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## A pluvial episode identified in arid Australia during the Medieval Climatic Anomaly

T J. Cohen

*University of Wollongong, [tcohen@uow.edu.au](mailto:tcohen@uow.edu.au)*

G C. Nanson

*University of Wollongong, [gnanson@uow.edu.au](mailto:gnanson@uow.edu.au)*

J D. Jansen

*Stockholm University, [jjansen@uow.edu.au](mailto:jjansen@uow.edu.au)*

L A. Gliganic


*University of Wollongong, [lukeg@uow.edu.au](mailto:lukeg@uow.edu.au)*

J.-H May

*University of Wollongong, [hmay@uow.edu.au](mailto:hmay@uow.edu.au)*

*See next page for additional authors*

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### Recommended Citation

Cohen, T J.; Nanson, G C.; Jansen, J D.; Gliganic, L A.; May, J.-H; Larsen, J R.; Goodwin, I D.; Browning, S; and Price, D M.: A pluvial episode identified in arid Australia during the Medieval Climatic Anomaly 2012, 167-171.

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# A pluvial episode identified in arid Australia during the Medieval Climatic Anomaly

## Abstract

Optically stimulated luminescence (OSL) ages from a relict shoreline on Lake Callabonna record a major pluvial episode in southern central Australia between  $1050 \pm 70$  and  $1100 \pm 60$  Common Era (CE), within the Medieval Climatic Anomaly (MCA). During this pluvial interval Lake Callabonna filled to 10–12 times the volume of the largest historical filling (1974) and reached maximum depths of 4–5 m, compared to the 0.5–1.0 m achieved today. Until now there has been no direct evidence for the MCA in the arid interior of Australia. A multi-proxy, analogue-based atmospheric circulation reconstruction indicates that the pluvial episode was associated with an anomalous meridional atmospheric circulation pattern over the Southern extratropics, with high sea-level pressure ridges in the central Indian Ocean and Tasman Sea, and a trough extending from the Southern Ocean into central Australia. A major decline in the mobility of the Australian aboriginal hunter-gatherer coincides with this MCA period, in southern central Australia.

## Keywords

anomaly, pluvial, identified, episode, arid, australia, during, medieval, climatic

## Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

## Publication Details

Cohen, T. J., Nanson, G. C., Jansen, J. D., Gliganic, L. A., May, J., Larsen, J. R., Goodwin, I. D., Browning, S. & Price, D. M. (2012). A pluvial episode identified in arid Australia during the Medieval Climatic Anomaly. *Quaternary Science Reviews*, 56 (N/A), 167-171.

## Authors

T J. Cohen, G C. Nanson, J D. Jansen, L A. Gliganic, J.-H May, J R. Larsen, I D. Goodwin, S Browning, and D M. Price

## **A pluvial episode identified in arid Australia during the Medieval Climatic Anomaly**

T.J. Cohen<sup>a</sup>, G.C. Nanson<sup>a</sup>, J.D. Jansen<sup>b</sup>, L.A. Gliganic<sup>a</sup>, J-H. May<sup>a</sup>, Larsen, J.<sup>c,d</sup>,  
I.D. Goodwin<sup>e</sup>, S. Browning<sup>e</sup>, D.M. Price<sup>a</sup>.

<sup>a</sup>GeoQuEST Research Centre – School of Earth and Environmental Sciences  
University of Wollongong, Wollongong, NSW, 2522, Australia.

<sup>b</sup>Department of Physical Geography and Quaternary Geology, Stockholm University,  
Stockholm, Sweden.

<sup>c</sup>Connected Waters Initiative Research Centre, Water Research Laboratory, University of  
New South Wales, 110 King St. Manly Vale, NSW, 2093, Australia.

<sup>d</sup>National Centre for Groundwater Research and Training (NCGRT).

<sup>e</sup>Department of Environment and Geography, Macquarie University, NSW, Australia.

### **Corresponding author:**

**Dr Tim Cohen**

<sup>a</sup>GeoQuEST Research Centre – School of Earth and Environmental Sciences, University of  
Wollongong, Wollongong, NSW, 2522, Australia

Ph: (02) 4239 2375

Fax: (02) 4221 4250

e-mail: [tcohen@uow.edu.au](mailto:tcohen@uow.edu.au)

## **Abstract**

Optically stimulated luminescence (OSL) ages from a relict shoreline on Lake Callabonna record a major pluvial episode in southern central Australia between  $1050 \pm 70$  and  $1100 \pm 60$  Common Era (CE), within the Medieval Climatic Anomaly (MCA). During this pluvial interval Lake Callabonna filled to 10 - 12 times the volume of the largest historical filling (1974) and reached maximum depths of 4 - 5 m, compared to the 0.5 – 1.0 m achieved today. Until now there has been no direct evidence for the MCA in the arid interior of Australia. A multi-proxy, analogue-based atmospheric circulation reconstruction indicates that the pluvial episode was associated with an anomalous meridional atmospheric circulation pattern over the Southern extratropics, with high sea-level pressure ridges in the central Indian Ocean and Tasman Sea, and a trough extending from the Southern Ocean into central Australia. A major decline in the mobility of the Australian aboriginal hunter-gatherer coincides with this MCA period, in southern Central Australia.

**Keywords:** mega-lake, Lake Callabonna, Medieval Climatic Anomaly, OSL, palaeoshoreline,

## **1.Introduction**

The Medieval Climatic Anomaly (950 – 1250 CE) has classical climatic connotations for the northern hemisphere (e.g. severe drought in North America, Feng e al., 2008) and associated cultural developments (e.g. the settlement of Iceland and Greenland at ~ CE 874 and ~ CE 985, respectively; Xoplaki et al., 2011). A number of studies have examined the temporal and regional variation in the MCA for different regions, although almost exclusively within the Northern Hemisphere, and with no robust evidence for MCA hydroclimate impacts in Australasia. This time interval is however particularly notable in continental Australia because recent archaeological evidence suggests for a rapid expansion in human population during and following the MCA (Smith and Ross, 2009; Williams et al., 2010). However, the role of climate in this expansion remains to be determined, and unlike the situation in the Northern Hemisphere, little is known as to whether this interval was warm, wet, cool or dry.

At a global scale, major shifts in climate at this time are hypothesised to be a result of a strongly positive North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) (Trouet et al., 2009), together with a shift towards a La Niña -like mean state in the Pacific (Clement et al., 1996; Mann et al., 2009). We assess the nature and timing of a major pluvial episode in southern central Australia that corresponds to the MCA by excavating relict shorelines and dating them with a range of independent dating techniques. We also examine the association between the hydroclimate and atmospheric circulation in southern Central Australia.

## 2. Regional setting and methods

Lake Callabonna is part of the Lake Mega-Frome system (Lakes Frome, Callabonna, Blanche and Gregory, Fig.1), which coalesces at  $5 \pm 2$  m depth to form a single major waterbody surrounding the eastern and northern margins of the Flinders Ranges in arid central Australia (Fig.1). These playa lakes have lake-floor elevations that range from  $-2$  to  $+1$  m Australian Height Datum (AHD – equivalent to mean height above sea level). Historically, Lakes Frome and Callabonna have filled to depths of 0.5 to 1.0 m in exceptionally wet years (e.g. 1974) and more recently but to a lesser extent in the 2009-2010 La Niña events. In general, elevated shorelines are best preserved on the western and southern margins of the lakes (upwind side) with larger lunettes and dunefields occurring on the downwind eastern and northern margins of the lakes. Relict shorelines occur up to 15 m above the playa floor and the lower most of these forms the focus of this paper.

Cohen et al., (2011; 2012) report a history of continental aridification from a palaeoshoreline record that extends back to Marine Isotope Stage (MIS) 5. In addition, an optically stimulated luminescence (OSL) age of 0.95 ka was obtained from a shoreline 4 m above the modern playa floor, indicating a historical lake-filling episode significantly greater than any of the modern hydrological observations. These mega-lakes have at times represented immense waterbodies and suggest vastly different climatic regimes once existed in the now arid interior of Australia. Today, these lakes can receive floodwaters from remote Austral summer-season, tropical rainfall delivered via Strzelecki Creek (a tributary of Cooper Creek) or from the adjacent Flinders Ranges. Alternatively, floodwaters can be derived from local Austral autumn to spring season rainfall over the adjacent Flinders Ranges catchment, which is associated with the tracks of southern maritime low pressure systems over mid-latitude

continental Australia. As such, the hydrological record of Lake Mega-Frome reflects a record of either tropical or extratropical moisture sources, or a combination of both.

The stratigraphy of the relict beach ridge was examined via multiple excavations, and deposits were dated using OSL, thermoluminescence (TL) and accelerator mass spectrometer (AMS)  $^{14}\text{C}$  from freshwater molluscs, charcoal and emu eggshell to further constrain the timing of this pluvial episode. All geochronological data is provided in Tables 1 – 5 of the Supplementary Data. Sampling was concentrated on stratified high-energy beach deposits collected from each 2 – 3 m excavation using stainless steel tubing. OSL ages were obtained by measuring equivalent doses using single sand-sized quartz grains, and a full description of sample preparation and analysis techniques is provided in Cohen et al. (2011; 2012) and Gliganic et al. (in press) with procedures for the multi-grain TL outlined in Shepperd and Price (1990). A 90 m grid-cell digital elevation model (DEM) was used to construct lake-floor morphology and hypsometry (Cohen et al., 2012; Leon and Cohen, 2012) and we have assumed negligible lake-floor deflation since the MCA lake-filling episode.

### **3. Chronology of the Lake Callabonna relict shorelines**

The lake margin transect represents a relatively steep margin with four prominent shorelines above the modern floor, dissected by modern streams (Fig.1). Five excavations were undertaken to supplement the original stratigraphic section undertaken by Cohen et al., (2011; 2012) to test the validity of the initial MCA chronology. The additional stratigraphic sections confirm the presence of a 0.5 – 0.6 m thick beach unit from the lowest shoreline, which is  $4 \pm 0.2$  m above the playa floor (*upper beach unit*, Fig.2). This unit contains weakly-defined landward dipping crossbeds, and a poorly sorted mix of silts to fine gravel (10 to 13 mm),

typical of high-energy beach facies examined elsewhere (Cohen et al. 2011). Two single-grain OSL ages from separate excavations demonstrate excellent consistency with ages of  $1050 \pm 70$  CE and  $1100 \pm 60$  CE respectively (Fig.2). Some evidence of post-depositional mixing is evident in the upper beach unit with the multi-grain TL estimate at Pit 6A of  $360 \pm 250$  CE (Fig.2). An overestimation from such a multi-grain technique is expected, considering the observed mixing in the single-grain distributions (see supplementary data).

Further stratigraphic complexity is exemplified by an AMS  $^{14}\text{C}$  age from a broken freshwater bi-valve from within the beach facies which returned a mid-Holocene age of  $4690 \pm 80$  cal. BP (Fig. 2), suggesting the incorporation of older shell from the Holocene shoreline into the MCA beach facies. Two AMS  $^{14}\text{C}$  ages from Pit 6B yield conflicting results. Emu eggshell from the beach facies returns an age of  $1575 \pm 90$  CE (~ 250 years younger than the OSL estimate; Fig.2) whilst the AMS  $^{14}\text{C}$  age on the charcoal returned a modern age (both suggestive of bioturbation as evident in the single-grain distribution) (Fig.2; supplementary data). The upper (MCA) beach unit unconformably overlies an older beach unit dated with OSL at  $2.7 \pm 0.17$  ka (Fig.2), and together these late Holocene shoreline deposits blanket a basal post-LGM shoreline deposit containing poorly-sorted and cemented cross-bedded sand and gravel facies and reworked lake floor sediments. The entire shoreline complex rests upon an eroded Pleistocene lacustrine sequence dated by TL at  $199 \pm 22$  ka (Fig. 2; supplementary data); an age that should be interpreted as a minimum estimate.

#### **4. Discussion and conclusion**

Shoreline evidence for an MCA pluvial episode at Lake Callabonna is supported by studies documenting high-magnitude flooding in rivers draining the central Australian ranges (Pickup et al., 1988; Patton et al., 1993), the Barrier Ranges ~150 km to the east of Lake Frome



(Jansen and Brierley, 2004), and the Flinders Ranges, where at least one major flood has occurred since 300 CE (Quigley et al., 2007). Unlike the Flinders Ranges and Barrier Ranges, no record of major flooding occurs along the Strzelecki Creek distributary channel (Larsen, 2012). The chrono-stratigraphic evidence from Lake Callabonna (Fig.2) would suggest that the lake filled to depths of  $4 - 5 \pm 0.5$  m in the MCA. At 4 m AHD the four lakes that comprise Lake Mega-Frome (Frome, Callabonna, Blanche and Gregory) would be four discrete water bodies joined by overflow channels (as seen in 1974) and by groundwater equilibration, with a combined area of  $\sim 3600$  km<sup>2</sup> and a volume of  $\sim 11$  km<sup>3</sup>. The time required to fill each of the lakes is unknown however the dimensions of the MCA shoreline at Lake Callabonna are much larger than anything produced under the modern hydrological regime on any of the four lakes. Owing to the rugged topography, thin soils and sparse vegetation on the adjacent Flinders Ranges, extreme rainfall events in today's hydrological regime are converted to runoff quickly with lake inflow occurring within 2 – 5 days after large rainfall events but with high transmission losses and low mean annual runoff coefficients of 0.038 to 0.05 (McMahon et al., 2008). From their maximum highstands, and assuming no additional significant inflow, the MCA equivalent of Lakes Frome, Callabonna, Blanche, and Gregory would have persisted for 25-27 months (see Supplementary data). These calculations use lake area and volume estimates from the DEM and assume modern seasonal variations in the lake surface evaporation rate (Bonython 1955; Tetzlaff and Bye 1978), and are likely to vary by up to 10% depending on groundwater dynamics (seepage gains or losses).

To explore the palaeo-synoptic circulation pattern responsible for the interpreted MCA lake filling/hydrological anomaly, we draw on a new multi-proxy, analogue-based atmospheric circulation reconstruction presented in Goodwin et al. (submitted). The method uses modern

regional analogues to determine the low-frequency climate variability recorded by the multiple climate proxys and draws on the synoptic typing approach using daily and seasonal data from reanalysis archives and global climate model output. The OSL ages of palaeoshorelines for Lake Callabonna indicate that the last lake-full phase was between 1050-1100 CE. Hence, we have used the reconstruction for the time slice 900 to 1000 CE from Goodwin et al. (submitted) to explore the synoptic drivers of the high frequency flooding.

The mean sea-level pressure and anomaly patterns are shown in Figure 3a for the Australasian region. The circulation has a strong meridionality with extratropical ridging at 90° E in the central Indian Ocean and in the Tasman Sea at 150° E to 170° E, that is associated with persistent high pressure blocking on synoptic time scales. This is a key factor in the formation of the climatological deep low pressure trough extending from the Southern Ocean into central Australia. This synoptic pattern is typical for high frequency of frontal rainfall over the Lake Frome catchment as Southern Ocean lows are forced to track northwards over Southern Australia. Figure 3b shows the key synoptic features that result in high rainfall, being the interaction between cold fronts and north-west cloud bands. The location of the north-west clouds bands over Southern Australia is often associated with the position of the high in the central Indian Ocean, near 90° E, which is also a key feature in the reconstruction for 900 to 1000 CE.

Whilst this reconstruction shows a bias towards the Austral spring season, it has been observed in the instrumental record that high lake inflows also occur from a strong monsoon trough over Central Australia in summer. The latter may well have contributed to the lake filling event and/or the maintenance of the MCA lake level. Further research is required to isolate the relative role of the high interannual to decadal frequency of Southern Ocean

derived continental lows over South Australia versus monsoonally derived rainfall in this pluvial episode. The climate-driven increase in water availability and lake permanence at this time may have resulted in a change in aboriginal indigenous society. The pluvial episode is contemporaneous with a minimum in the sum probability analysis of the aboriginal archaeological signature across southern Central Australia (Williams et al., 2011). Such a wet phase in southern Central Australia is one explanation for the decline in hunter-gather mobility, and the trend towards sedentary aboriginal society near semi-permanent water bodies (after Williams et al., 2011).

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**Fig. 1** Locality map and digital elevation model (DEM – based on 30 m shuttle data) of Lakes Frome, Callabonna, Blanche and Gregory (a – b) with the modern maximum 1 m filling contour and the 5 m (maximum MCA) filling limit; (c) Google earth image with mapped shorelines, lake margin transect (A' – A'') and 5 and 1 m derived contours.

**Fig. 2** Locations of stratigraphic sections (6 – 6D) from Lake Callabonna with chronostratigraphy from Pits 6, 6A and 6B and interpretation of shoreline stratigraphy. All errors for OSL are  $1 \sigma$  and the OSL age of  $15.8 \pm 1.2$  ka is taken from Cohen et al., (2011, 2012). Errors on AMS ages are  $2 \sigma$  and expressed as calibrated years before present (cal. BP) using CALIB v6 (see supplementary data).

**Fig. 3** (a) Australasian region section of a multi-proxy sea-level pressure (SLP) reconstruction for 900 to 1000 CE after Goodwin et al. (submitted). The black lines represent the mean SLP pressure field and the colours represent the SLP anomalies for the time-slice 900 – 1000 CE. The scale of the SLP anomalies is in Pascals (Pa), with low (high) SLP anomalies denoted by cool (warm) colours. (b) Example of synoptic meteorology that we hypothesise was more frequent during 900-1000 CE and was associated with lake filling. Daily composite anomaly of surface outgoing longwave radiation (OLR) in  $\text{W/m}^2$ , for 27 July, 1980, (from NCEP-NCAR Reanalysis) with cool colours representing thick convective cloud cover associated with northwest cloud bands (low OLR). Key synoptic features in this pattern are the poleward high pressure ridge over the Tasman Sea, a deep trough over the Southern Ocean and Southern Central Australia, and an equatorward high pressure ridge over the eastern Indian Ocean region. The intersection of the extratropical frontal system with the

tropical north-west cloud bands resulted in rainfall over the lake's catchment greater than 60% of the mean monthly total. Lake Callabonna location is shown by the solid black dot.

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**Table 5** – AMS  $^{14}\text{C}$  measurements

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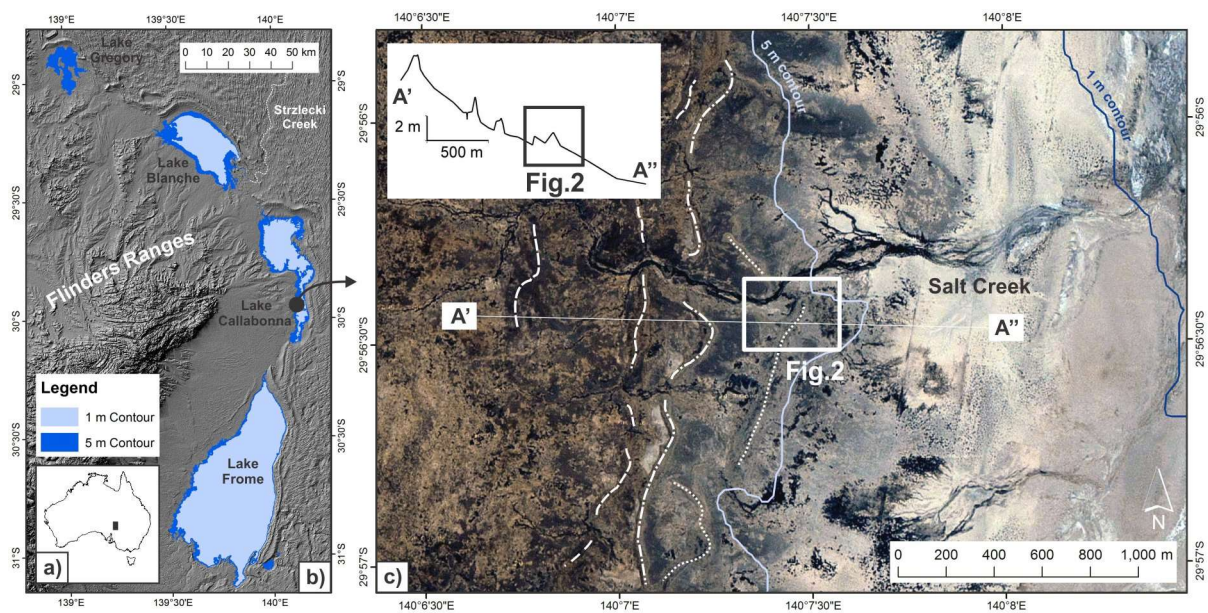




Figure 2

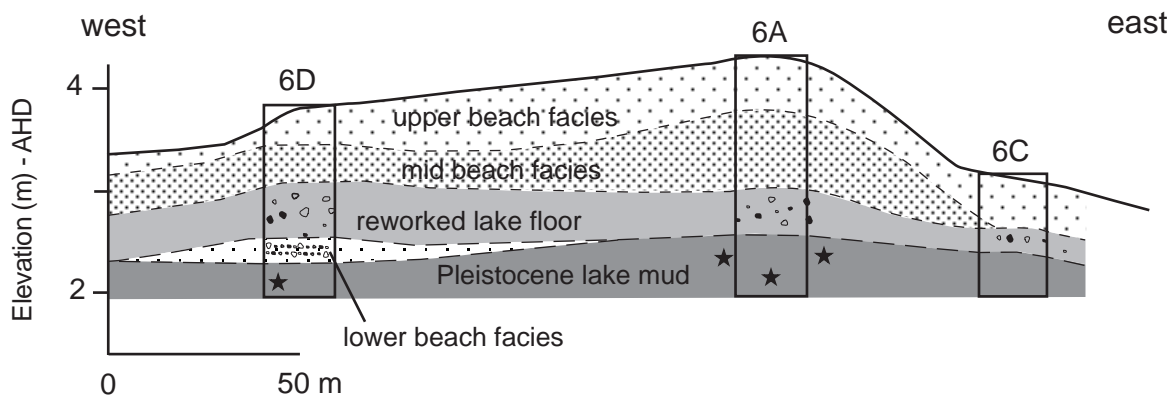
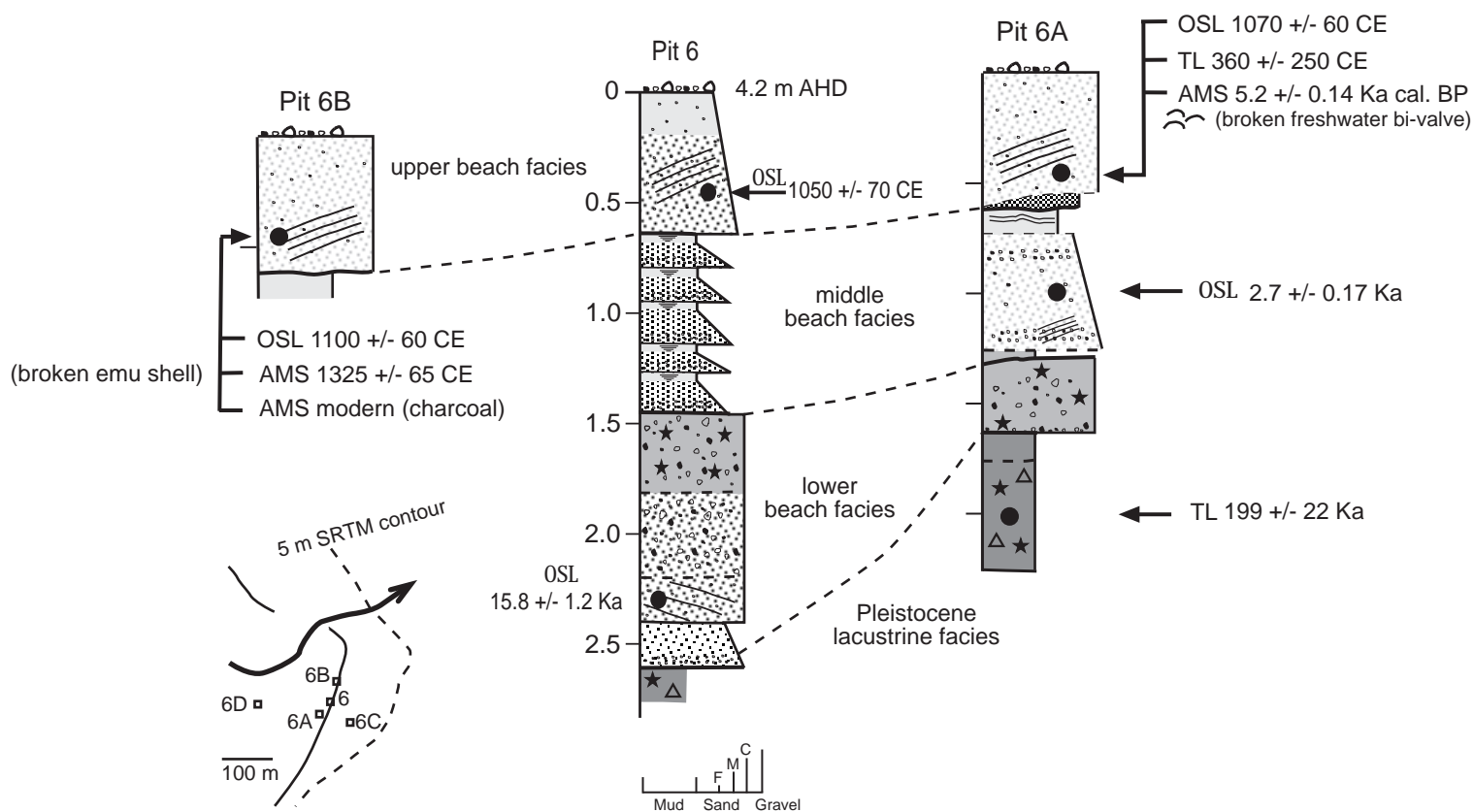
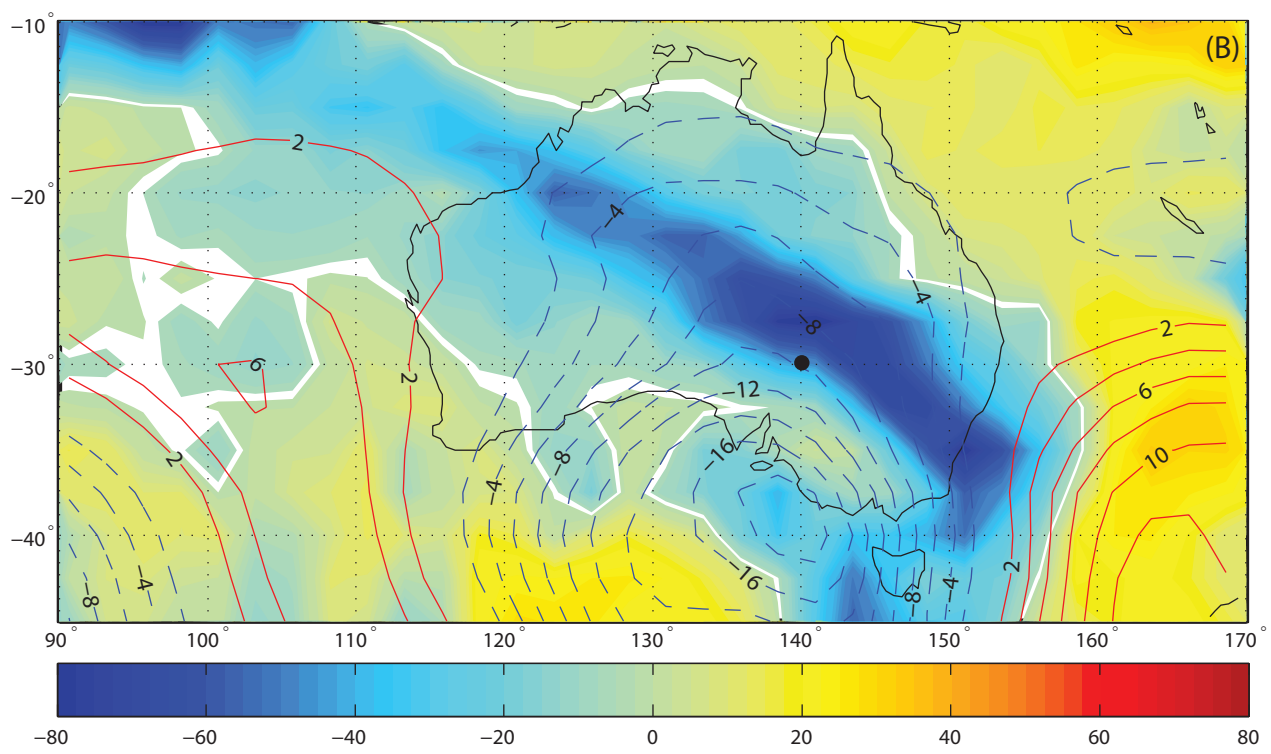
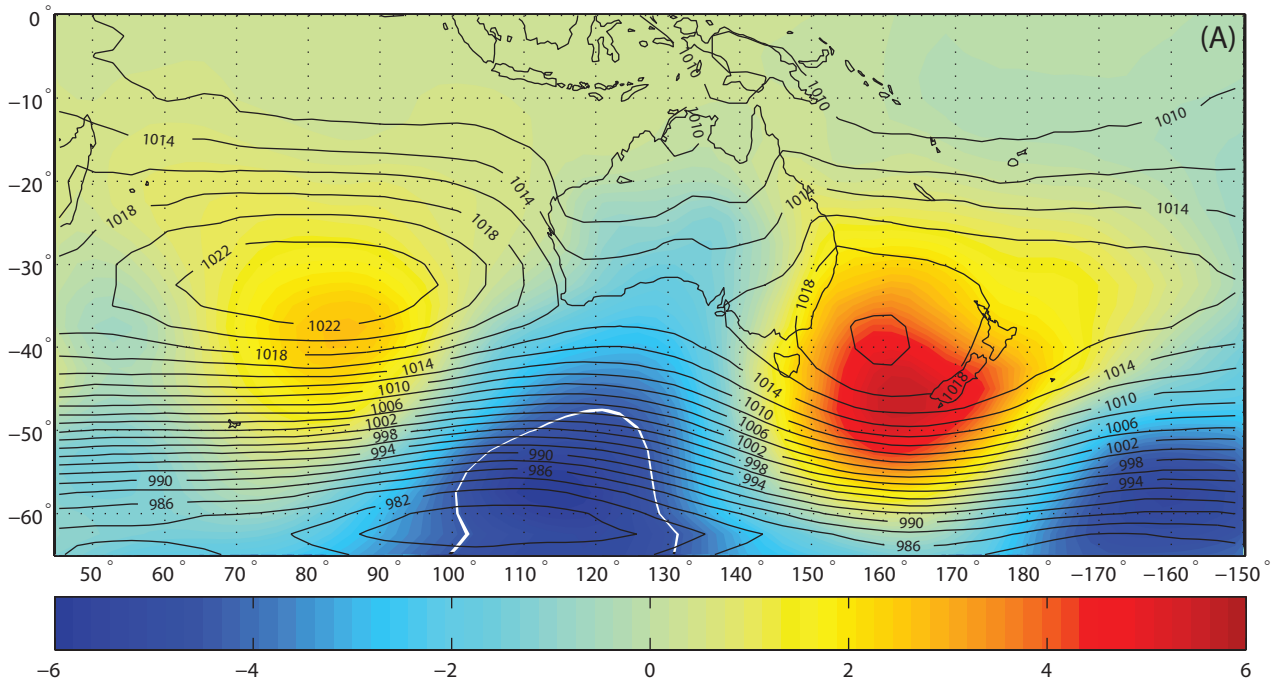


Figure 3



**Supplementary Table 1** Single-grain rejection criteria statistics

|                                            | SC6_0.4     | SC6A_0.5    | SC6A_1.0    | SC6B_0.4    |
|--------------------------------------------|-------------|-------------|-------------|-------------|
| No. of grains measured                     | 600         | 1000        | 1000        | 1000        |
| Grains rejected for the following reasons: |             |             |             |             |
| TN < 3xBG                                  | -           | 819         | 774         | 789         |
| fail recycling ratio                       | -           | 35          | 47          | 47          |
| Depletion by IR                            | -           | 67          | 79          | 51          |
| Recuperation test                          | -           | 23          | 21          | 45          |
| Class-3 grains                             | 0           | 1           | 0           | 0           |
| Sum of rejected grains                     | 589         | 945         | 921         | 932         |
| No. of accepted De values                  | 11          | 55          | 79          | 68          |
| CAM overdispersion (%)                     | 13 ± 4      | 28 ± 4      | 30 ± 3      | 46 ± 5      |
| CAM De-value (Gy)                          | 2.38 ± 0.13 | 2.68 ± 0.13 | 6.98 ± 0.28 | 2.62 ± 0.17 |

\* Sample SC6 was analysed and presented in Cohen et al, (2011; 2012)

**Supplementary Table 2** Single grain equivalent dose ( $D_e$ ) central age model (CAM) values and finite mixture model values

| Sample/<br>depth (m) | No. of<br>grains<br>measured | No. of<br>grains<br>accepted | CAM $D_e$<br>(Gy) | CAM<br>overdispersion<br>(%) | <b>Finite Mixture Model results</b> |                       |                                                   |                                  |
|----------------------|------------------------------|------------------------------|-------------------|------------------------------|-------------------------------------|-----------------------|---------------------------------------------------|----------------------------------|
|                      |                              |                              |                   |                              | No.<br>components<br>fitted         | Overdispersion<br>(%) | Proportion of grains<br>in major component<br>(%) | Major<br>component<br>$D_e$ (Gy) |
| SC6/0.4*             | 600                          | 11                           | 2.38 ± 0.14       | 13 ± 6                       | -                                   | -                     | -                                                 | -                                |
| SC6A/0.5             | 1000                         | 55                           | 2.68 ± 0.13       | 28 ± 4                       | 2                                   | 15                    | 93.0 ± 4.4                                        | 2.54 ± 0.10                      |
| SC6A/1.0             | 1000                         | 79                           | 6.98 ± 0.28       | 30 ± 3                       | 2                                   | 20                    | 92.9 ± 4.2                                        | 6.65 ± 0.24                      |
| SC6B/0.4             | 1000                         | 68                           | 2.62 ± 0.17       | 46 ± 5                       | 2                                   | 20                    | 98.5 ± 1.5                                        | 2.53 ± 0.09                      |

\* Sample SC6 was analysed and presented in Cohen et al, (2011; 2012)

**Supplementary Table 3** Dose rate, equivalent dose ( $D_e$ ) and single grain optical ages from palaeoshoreline deposits

| Sample/<br>depth (m) | Field water<br>content (%) | External dose rate (Gy/ka) |             |             | Internal dose<br>rate (Gy/ka) | Total dose<br>rate (Gy/ka) | $D_e$ (Gy)  | Age (ka)    | Age (CE)  |
|----------------------|----------------------------|----------------------------|-------------|-------------|-------------------------------|----------------------------|-------------|-------------|-----------|
|                      |                            | Beta                       | Gamma       | Cosmic      |                               |                            |             |             |           |
| SC6/0.4*             | 0.1 ± 0.05                 | 1.43 ± 0.05                | 0.83 ± 0.03 | 0.20 ± 0.02 | 0.03 ± 0.01                   | 2.48 ± 0.11                | 2.38 ± 0.14 | 0.96 ± 0.07 | 1050 ± 70 |
| SC6A/0.5             | 1.4 ± 0.7                  | 1.56 ± 0.08                | 0.90 ± 0.03 | 0.19 ± 0.02 | 0.03 ± 0.01                   | 2.69 ± 0.11                | 2.54 ± 0.10 | 0.94 ± 0.06 | 1070 ± 60 |
| SC6A/1.0             | 2.1 ± 1.1                  | 1.35 ± 0.08                | 0.91 ± 0.03 | 0.18 ± 0.02 | 0.03 ± 0.01                   | 2.46 ± 0.12                | 6.65 ± 0.24 | 2.70 ± 0.17 | -         |
| SC6B/0.4             | 0.9 ± 0.4                  | 1.62 ± 0.09                | 0.93 ± 0.03 | 0.20 ± 0.02 | 0.03 ± 0.01                   | 2.78 ± 0.13                | 2.53 ± 0.09 | 0.91 ± 0.06 | 1100 ± 60 |

\* Sample SC6 was analysed and presented in Cohen et al, (2011; 2012)

**Supplementary Table 4** – TL equivalent dose and multi-grain TL ages

| Sample/<br>depth (m) | Sample<br>No. | Field water    | Temp. Plateau   | U + Th Specific<br>Activity (Bq/kg) | K (%)<br>± 0.05 | Total dose<br>(Gy/ka) | $D_e$ (Gy) | Age (ka)               | Age (CE)  |
|----------------------|---------------|----------------|-----------------|-------------------------------------|-----------------|-----------------------|------------|------------------------|-----------|
|                      |               | content<br>(%) | Region<br>(° C) |                                     |                 |                       |            |                        |           |
| SC6A/0.5             | W4442         | 0.8            | 275-500         | 46 ± 1.2                            | 1.5             | 2.7 ± 0.06            | 4.5 ± 0.7  | 1.65 ± 0.25            | 360 ± 250 |
| SC6A/2.0             | W4443         | 10.7           | 350-450         | 50.2 ± 1.1                          | 0.24            | 1.88 ± 0.04           | 375 ± 44   | 199 ± 22<br>(242 ± 27) | -         |

Sample W4442 was analysed using the 90 – 125 µm quartz

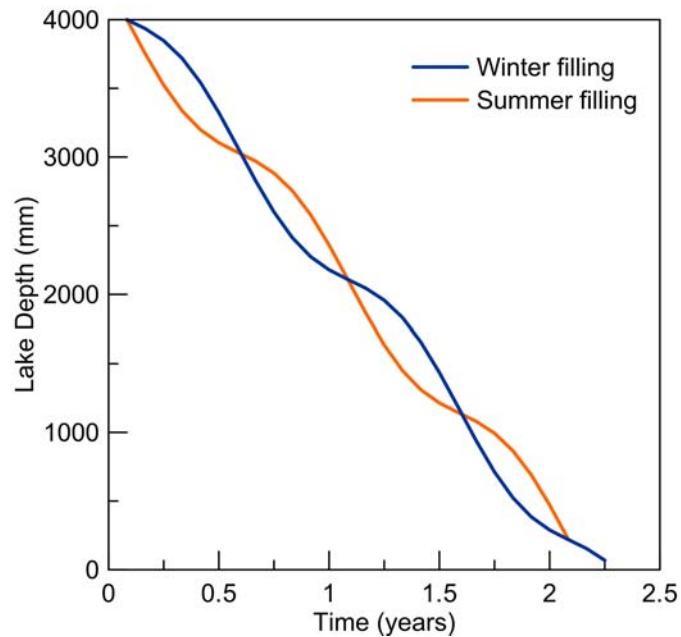
Sample W4443 was analysed using the 1- 8 µm polymineral grain fraction. Bracketed age includes a fading factor measured after 14 days storage at 80° C.

**Supplementary Table 5** AMS  $^{14}\text{C}$  measurements - All errors are  $1\sigma$  for measured radiocarbon ages but  $2\sigma$ 

| Sample/<br>depth (m) | Lab<br>Code | Sample material    | $\delta$ ( $^{13}\text{C}$ )<br>per mil | Measured<br>radiocarbon age (BP) | Calibrated radiocarbon age<br>(cal. BP) $2\sigma$ | Age (CE) $2\sigma$ |
|----------------------|-------------|--------------------|-----------------------------------------|----------------------------------|---------------------------------------------------|--------------------|
| SC6A/0.44            | Beta-283857 | Freshwater mollusc | -3.9                                    | 4190 ± 40                        | 4690 ± 80                                         | -                  |
| SC6B/0.4             | Beta-283858 | Emu eggshell       | -0.4                                    | 290 ± 40                         | 375 ± 90                                          | 1575 ± 90          |
| SC6B/0.5             | Beta-283859 | Charcoal           | -24.7                                   | 150 ± 40                         | 290 – 0 *                                         | 1810 ± 150         |

pMC = percent modern carbon

Calibration of samples has used CALIB v6: intcal09.14c



**Supplementary Figure 1** Model drying for 4m deep lakes in the Lake Frome system. Filling the lake in summer (January) would allow water to exist for 25 months, while winter (July) filling would allow 27 months. Both these scenarios assume no additional lake inflow, and that lake recession is controlled only by evaporation. We use monthly evaporation rates estimated as a sine function fitted to the monthly Lake Eyre evaporation data of Bonython (1955), Penman (1955), and Tetzlaff and Bye (1978). Although groundwater gains and / or losses almost certainly would occur under these conditions, these are only likely to impact on our estimates of lake drying time by up to 10%. This is because groundwater seepage rates are lagged at the lake margins, but very low volume, and any potential infiltration losses are largely unknown but likely to be minimal given these lakes are typically sites of net groundwater discharge (Tetzlaff and Bye 1978).

### References:

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- Penman, L. 1955. Evaporation from Lake Eyre. Lake Eyre, South Australia: The Great Flooding of 1949-50. The report of the Lake Eyre Committee, the Royal Geographic Society of Australasia, South Australian Branch, 57 -62.
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