6})$$

Environmental water $\delta^{18}\text{O}$ values are reported relative to the

standard Vienna Standard Mean Ocean Water (VSMOW).

4. Results

4.1. Radiocarbon dating

The new AMS ^{14}C data obtained in the present study are summarised in Table 1. All samples yielded ^{14}C ages of >41 ka cal BP. The two samples (LCP2 0.85 and CSP1 1.0) with radiocarbon ages also reported by Cohen et al. (2012) both fall within 1 sigma uncertainties of the previous ^{14}C ages. Sample WPLE P4B has an estimated ^{14}C age of ~ 46.4 ka cal BP but was collected from a *Coxiella* beach deposit that has previously been OSL dated to 71 ± 4 ka (79–63 ka; 95% C.I.) (Cohen et al., 2022). Similarly, sample LFP1 1.3 was collected from a palaeoshoreline dated to ~ 64 ka using OSL (Cohen et al., 2012) but returned a younger radiocarbon age of ~ 46.1 ka cal BP. Most of the samples are near the maximum age detectable by ^{14}C dating.

4.2. Single-grain TT-OSL dating

Table 2 provides a summary of the environmental dose rate, single-grain D_e values and final TT-OSL age for sample LC19-10 from the +20.8m AHD shoreline at Lake Callabonna. The single-grain D_e distribution of grains that passed the SAR quality assurance criteria are shown in Fig. 3. The single-grain TT-OSL D_e distribution displays limited scatter and contains a single dose population, with the majority of individual D_e values falling within the 95% C.I. of the weighted mean D_e value (grey shaded band of Fig. 3). The D_e dataset exhibits low overdispersion ($15 \pm 4\%$), consistent with values reported elsewhere for well-bleached and unmixed single-grain TT-OSL D_e datasets (e.g., Demuro et al., 2014, 2015, 2022, 2023; Arnold et al., 2019, 2022). The D_e distribution is not considered significantly positively skewed according to the weighted skewness test outlined by Bailey and Arnold (2006) and Arnold and Roberts (2011), while application of the maximum log likelihood (L_{max}) test (Arnold et al., 2009) indicates that the central age model (CAM) is statistically favoured over the three- or four-parameter minimum age models (MAM-3 or MAM-4) of Galbraith et al. (1999). These D_e characteristics suggest that the sample was not significantly affected by partial bleaching or post-depositional complications (e.g., sediment mixing or beta dose rate heterogeneity). Consequently, a representative single-grain TT-OSL burial dose estimate has been calculated using the weighted mean (CAM) D_e estimate (Table 2).

The final TT-OSL age for the shell-rich deposits is 195.7 ± 11.9 ka (1σ), indicating that the +20.8m AHD shoreline feature most likely accumulated during the MIS-7 interglacial complex (243–191 ka; Lisiecki and Raymo, 2005), or potentially during early MIS-6 (191–130 ka) when taking into account the associated 2σ uncertainty ranges.

4.3. Combined lake shoreline chronologies

The newly obtained ^{14}C and TT-OSL ages have been used in tandem with the previously published ^{14}C and OSL ages (Cohen et al., 2012, 2017, 2022) to establish a combined chronological framework for the studied mollusc samples, as shown in Table 3. The new ^{14}C ages obtained in this study support previous ^{14}C dating attempts, suggesting shells within the sampled stratigraphic layers were deposited coevally, rather than being the products of multiple filling episodes.

Radiocarbon dating of terrestrial shells is not straightforward as several environmental factors can influence their measured ^{14}C ages. The feeding of ^{14}C -depleted groundwater into the lakes may have resulted in shell ^{14}C ages appearing older than they should be. Furthermore, shells could have been reworked into younger sediments, which may have occurred at Salt Creek and Lake Callabonna, where radiocarbon ages are older than the associated OSL ages (Table 3).

In addition, potential secondary carbonate contamination or shell recrystallization, which incorporates younger carbon into the shell

Table 1
AMS¹⁴C measurements for central Australian lake molluscs.

Sample ID	ANSTO code	Shell species	Sample mass	pMC	Conventional ¹⁴ C Age ^a	Calibrated radiocarbon age ^a
			mg		yrs BP	ka cal BP
<i>Salt Creek</i>						
LCP1 0.8	OZBI63	Coxiella sp	9.2	0.24 ± 0.02	48,600 ± 750	51.7 ± 1.4
LCP2 0.85	OZBI64	Coxiella sp	10.8	1.08 ± 0.03	36,400 ± 250	41.4 ± 0.2
<i>Lake Callabonna</i>						
CSP1 1.0	OZBI65	Coxiella sp	11.8	0.22 ± 0.02	49,100 ± 800	52.7 ± 1.3
CSP1 1.05	OZBI66	Coxiella sp	9.7	0.12 ± 0.02	53,800 ± 1300	54.4 ± 1.5
<i>Lake Frome</i>						
LFP1 1.3	OZBI67	Coxiella sp	11.1	0.43 ± 0.02	43,700 ± 450	46.1 ± 0.4
<i>Kati Thanda-Lake Eyre</i>						
WPLE P4B	OZBI68	Coxiella sp	11.5	0.42 ± 0.03	44,000 ± 500	46.4 ± 0.6

^a errors reported as ± 1σ.

Table 2
Summary of single-grain TT-OSL dating results for the +20.8 AHD shoreline deposits at Lake Callabonna.

Sample ID	Environmental dose rate (Gy/ka)						Equivalent dose (D _e) data			Age (ka) ^{f,j}
	Water content (%) ^a	Beta dose rate ^b	Gamma dose rate ^c	Cosmic dose rate ^d	Internal dose rate ^e	Total dose rate ^e	No. of grains ^g	OD (%) ^h	D _e (Gy) ^{i,j}	
LC19-10	2.5	1.37 ± 0.07	1.06 ± 0.04	0.18 ± 0.02	0.03 ± 0.01	2.65 ± 0.12	92/1600	15 ± 4	518 ± 18	195.7 ± 11.9

^a Long-term water content, expressed as % of dry mass of mineral fraction, with an assigned 1σ relative uncertainty of ±50%.

^b Beta dose rate of sample was calculated on dried and powdered sediment using a Risø GM-25-5 low-level beta counter (Bøtter-Jensen and Mejdahl, 1988). Radionuclide concentrations and specific activities of beta counting standards have been converted to dose rates using the conversion factors given in Guérin et al. (2011).

^c Gamma dose rate was calculated from *in situ* measurements made with an NaI:Tl detector, using the ‘energy windows’ approach (e.g., Arnold et al., 2012; Duval and Arnold, 2013). Radionuclide concentrations and specific activities of gamma spectrometry calibration materials, and K, U, Th concentrations determined from the field gamma-ray spectra have been converted to dose rates using the conversion factors given in Guérin et al. (2011).

^d Cosmic-ray dose rates were calculated according to Prescott and Huntley (1994) and assigned a relative 1σ uncertainty of ±10%.

^e The assumed internal alpha + beta dose rate for quartz, with an assigned relative 1σ uncertainty of ±30%, is based on intrinsic ²³⁸U and ²³²Th contents published by Mejdahl (1987), Bowler et al. (2003), Jacobs et al. (2006), Pawley et al. (2008), and Lewis et al. (2020), and an a-value of 0.04 ± 0.01 (Rees-Jones, 1995; Rees-Jones and Tite, 1997). Intrinsic radionuclide concentrations and specific activities have been converted to dose rates using the conversion factors given in Guérin et al. (2011), making allowance for beta dose attenuation due to grain-size effects (Mejdahl, 1979).

^f Mean ± total uncertainty (68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.

^g Number of D_e measurements that passed the SAR rejection criteria and were used for D_e determination/total number of D_e values analysed.

^h OD = overdispersion, which represents the relative spread in the D_e dataset beyond that associated with the measurement uncertainties for individual D_e values.

ⁱ Sample-averaged D_e value for each sample, calculated using the central age model (CAM) of Galbraith et al. (1999).

^j Total uncertainty includes a systematic component of ±2% associated with laboratory beta-source calibration.

matrix, can result in younger shell ages than they should be. XRD data revealed that most samples are near-pure aragonite, although a relatively high concentration of calcite (~16%) was detected for sample LCP1 0.8 (Table S4). However, due to the small amounts of sample material available, mineral abundances inferred from XRD should only be considered semi-quantitative. Nevertheless, diagenesis can be assumed to be negligible, so shell ¹⁴C ages can be considered as maximum ages unless carbon contamination is dominant.

Consequently, the radiocarbon ages from this study and previous work by Cohen et al. (2012, 2017) cannot confidently be used as direct ages of mollusc shell formation (or the depositional ages of the sediments) in the studied central Australian playa lakes. Instead, the timing of shell formation is better constrained by OSL and TT-OSL dating of palaeoshoreline sediments, with these OSL and TT-OSL dates used where possible for estimating the ages of the mollusc shell samples. However, the mollusc-bearing sediment layers may not have been directly sampled as part of the previous OSL dating studies (Cohen et al., 2012, 2022), leading to large uncertainties with regards to the timing of the molluscs’ growth and subsequent deposition for some samples. The inferred mollusc sample ages shown in Table 3 are therefore based on the surrounding OSL ages and age dating model (Cohen et al., 2012, 2022), with the error bars denoting the upper and lower age ranges for most samples (Table 3). The exception is the age of the shell samples from the Lake Callabonna +20.8m ADH shoreline, since this is based on a TT-OSL sample collected directly from the shell-rich layer that has been analysed for isotopic analysis. Changes in sedimentology and

isotopic composition can be used to infer that samples with the same maximum/minimum age constraints were not deposited by the same lake filling event. An example of this is Pit 1 from Salt Creek, where three sampled shell layers share the same maximum age constraint, but varying sedimentology and isotopic compositions imply shell growth and deposition during different filling events (Fig. 4c).

4.4. Clumped isotope analyses

Stable isotope data (δ¹⁸O and δ¹³C) and estimated water and air temperatures from the analysed molluscs are summarised in Table 4, with Δ₄₇ data and further information presented in Table S5. For modern samples, water temperatures recorded at the time of collection and recorded average air temperature for the sample collection year can be found in Table S3. Errors are provided as ± 1 S.E., unless stated otherwise, with the number of replicates used shown for individual samples. For the modern *Coxiella* samples from Esperance, Western Australia, shell carbonate δ¹⁸O (δ¹⁸O_{carb}) values vary from 1.9‰ to 3.5‰ (VPDB), with an average of 2.4 ± 0.2‰ (9 samples), while δ¹³C values range from −11.5‰ to −6.0‰ (VPDB), with an average of −7.9 ± 0.6‰ (9 samples). Reconstructed water temperatures (T(Δ₄₇)) fall within the range of 15.5 °C–25.1 °C, with an average of 18.3 ± 1.1 °C (9 samples) (16.1–20.5 °C; 95% C.I.). Individual T(Δ₄₇) values were comparable to water temperatures recorded when the samples were collected (Table S6). Estimated mean annual air temperatures (MAAT) values range from 13.8 °C to 22.4 °C, with an average of 16.7 ± 1.0 °C (9

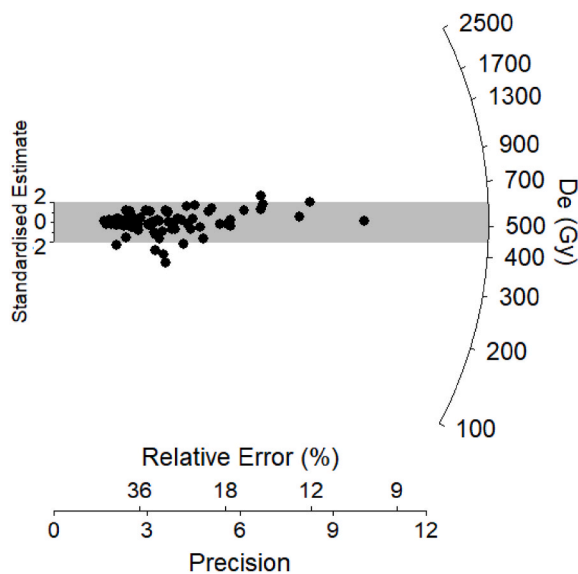


Fig. 3. Single-grain D_e distribution for the TT-OSL dating sample, shown as a radial plot. The grey band is centred on the D_e value used for age calculation, which has been derived using the central age model (CAM). Individual D_e values that fall within the shaded region are consistent with the CAM burial dose used for age calculation at 2σ .

samples) ($14.7\text{--}18.7\text{ }^{\circ}\text{C}$; 95% C.I.) for lakes near Esperance and a single MAAT estimate from Green Head of $17.5 \pm 2.0\text{ }^{\circ}\text{C}$ (1 sample, $n = 6$) ($13.6\text{--}21.4\text{ }^{\circ}\text{C}$; 95% C.I.). Weather observations from 2015 to 2022 show that the average air temperature for this period was $17.4\text{ }^{\circ}\text{C}$ for Esperance and $19.6\text{ }^{\circ}\text{C}$ for Green Head, which support the clumped isotope-based MAAT estimates.

Δ_{47} measurements were obtained for 8 *Coxiella* and 6 *Corbicula australis* samples from ancient shorelines in central Australia, with an

additional *Coxiella* sample from KT-LE (LEHS_76) containing insufficient carbonate material to obtain a reliable Δ_{47} value (Table 4). Stratigraphic logs for the central Australian samples from Lake Mega-Frome are presented in Fig. 4. For the central Australian palaeoshorelines, shell $\delta^{18}\text{O}_{\text{carb}}$ values vary from -1.6‰ to $+4.6\text{‰}$, whilst $\delta^{13}\text{C}$ values range from -5.2‰ to $+0.7\text{‰}$. Shell Δ_{47} values range from $0.5999 \pm 0.0052\text{‰}$ ($n = 9$) to $0.6268 \pm 0.0054\text{‰}$ ($n = 8$) (I-CDES; Table S5), with $T(\Delta_{47})$ values ranging from $14.6 \pm 1.7\text{ }^{\circ}\text{C}$ ($n = 8$) ($11.3\text{--}17.9\text{ }^{\circ}\text{C}$; 95% C.I.) to $23.2 \pm 1.7\text{ }^{\circ}\text{C}$ ($n = 9$) ($19.9\text{--}26.5\text{ }^{\circ}\text{C}$; 95% C.I.). MAAT estimates range from $12.7 \pm 1.8\text{ }^{\circ}\text{C}$ ($n = 8$) ($9.0\text{--}16.4\text{ }^{\circ}\text{C}$; 95% C.I.) to $19.8 \pm 2.1\text{ }^{\circ}\text{C}$ ($n = 9$) ($17.5\text{--}24.9\text{ }^{\circ}\text{C}$; 95% C.I.). Environmental water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{water}}$) values calculated from $T(\Delta_{47})$ range from $-2.6 \pm 0.3\text{‰}$ ($n = 10$) to $+3.9 \pm 0.4\text{‰}$ ($n = 10$) (VSMOW). No statistical correlation was observed between calculated $\delta^{18}\text{O}_{\text{water}}$ and $T(\Delta_{47})$ ($P > 0.05$), while $\delta^{18}\text{O}_{\text{carb}}$ correlates with $\delta^{18}\text{O}_{\text{water}}$ ($p < 0.05$, $R^2 = 0.89$) (Fig. S1). No statistical correlation was observed between $\delta^{18}\text{O}_{\text{carb}}$ and either $\delta^{13}\text{C}$ or $T(\Delta_{47})$ for the combined lakes, but can be seen for individual sites, albeit from small samples sizes (Fig. S1).

While there are only a small number of *Coxiella* and *Corbicula* samples (Table S2) and no cases in which the two were deposited in the same sedimentary layer, subtle differences in the ranges of isotope compositions for the two data sets can be seen. Shell $\delta^{18}\text{O}_{\text{carb}}$ values vary from 0.4‰ to 4.6‰ for *Coxiella* and -1.6‰ to $+3.9\text{‰}$ for *Corbicula australis*. Similarly, $\delta^{18}\text{O}_{\text{water}}$ values estimated from *Coxiella* samples vary from 1.0‰ to 3.9‰ , with a range of -2.6‰ to $+3.7\text{‰}$ for *Corbicula* samples. The three samples from Salt Creek, constrained by a maximum age of $\sim 33\text{ ka}$, have diverse $\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{water}}$ values, although the two *Corbicula australis* samples (LCP1 0.45 and LCP1 0.96) have similar $\delta^{13}\text{C}$ values (-3.6 and -3.8‰) that are much lower than the *Coxiella* sample (LCP1 0.8, which has $\delta^{13}\text{C} = 0.1$).

A bivalve shell from the $196 \pm 12\text{ ka}$ shoreline at Lake Callabonna was estimated to have grown at an average air temperature of $17.8 \pm 1.7\text{ }^{\circ}\text{C}$ ($n = 10$) ($14.5\text{--}21.1\text{ }^{\circ}\text{C}$; 95% C.I.). MAAT estimates peak at $\sim 21\text{ }^{\circ}\text{C}$ when Lake Mega-Eyre filled at $71 \pm 4\text{ ka}$, with a decrease in air temperature of $\sim 4\text{--}6\text{ }^{\circ}\text{C}$ between 64 ± 7 and $48 \pm 4\text{ ka}$. MAAT values

Table 3

Calibrated ^{14}C , OSL, and TT-OSL ages for central Australian lake molluscs. Radiocarbon ages reported by Cohen et al. (2012, 2017) have been recalibrated using the SHCal20 calibration curve.

Sample ID	^{14}C (this study) ^a ka cal BP	^{14}C (Cohen et al.) ^a ka cal BP	(TT-)OSL (max) ^a ka	(TT-)OSL (min) ^a ka	Notes
<i>Salt Creek</i>					
LCP1 0.45			33.4 ± 2.9^b		Maximum age only. Deposited by different filling event than LCP1 0.8 and LCP1 0.96.
LCP1 0.8	51.7 ± 1.4		33.4 ± 2.9^b		Old shell that's been reworked? Possible groundwater influence?
LCP1 0.96			33.4 ± 2.9^b		Older shell that's been reworked? Possible groundwater influence? ^{14}C shows LCP1 0.8 was $\sim 51.7\text{ ka cal BP}$.
LCP2 0.85	41.4 ± 0.2	40.6 ± 0.6^b			
<i>Lake Callabonna</i>					
CallaSpit 0.5			196 ± 12	196 ± 12	Shells collected from same layer as the TT-OSL sample (55 cm below shoreline surface).
CSP1 1.0	52.7 ± 1.3	53.3 ± 1.1^b	47.1 ± 4.1^b	48.4 ± 4.2^b	
CSP1 1.05	54.4 ± 1.5		47.1 ± 4.1^b	48.4 ± 4.2^b	Older shell that's been reworked? Possible groundwater influence?
CSP1 2.0		49.5 ± 0.9^b		47.1 ± 4.1^b	Older shell that's been reworked? Possible groundwater influence?
<i>Lake Frome</i>					
LFP1 1.5			63.7 ± 6.9^b		Maximum age only.
LFP1 1.3	46.1 ± 0.3		63.7 ± 6.9^b		Contaminated ^{14}C age? Different deposition event?
LFP1 2.1		53.2 ± 1.2^b	109.9 ± 7.5^b	68.2 ± 4.2^b	Constrained within a broad range; stratigraphy suggests it may be closer to $68.2 \pm 4.2\text{ ka}$.
<i>Kati Thanda-Lake Eyre</i>					
WPLE P4B	46.4 ± 0.6		70.0 ± 4.0^c	53.4 ± 3.2^c	Contaminated ^{14}C age?
LEHP S1 0.35		Modern ^d			Collected from Hunt Peninsula Wpt_106
LEHS_114		35.8 ± 0.2^d			Collected from Hunt Peninsula Wpt_114

^a errors reported as $\pm 1\sigma$.

^b Cohen et al. (2012).

^c reported in Cohen et al. (2022).

^d reported in Cohen et al. (2017).

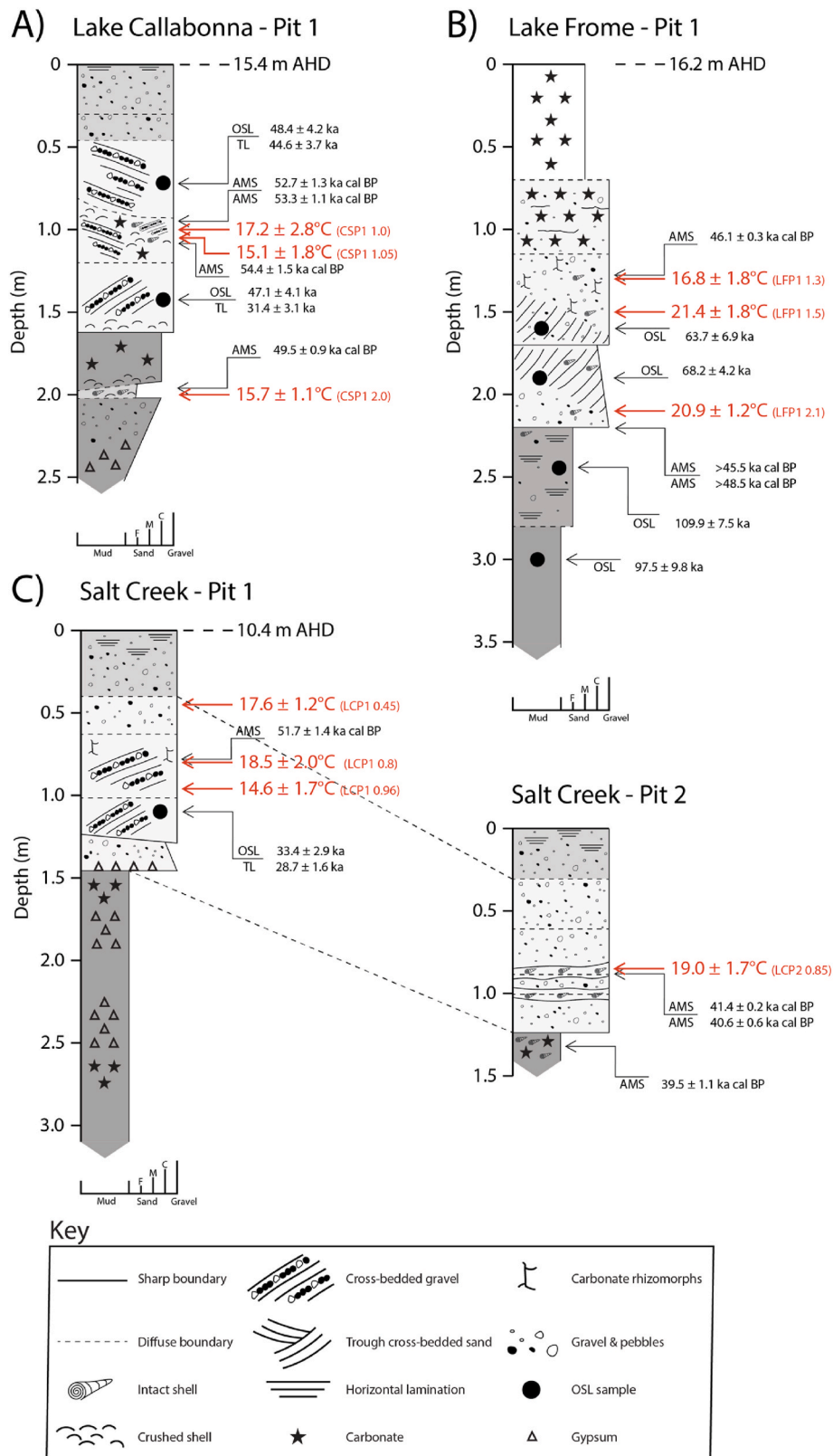


Fig. 4. Lake Mega-Frome palaeoshorelines with reconstructed $T(\Delta_{47})$ estimates from A) Lake Callabonna; B) Lake Frome; and C) Salt Creek. Please refer to [Cohen et al. \(2012\)](#) for further details regarding age data and sedimentary descriptions.

fall within the range of 12–18 °C from ~50 to 33 ka, with no significant difference between the studied lake sites. A single sample was recovered from a near-modern shoreline at KT-LE, which returned a MAAT value of 19.9 ± 2.1 °C ($n = 8$) (15.8–24.0 °C; 95% C.I.), which is within error of

average regional MAAT observations of ~21 °C ([Table S1](#)). Water and air temperature values calculated for *Corbicula australis* samples appear to be ~1–2 °C cooler than *Coxiella* samples from similar periods, although there are too few samples to adequately explore this

Table 4

Stable isotope data for central Australian and Western Australian lacustrine mollusc shells, and estimated water and mean annual air temperatures calculated from Δ_{47} . Ages are taken from OSL and TT-OSL ages where possible, as discussed in Section 4.3. Errors for stable isotope data were calculated using long-term reproducibility of analysed ETH standards. Additional data, including Δ_{47} , 95% CL values, and the number of replicates can be found in Table S5 in the Supplementary Material.

Sample ID	Shell type	Age	$\delta^{13}\text{C}$	$\delta^{18}\text{O}_{\text{carb}}$	Estimated water temperature	Error ^a	Estimated MAAT	Error ^a	$\delta^{18}\text{O}_{\text{water}}$	Error ^a
		ka or ka cal BP	‰ VPDB	‰ VPDB	°C		°C		‰ VSMOW	
Salt Creek										
LCP1 0.45	<i>Corbicula australis</i>	<33.4 (2.9) ^b	−3.6	−1.6	17.6	1.2	16.1	1.4	−2.6	0.3
LCP1 0.8	<i>Coxiella</i> sp	<33.4 (2.9) ^b	0.1	2.0	18.5	2.0	17.2	2.2	1.1	0.4
LCP1 0.96	<i>Corbicula australis</i>	<33.4 (2.9) ^b	−3.8	0.8	14.6	1.7	12.7	1.8	−0.9	0.4
LCP2 0.85	<i>Coxiella</i> sp	41.4 (0.2)	−0.8	4.6	19.0	1.7	17.6	1.9	3.9	0.4
Lake Callabonna										
CallaSpit 0.5	<i>Corbicula australis</i>	196 (12)	−2.8	0.3	19.2	1.5	17.8	1.7	−0.4	0.3
CSP1 1.0	<i>Coxiella</i> sp. ^a	47.1 (4.1) ^b	0.7	2.9	17.2	2.8	15.7	3.2	1.7	0.6
CSP1 1.05	<i>Coxiella</i> sp	48.4 (4.2) ^b	0.3	2.6	15.1	1.8	13.3	2.0	1.0	0.4
CSP1 2.0	<i>Coxiella</i> ^a	49.5 (0.9) ^b	0.6	3.4	15.7	1.1	14.0	1.3	2.0	0.2
Lake Frome										
LFP1 1.5	<i>Corbicula australis</i>	<63.7 (6.9) ^b	0.2	3.9	21.4	1.8	19.8	2.1	3.7	0.4
LFP1 1.3	<i>Coxiella</i> sp	46.1 (0.3)	−1.5	2.8	16.8	1.8	15.3	2.0	1.6	0.4
LFP1 2.1	<i>Corbicula australis</i>	>68.2 (4.2) ^b	−2.1	2.4	20.9	1.2	19.4	1.5	2.1	0.3
Kati Thanda-Lake Eyre										
WPLE P4B	<i>Coxiella</i> sp	70.0 (4.0) ^c	−0.6	1.6	23.2	1.7	21.2	1.9	1.8	0.4
LEHP S1 0.35	<i>Coxiella</i> sp. ^a	Near-modern ^d	−3.8	2.4	21.5	1.9	19.9	2.1	2.2	0.4
LEHS 76 ^e	<i>Coxiella</i> sp. ^a	39.7 (0.8) ^d	−5.2	0.4	−	−	−	−	−	−
LEHP 114	<i>Corbicula australis</i>	35.8 (0.2) ^d	−4.7	3.3	15.5	1.0	13.8	1.2	1.8	0.2
Western Australia										
Esperance 8_18	<i>Coxiella glauerti</i>	Modern	−6	2.1	16.4	2.0	15.6	2.2	0.8	0.3
Esperance 3_18	<i>Coxiella</i>	Modern	−6.8	1.9	21.1	1.3	14.8	1.4	1.6	0.5
	<i>pyrrhostoma</i>									
Esperance 4_18	<i>Coxiella</i>	Modern	−7.7	2.5	17.1	2.3	19.6	2.5	1.4	0.4
	<i>pyrrhostoma</i>									
Green Head 2	<i>Coxiella striatula</i>	Modern	−8	3.1	18.8	1.9	17.5	2.0	2.4	0.4
Esperance 14_20	<i>Coxiella</i>	Modern	−9.3	2.9	16.6	1.1	22.4	1.2	1.6	0.4
	<i>pyrrhostoma</i>									
Esperance 4_20	<i>Coxiella</i>	Modern	−9.2	1.9	25.1	1.9	15.1	2.1	2.4	0.2
	<i>pyrrhostoma</i>									
Esperance 11_20	<i>Coxiella glauerti</i>	Modern	−11.5	2.4	18.3	1.5	16.9	1.6	1.5	0.3
Esperance 3_20	<i>Coxiella</i>	Modern	−6.7	2.1	18.2	1.7	16.9	1.8	1.3	0.3
	<i>pyrrhostoma</i>									
Esperance 7_20	<i>Coxiella</i> sp	Modern	−6.7	2.2	16.5	1.6	15.0	1.7	1.0	0.3
Esperance 22_21	<i>Coxiella glauerti</i>	Modern	−7.3	3.5	15.5	1.4	13.8	1.5	2.1	0.3

^a errors reported as ± 1 standard error (S.E.).

^b reported in Cohen et al. (2012).

^c reported in Cohen et al. (2022).

^d reported in Cohen et al. (2017).

^e insufficient carbonate material for Δ_{47} .

observation.

The highest $\delta^{18}\text{O}_{\text{water}}$ values are estimated for shell samples from ~64 ka ($3.7 \pm 0.4\text{‰}$ ($n = 10$)) and ~41 ka ($3.9 \pm 0.4\text{‰}$ ($n = 10$)) shorelines. The majority of $\delta^{18}\text{O}_{\text{water}}$ values fall within the range of 1–2‰, with similar values observed for coeval samples from the four study sites, suggesting similar palaeohydrological conditions in a given time period. A $\delta^{18}\text{O}_{\text{water}}$ value of $2.2 \pm 0.4\text{‰}$ ($n = 8$) (1.4–3.0‰; 95% C. I.) was calculated for the near-modern sample from KT-LE, which is comparable to the water samples collected from KT-LE in July 2022, which returned an average $\delta^{18}\text{O}_{\text{water}}$ value of $2.7 \pm 0.1\text{‰}$ ($n = 3$) (Table S7). Salt Creek exhibits the greatest variation in $\delta^{18}\text{O}_{\text{water}}$ of all the studied lake sites, ranging from −2.6‰ to +3.9‰ and representing the only values below 1‰ in the last 75 ka.

5. Discussion

5.1. Lake conditions and mollusc ecology

Δ_{47} analysis of aquatic molluscs has been shown to provide reliable estimates of growth temperatures and the oxygen isotope compositions of host waters (Wang et al., 2021; Huyghe et al., 2022), which is

supported by the similarity between observed and calculated water temperatures from Western Australia. However, in an ideal scenario, the reconstruction of past air temperatures using Δ_{47} requires an understanding of potential seasonal and spatial biases in the precipitation of mollusc carbonate (Hren and Sheldon, 2012). This study focused on the analysis of fossil shells from the ancient shorelines of lakes that are ephemeral today – predominantly dry – and thus do not provide a comparable analogue for the conditions under which the molluscs lived.

In the absence of detailed ecological studies (summarised in Supplementary Note 3), both *Coxiella* and *Corbicula australis* fossils are assumed to have exhibited similar seasonal and spatial preferences to comparable communities living in modern permanent lakes. *Coxiella* have been observed reproducing and growing in the upper 6 m of the water columns of modern Australian salt lakes irrespective of lake depth (Timms, 1976), although this is challenged by some observed lake distributions (Williams and Mellor, 1991). Individuals are presumed to live up to 2 years (Williams and Mellor, 1991) and either floated or were windblown to shore after dying (De Deckker et al., 2011). *Corbicula australis* are assumed to have lived as benthic filter feeders, with maximum water depths of ~25 m for Lake Mega-Eyre and ~15 m for Lake Mega-Frome since MIS-5.

While summer filling may realistically be assumed for KT-LE, lakes Callabonna and Frome experience both summer and winter filling events today (Miller and Magee, 1998; Nanson et al., 1998; Jewell et al., 2003), complicating the interpretation of $\delta^{18}\text{O}_{\text{water}}$ values for Lake Mega-Frome. For KT-LE, we suggest that the studied molluscs reproduced and grew during increased discharge from the catchment area (in late summer through to autumn) before presumably dying en masse when salinity increased as the lake evaporated (Hammer, 1986; Williams and Mellor, 1991; Lawrie et al., 2021). Generally speaking, it is reasonable to assume that mollusc abundances and their isotope compositions reflect near-surface water conditions during the initial phases of the wet season. Given the absence of any evidence to the contrary, we assume that the conditions for shell growth were constant throughout the studied period.

Unfortunately, due to our analytical setup, the effects of reaction kinetics on Δ_{47} (Daëron et al., 2019) could not be identified or quantified using simultaneously obtained Δ_{47} and Δ_{48} values (Fiebig et al., 2019, 2021; Bajnai et al., 2020). If non-equilibrium isotope fractionation occurred during carbonate precipitation, the likely effect would be an offset between taxa for similar aged samples. However, there are no palaeoshorelines with both *Coxiella* and *Corbicula australis* samples. Furthermore, both the difference in temperature and the number of samples is relatively small, so it is unclear if any potential offset in Δ_{47} is the result of varying environmental conditions or a systematic disequilibrium effect. Concerns about suitability of the Hren and Sheldon (2012) calibration – which is based on a wide variety of lakes, mostly from the Northern Hemisphere – are somewhat alleviated by the similarities between recorded weather data and Δ_{47} -inferred MAAT from modern Western Australian shells (Table S6) and a near-modern *Coxiella* sample from KT-LE. This provides increased confidence in the use of clumped isotope geochemistry for the ancient mollusc shells, albeit under the assumption that shells from lakes Callabonna, KT-LE, and Frome grew at the same time of year as those in modern Western Australia.

Given the size of the catchments for the studied lakes, it can take several months for increased rainfall to result in lake maxima being reached. Consequently, it is feasible that the conditions for maximum productivity occurred during spring or autumn seasons irrespective of the seasonal bias of precipitation, as occurs for modern salt lakes in Australia (Lawrie et al., 2021). If this logic is correct, mollusc $T(\Delta_{47})$ values can be assumed to have been similar to MAAT, as modern lake temperatures during spring are typically similar to annual averages (Peeters et al., 2002; Haddout et al., 2018). However, it should be considered that past spring and autumn temperatures may have differed significantly from today's, potentially resulting in a misrepresentation of the mean annual temperature.

The inferred lake water depths for the studied lakes (ranging from ~4 m to ~25 m; Cohen et al., 2011, 2012, 2022) were always small relative to the large lake surface areas, implying that lake water temperature profiles would have been consistently well mixed (Imboden and Wüest, 1995; Haddout et al., 2018). Furthermore, whilst synthesis of carbonate in slightly deeper waters may have resulted in lower temperature estimates, this difference was likely smaller than the uncertainty associated with $T(\Delta_{47})$ and air temperature estimates (Haddout et al., 2018). It is probable that the mollusc shell temperature estimates do not reflect long-term climate due to the assumption that the lake filling events occurred during infrequent and anomalously large monsoon events (Bowler, 1986; Magee and Miller, 1998; Croke et al., 1999; Hesse et al., 2004), and because the number of shells sampled per unit was relatively small (1–20 shells per sample; Table S2). Therefore, each sample represents a snapshot of the conditions during lake filling, or shortly thereafter. Consequently, $T(\Delta_{47})$ and MAAT estimates may not reflect long-term temperature averages, but rather the palaeoenvironmental conditions during those brief, extreme lake filling events.

5.2. Shell preservation

Shell taphonomy is also poorly understood, so isotopic compositions may have been influenced by post-depositional events such as dissolution, coating, and vertical movement within sediment (Williams and Mellor, 1991). The reworking of older shells is supported for some samples by the fact that their radiocarbon ages are significantly older than the OSL ages obtained on associated sediments, although this could also be a result of methodological unreliability issues with the ^{14}C dataset. Cohen et al. (2022) speculated that some shell samples may have been affected by diagenesis associated with meteoric water passing through the sediments. Aragonite is thermodynamically less stable than calcite and recrystallization to calcite is often an indicator of diagenetic alteration (Sharp, 2007), which can have important consequences for Δ_{47} values (Staudigel and Swart, 2016; Chen et al., 2019; Guo et al., 2019; Wang et al., 2021). XRD analysis suggests that most samples are generally composed of unaltered aragonite, although inferred mineral concentrations are only semi-quantitative and some samples could not be analysed due to insufficient sample material. Nevertheless, this implies that most samples have not experienced significant diagenetic alteration. The sole exception is for sample LCP1 0.8, which has a calcite concentration that is approximately double that of the other shells (Table S4), suggesting potential aragonite reordering to calcite. However, Δ_{47} does not significantly differ to other samples of a similar age (Table 4). Data from sample LCP1 0.8 has been included for the following discussion of central Australian palaeoclimate, although there would be no significant changes to our findings if it were omitted due to concerns of potential diagenetic alteration.

5.3. Late quaternary palaeotemperature

The reconstructed mollusc Δ_{47} estimates for lake water temperature and MAAT presented here represent the longest and most detailed record to date of past temperature variability for the iconic central Australian ephemeral lakes (Fig. 5), with broader implications for the Australian continental interior, Southern Hemisphere palaeoclimate, and arid landscapes worldwide. Confidence in absolute temperature values is increased by the analysis of modern *Coxiella* shells from WA, although the exact growth period for the ancient central Australian molluscs is unclear. Regardless, relative temperature differences can be more confidently ascertained (Henkes et al., 2013; Wang et al., 2016, 2021).

Shell Δ_{47} values are comparable for coeval shoreline deposits across different sites, increasing our confidence in the temperature estimates and suggesting air temperatures during the shells' growth period were similar across the studied ephemeral lakes during the Holocene and Late Pleistocene. This is to be expected for the Australian continental interior, which lacks significant topography and is typically considered a passive recorder for global-scale climate events (Miller et al., 1997; Hesse et al., 2004).

A single bivalve (*Corbicula australis*) sample from the 196 ± 12 ka shoreline at Lake Callabonna suggests that reconstructed mollusc growth temperatures and MAAT during late MIS-7 or early MIS-6 were comparable to modern climatic conditions, with an estimated lake water temperature of ~19 °C and MAAT of ~18 °C (Table 4). There are no coinciding central Australian palaeotemperature estimates for comparison, but near-modern MAAT values have also been inferred for MIS-7 using oxygen isotopes in Antarctic ice cores (Jouzel et al., 2007; Uemura et al., 2012).

Surprisingly, MAAT estimates for early MIS-4 were similar to that of the near-modern sample from KT-LE and water temperature recorded at KT-LE by the Royal Geographical Society of Australasia (1955), who observed mean maximum and minimum temperatures of 19.1 °C and 12.7 °C, respectively, for May 1951 and mean maximum and minimum temperatures of 30.1 °C and 18.7 °C, respectively, for December 1951. Unfortunately, the absence of present-day mollusc samples from the

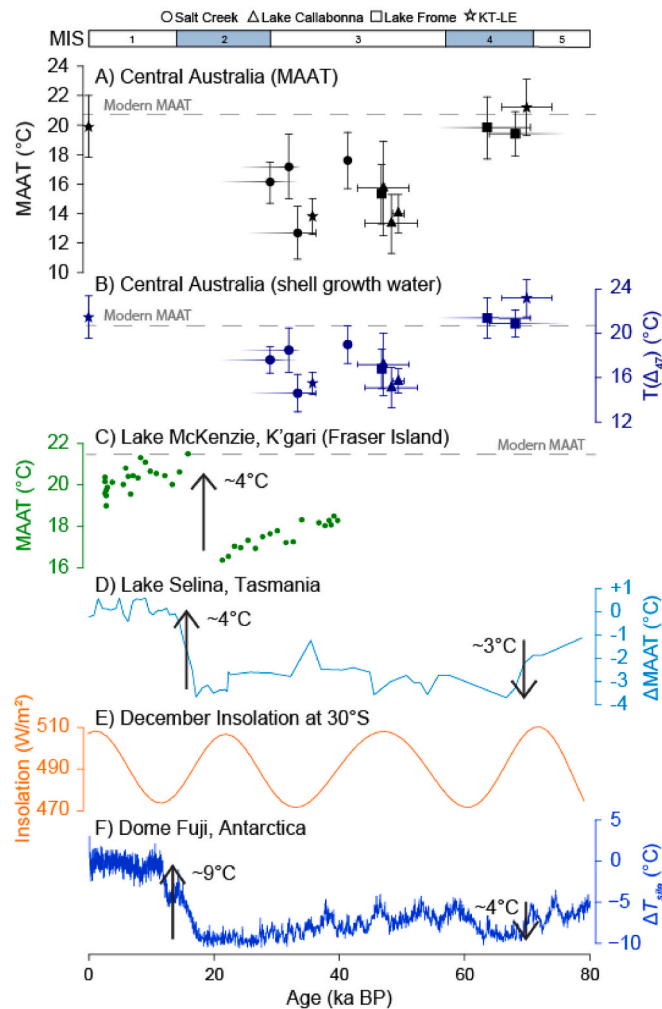


Fig. 5. Comparison of reconstructed palaeoclimate from this study with previous palaeoclimate estimates. A) central Australian MAAT and B) Δ_{47} mollusc shell carbonate precipitation temperature ($T(\Delta_{47})$), with faded age uncertainty bars indicating samples without a minimum and/or maximum age constraint (Table 3); C) branched GDGT-inferred MAAT from Lake McKenzie, K'gari (Fraser Island) (Woltering et al., 2014); D) pollen-inferred annual air temperatures from Lake Selina, Tasmania, relative to modern temperatures (Fletcher and Thomas, 2010); E) December insolation at 30°S (Berger, 1992); and F) reconstructed polar temperature using deuterium-excess data from ice cores at Dome Fuji, Antarctica, relative to present (Uemura et al., 2012). Modern MAAT values for central Australia and K'gari (Fraser Island) were calculated using weather observations from 1950 to 2022 (accessed via the SILO Australian climate database (<http://www.longpaddock.qld.gov.au/silo>)). Central Australian sample sites are indicated by circles = Salt Creek, triangles = Lake Callabonna, squares = Lake Frome, and stars = Kati Thanda-Lake Eyre.). MIS = marine isotope stage.

lakes prevented analysis of modern analogues from central Australia. Evidence from Lake Frome and a sample from KT-LE (WPLE P4B) suggest a cooling of $\sim 5^\circ\text{C}$ between 64 ± 7 ka and ~ 50 ka (Fig. 5), which roughly coincides with the transition from MIS-5a into MIS-4, although the exact timing of this transition is poorly constrained (Fig. 4b). These fossil shell units may represent a significant cooling event at the onset of MIS-4, which has not been previously identified in central Australia.

Pollen and speleothem-based MAAT reconstructions from Tasmania suggest up to $\sim 3^\circ\text{C}$ of cooling occurred at the onset of MIS-4; whereby MIS-5a MAAT was inferred to have been ~ 1 – 1.5°C cooler than present and MIS-4 MAAT ~ 3 – 4°C cooler than present in western Tasmania (Fig. 5d; Goede et al., 1986; Fletcher and Thomas, 2010). A Southern Ocean sea surface temperature (SST) composite record by Barrows et al.

(2007) also somewhat supports this study's MAAT estimates, with MIS-5 temperatures 0 – 2°C below present and MIS-4 temperatures $\sim 4^\circ\text{C}$ below present. A decrease in SST of $\sim 5^\circ\text{C}$ was also estimated for the start of MIS-4 by De Deckker et al. (2019), on the basis of marine sediment cores taken ~ 200 km south of the present South Australian coastline. As discussed by De Deckker et al. (2019), this rapid cooling at the beginning of MIS-4 may have coincided with a weakening of the Leeuwin Current and either the intensification or northward migration of the southern westerly winds, resulting in aridification in the continental interior (De Deckker et al., 2019, 2020; Gottschalk et al., 2019) or major shifts in evaporative conditions. Data from Antarctic ice cores suggest that changes in MAAT and atmospheric CO_2 concentrations at the onset of MIS-4 were almost as dramatic as those at the start of the LGM (Jouzel et al., 2007; Bereiter et al., 2012, 2018; Uemura et al., 2012; De Deckker et al., 2019), which is supported by the changes in central Australian $T(\Delta_{47})$ and MAAT inferred here.

Reconstructed MAAT fluctuated between ~ 13 and 16°C during the period from ~ 50 to 30 ka and suggests that the start of the LGM was approximately 4 – 6°C (3.6 – 6.0°C ; 95% C.I.) cooler than modern conditions in the region (Fig. 5). These MAAT estimates are similar to tentative estimates of 10 – 18°C at William Point, KT-LE for $\sim 71 \pm 4$ ka, as previously inferred from fossil shell $\delta^{18}\text{O}$ values by Cohen et al. (2022). This period broadly coincides with the earliest evidence for humans in the region (Hamm et al., 2016), implying that people first inhabited central Australia and nearby inland regions during much cooler conditions than those of the present day. Similarly, the extinction of the Australian megafauna occurred when Australia's continental interior was relatively cold and followed a period of relatively stable air temperature. However, quantification of palaeoclimate for the extinction event is complicated by the scarcity of MAAT estimates from the mollusc Δ_{47} record coinciding with the last occurrence of the megafauna at ~ 40 ka (Hocknull et al., 2020), in addition to the assumptions regarding the molluscs' life cycles and growth periods (Section 5.1).

The Δ_{47} derived water and annual air temperature dataset suggests that the magnitude of LGM-Holocene warming in central Australia was less pronounced than past air temperature estimates using amino acid racemisation (Miller et al., 1997), summer SST estimates (De Deckker et al., 2020), and periglacial deposits in southeastern Australia (Barrows et al., 2022). This may be because the coldest period was not sampled in our dataset. However, our estimates are similar to those based on branched GDGT analyses of lake sediments in south-eastern Queensland that suggest relatively stable MAAT between 37 and 22 ka, which was $\sim 4.1^\circ\text{C}$ below present (Fig. 5c; Woltering et al., 2014). Similarly, a $\sim 4^\circ\text{C}$ increase in MAAT between the LGM and early Holocene has also been estimated from terrestrial pollen obtained from marine sediments off the Cape Range Peninsula, Western Australia (van der Kaars and De Deckker, 2002, 2003; van der Kaars et al., 2006).

The magnitude of MAAT change from shell Δ_{47} is comparable to low elevation, low-to-mid-latitude land surfaces elsewhere (45°S to 35°N), which have been estimated to be ~ 5 – 6°C cooler during the last glacial period (Seltzer et al., 2021). Similar post-LGM warming has been inferred for global mean surface air temperature (GMST), with estimates of LGM GMST ranging from 1.7 to 8.0°C lower than the Holocene (Schneider von Deimling et al., 2006; Schmittner et al., 2011; Shakun et al., 2012; Snyder, 2016; Bereiter et al., 2018) and an assimilated data reconstruction by Tierney et al. (2020a) providing estimating a post-LGM warming of -6.1°C (6.5 – 5.7°C ; 95% C.I.). We therefore suggest that these estimates for postglacial warming are applicable to both the Australian coastline and interior, with implications for understanding both hydrological and ecological change in the region.

5.4. Central Australian palaeohydrology

Beyond the ability to quantify past lake water and annual air temperatures, Δ_{47} analyses enable the calculation of lake water $\delta^{18}\text{O}$ values, which are a valuable tracer of hydrological processes. For all central

Australian ephemeral lakes, $\delta^{18}\text{O}_{\text{water}}$ presumably followed a ‘lifespan’ trajectory arc of filling and ultimately evaporation, with a superimposed seasonal cycle (Cohen et al., 2022). Variable $\delta^{18}\text{O}_{\text{water}}$ values can also be attributed to lake water replenishment in seasonal pulses (Cohen et al., 2022). The evolution of $\delta^{18}\text{O}_{\text{water}}$ over the life of the playa lakes can be assumed to be controlled by lake volume, seasonal evaporation rates, humidity, and $\delta^{18}\text{O}$ from inflowing water. $T(\Delta_{47})$ variability is not correlated with water or mollusc shell $\delta^{18}\text{O}$ (Fig. S1), suggesting that $\delta^{18}\text{O}$ variability can be attributed to changes in lake volume via the balance of precipitation versus evaporation, as well as changes in the $\delta^{18}\text{O}$ of precipitation (Beuning et al., 2002; Evans et al., 2018). Higher $\delta^{18}\text{O}_{\text{water}}$ generally corresponds with higher temperatures (Fig. S1; Table 4), in agreement with the expected relationship between temperature and evaporation (Schaffner and Swart, 1991; Koch, 1998; Srivastava et al., 2015; Miller and Fogel, 2016), although this relationship is not particularly strong. Central Australia’s ephemeral lakes are characterised by large degrees of evaporation, which is reflected in high estimated $\delta^{18}\text{O}_{\text{water}}$ values (-2.6‰ to $+3.9\text{‰}$; Fig. 6a), relative to other Australian lakes and modern freshwater input ($\sim -5\text{‰}$ – 0‰) (Cendón et al., 2010).

A reconstructed $\delta^{18}\text{O}_{\text{water}}$ value of $-0.4 \pm 0.3\text{‰}$ from 196 ± 12 ka suggests central Australia was either wetter or experienced less intense evaporation during late MIS-7 than during the last ~ 75 ka. Previous research indicates that KT-LE was full during this period (Fu et al., 2017) and multiple sites in eastern Australia were wetter than during the Holocene (Kershaw et al., 2007; Moss and Kershaw, 2007), coinciding with stronger southern westerlies and a more active IASM (Kemp et al., 2020).

Between ~ 75 and 57 ka, $\delta^{18}\text{O}_{\text{water}}$ values of $1.8 \pm 0.4\text{‰}$ and $2.1 \pm 0.3\text{‰}$ were estimated for KT-LE and Lake Frome, respectively (Fig. 6a), which is consistent with mixing when the two mega-lakes were joined. Both playas appear to have experienced greater evaporation relative to 196 ± 12 ka ($\delta^{18}\text{O}_{\text{water}}$ values $> 2\text{‰}$ higher), which is supported by lake filling records from the region (Fig. 6d) (Cohen et al., 2015, 2022). $\delta^{18}\text{O}_{\text{water}}$ values of 1 – 2‰ from Lake Mega-Frome between ~ 52 and 43 ka (Fig. 6a) coincide with high flow from the north via Copper Creek (Maroulis et al., 2007; Cohen et al., 2012), and imply a lower ratio of precipitation to evaporation compared to MIS-7. The $\delta^{18}\text{O}_{\text{water}}$ estimates from Salt Creek suggest relatively low evaporation intensity at ~ 33 ka, when water from Lake Callabonna may have flowed through Salt Creek to Lake Frome, resulting in a significantly shorter residence time for waters at Salt Creek, relative to the other sampled central Australian lake sites. Relatively high $\delta^{18}\text{O}_{\text{water}}$ values during the entire record suggest that the playa lakes were terminal during the last ~ 200 kyr, which is consistent with the absence of potential outflows identified from modern topography (Leon and Cohen, 2012).

Our estimates of lake $\delta^{18}\text{O}_{\text{water}}$ are generally lower than those from gypsum hydration water for KT-LE by Cohen et al. (2022), who estimated $\delta^{18}\text{O}_{\text{water}}$ values of $3.8 \pm 1.2\text{‰}$ and $\delta^2\text{H}$ values of $-1.5 \pm 10\text{‰}$ between 95 and 78 ka. However, their study also concluded that calculation of plausible water temperatures (10 – 20°C) from gyrogonites and *Coxiella* shells requires $\delta^{18}\text{O}_{\text{water}}$ values between 1‰ and 3‰ , implying that gypsum precipitation recorded the highest salinity and evaporation conditions (Cohen et al., 2022). Most stable isotope compositions from mollusc shells are also lower than modern water samples collected from KT-LE in July 2022 ($\delta^{18}\text{O}_{\text{water}} = 2.7\text{‰}$ and $\delta^2\text{H} = 2.2\text{‰}$), consistent with the hypothesis that the molluscs grew when the lakes first filled before dying and accumulating when salinity increased as the lakes evaporated (Hammer, 1986; Williams and Mellor, 1991; Lawrie et al., 2021). Consequently, $\delta^{18}\text{O}_{\text{water}}$ values from molluscs may not be able to capture late stages of lake evaporation because salinity was too high for them to survive.

The studied fossil shells were deposited at times when the lakes were full of water and in most cases the inferred water and annual air temperatures are $>3^\circ\text{C}$ cooler than Holocene/modern temperatures, although some samples approach modern temperatures. Overall, our

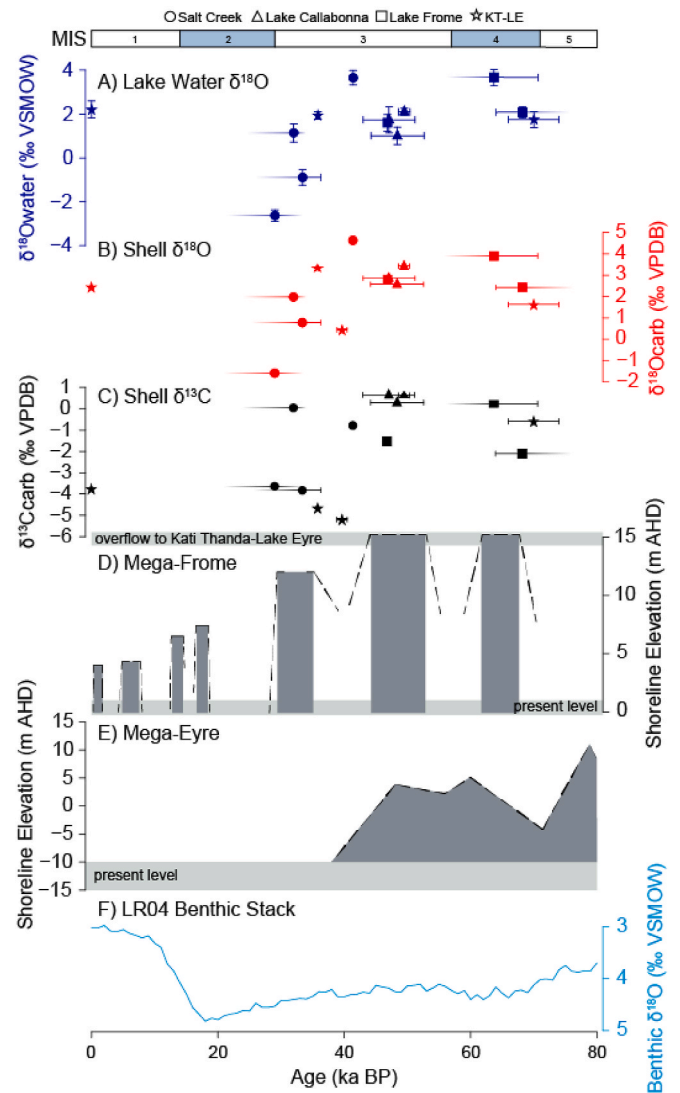


Fig. 6. A) Inferred playa lake water $\delta^{18}\text{O}$; B) lake mollusc shell $\delta^{18}\text{O}$ and C) $\delta^{13}\text{C}$; reconstructed shoreline elevations for D) Lake Mega-Frome (Cohen et al., 2012) and E) Lake Mega-Eyre (Magee et al., 2004); and F) “LR04” stacked (averaged) benthic $\delta^{18}\text{O}$ record (Lisiecki and Raymo, 2005). For the lake and mollusc stable isotope data, sample sites are indicated by circles = Salt Creek, triangles = Lake Callabonna, squares = Lake Frome, and stars = Kati Thanda-Lake Eyre.

data indicate that lake filling generally occurred during periods of low temperature. Weij et al. (2024) recently suggested that increased moisture availability occurred in Australia during periods of climatic cooling. However, samples from between ~ 75 and 57 ka indicate that lake filling also occurred when temperatures were relatively warm, although these temperature estimates are warmer than expected for MIS-4. Furthermore, there are no strong correlations between temperature and lake depth ($R^2 = 0.01$) or between temperature and $\delta^{18}\text{O}_{\text{water}}$ for any of the studied lakes (Fig. S1), implying that the relationship between temperature and rainfall may not be as definitive as proposed by Weij et al. (2024) and is instead reliant on multiple large scale climate factors. Unfortunately, it is unlikely that the exact relationship between past temperature and hydrological conditions of the lakes can be determined without a more complete understanding of the ecology of the molluscs.

Other semi-arid and arid regions, such as the Mongolian desert (Klinge and Sauer, 2019) and much of central and southern America (e. g. Labraga and Villalba, 2009; Roy et al., 2019), may benefit from the

findings of this study. Like central Australia, quantitative reconstruction of past temperature and hydrological variability in these dry terrestrial regions is generally complicated by an absence of continuous sedimentary deposits and poor preservation of organic matter. This study demonstrates that Δ_{47} from lake mollusc shells can be a valuable tool for reconstructing palaeoclimate in these regions, which would provide greater insight into past and future climatic change in arid continental regions worldwide.

6. Conclusions

This study represents the first attempt to infer past temperature and hydrological change in central Australia using clumped isotope thermometry. Despite a relatively sparse temporal coverage and sample density, our data offer arguably the most comprehensive record to date of temperature for the last glacial period in Australia's arid interior. The dataset highlights the potential application of clumped isotope analysis to infer air temperatures from palaeoshoreline sediments and provides further environmental context for the first arrival of humans into Australia's continental interior and the extinction of the Australian megafauna.

Reconstructed water and mean annual air temperatures in central Australia indicate that temperatures during the last glacial period were approximately 4–6 °C (3.6–6.0 °C; 95% C.I.) cooler than modern day, which is consistent with the few records from temperate and coastal Australia. Temperatures during late MIS-7 and early MIS-4 were similar to the Holocene. These findings are somewhat limited by uncertainty regarding potential disequilibrium effects and the timing of shell precipitation, which likely occurred during more humid seasons. Oxygen isotope ratios in palaeo-lake waters in central Australia's ephemeral lakes mostly reflect changes in the relative balance of evaporation over precipitation, with MIS-7 data suggesting that this period was less evaporative than the last ~75 ka.

Author contributions

FCN – Project design and conceptualisation, data analysis, methodology, writing: original draft preparation. JJT – Project design and conceptualisation, writing: review and editing. RMK – Data analysis, methodology. SCP – Project design and conceptualisation, writing: review and editing. QH – Data analysis, writing: review and editing. LJA – Data analysis, writing: review and editing. TJC – Project design and conceptualisation, fieldwork, writing: review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2024.109157>.

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