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

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Abstract

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Keywords

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

Disciplines

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

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

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Abstract

Optically stimulated luminescence (OSL) ages from a relict shoreline on Lake Callabonna record a major pluvial episode in southern central Australia between 1050 ± 70 and 1100 ± 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 exclulsively 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 ± 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 distributary 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 used OSL, thermoluminescence (TL) and accelerator mass spectrometer (AMS) ^{14}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 ± 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 ± 70 CE and 1100 ± 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 ± 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}C age from a broken freshwater bi-valve from within the beach facies which returned a mid-Holocene age of 4690 ± 80 cal. BP (Fig. 2), suggesting the incorporation of older shell from the Holocene shoreline into the MCA beach facies. Two AMS ^{14}C ages from Pit 6B yield conflicting results. Emu eggshell from the beach facies returns an age of 1575 ± 90 CE (~ 250 years younger than the OSL estimate; Fig.2) whilst the AMS ^{14}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 ± 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 ± 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 ± 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 ~3600 km^2 and a volume of ~11 km^3. 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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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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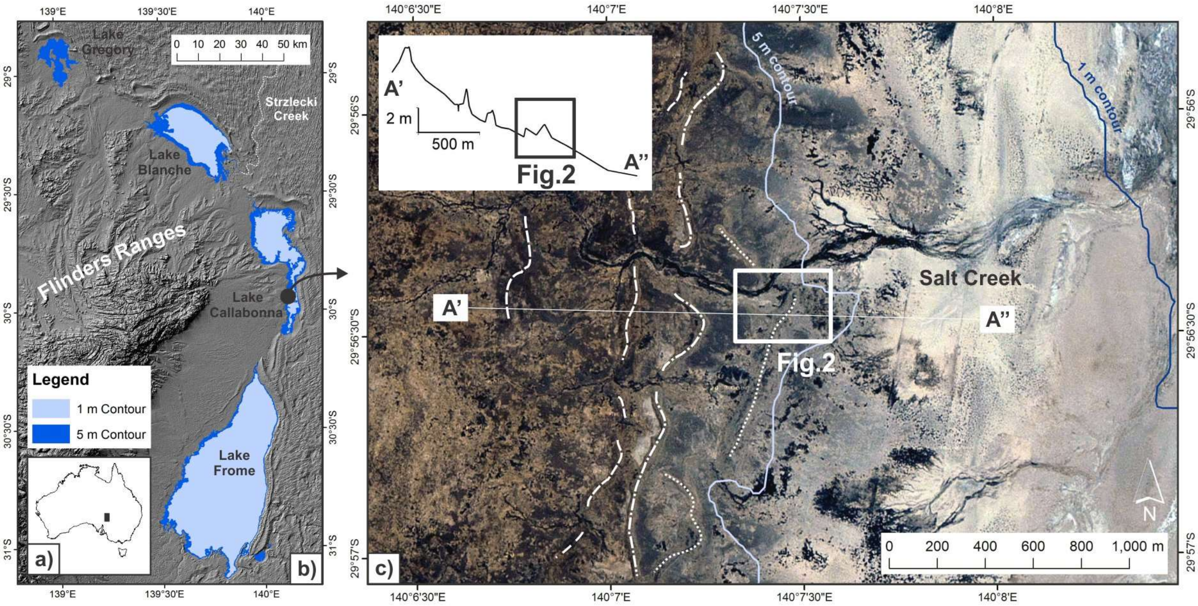
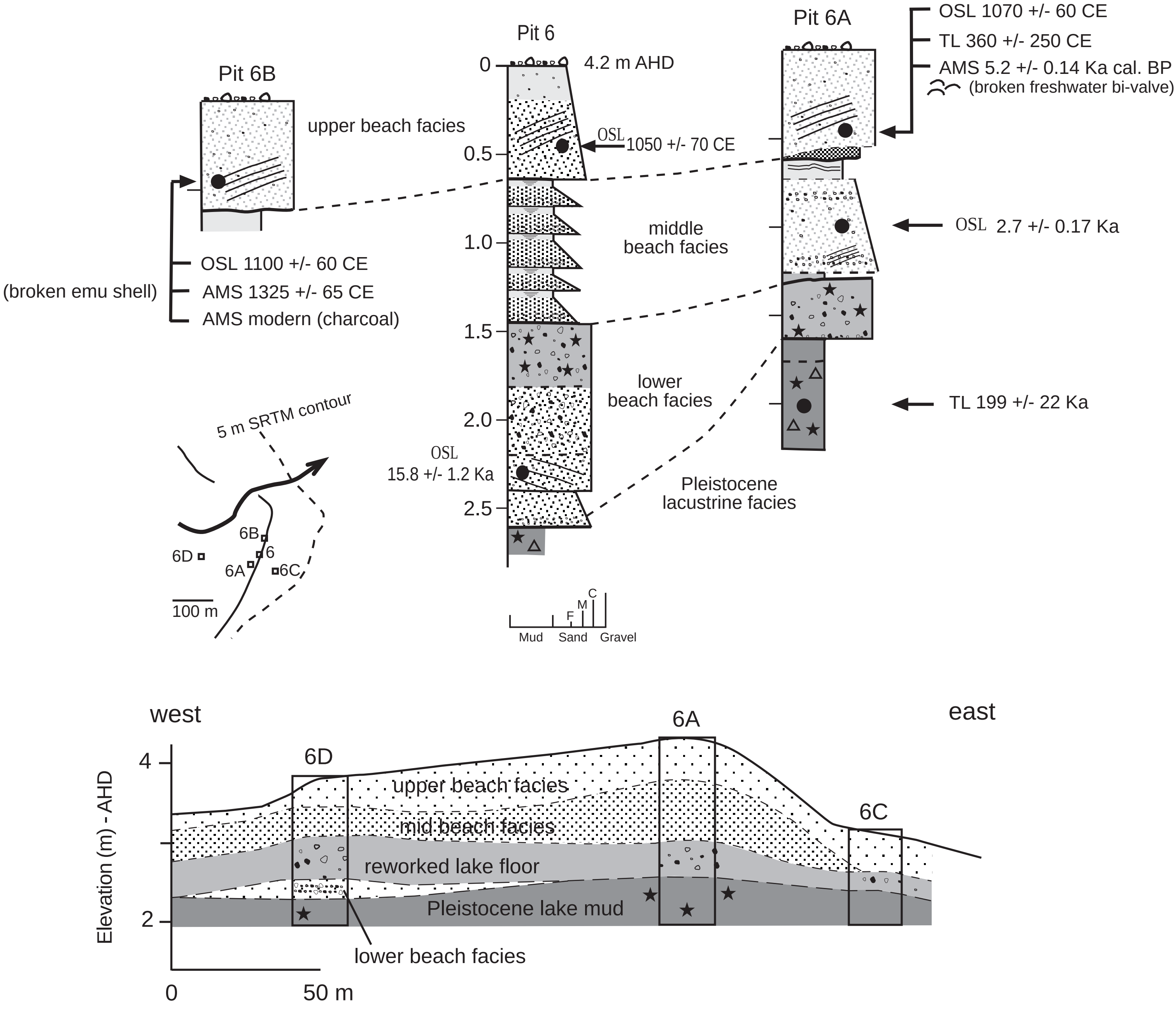
Figure 1



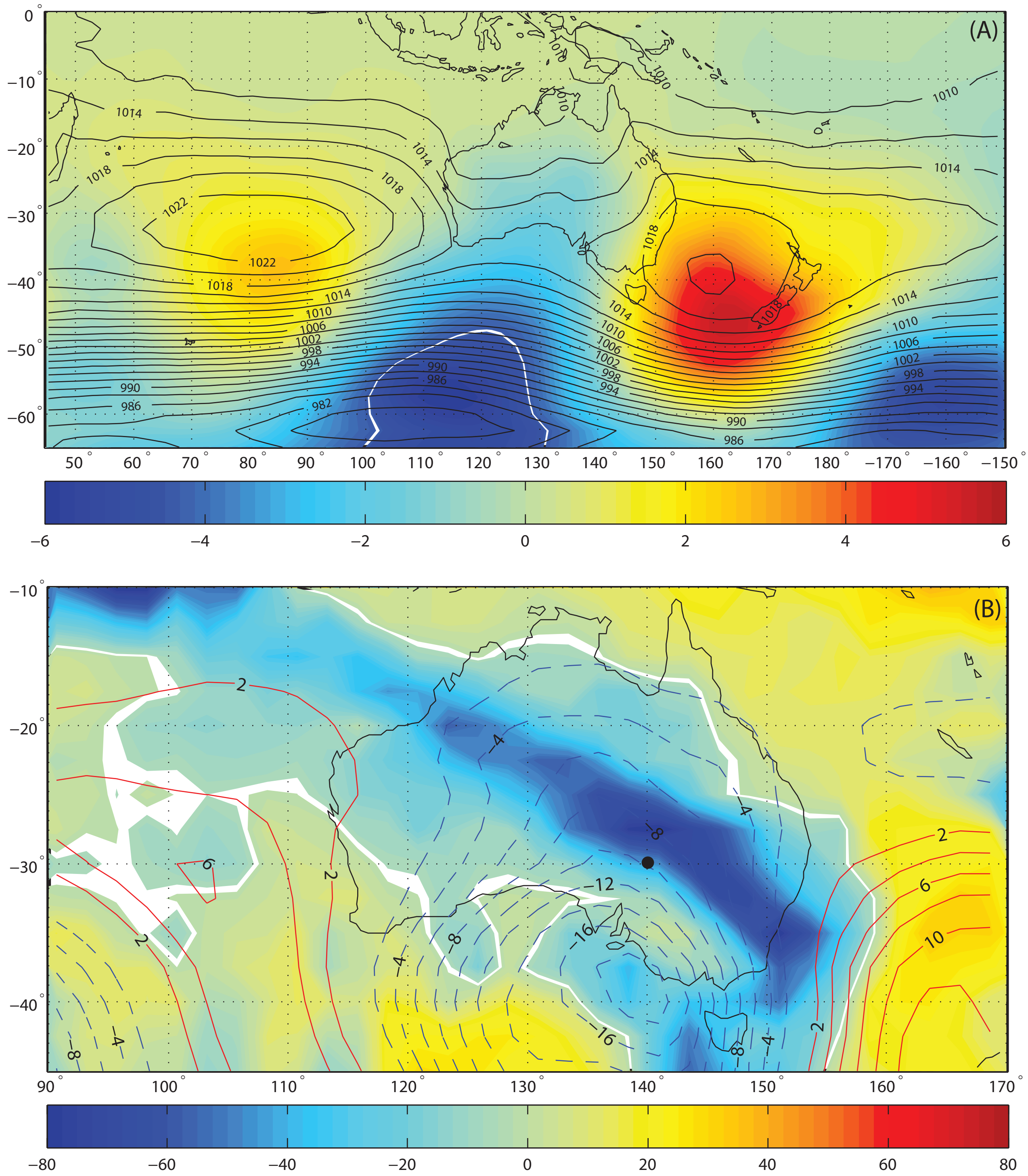
Lake Gregory
Strzlecki Creek
Lake Blanche
Flinders Ranges
Lake Callabonna
Lake Frome
Legend
1 m Contour
5 m Contour
a)
b)
c)
0 10 20 30 40 50 km
A'
A''
2 m
500 m
Fig.2
5 m contour
1 m contour
Salt Creek
0 200 400 600 800 1,000 m
N

Figure 2



Pit 6B
upper beach facies
OSL 1100 +/- 60 CE
(broken emu shell)
AMS 1325 +/- 65 CE
AMS modern (charcoal)
Pit 6
0
4.2 m AHD
OSL
1050 +/- 70 CE
0.5
1.0
1.5
2.0
2.5
middle
beach facies
lower
beach facies
OSL
15.8 +/- 1.2 Ka
Pleistocene
lacustrine facies
Mud
Sand
Gravel
F
M
C
Pit 6A
OSL 1070 +/- 60 CE
TL 360 +/- 250 CE
AMS 5.2 +/- 0.14 Ka cal. BP
(broken freshwater bi-valve)
OSL 2.7 +/- 0.17 Ka
TL 199 +/- 22 Ka
5 m SRTM contour
6B
6
6D
6A
6C
100 m
west
east
6D
6A
6C
upper beach facies
mid beach facies
reworked lake floor
Pleistocene lake mud
lower beach facies
Elevation (m) - AHD
4
2
0
50 m

Figure 3


(A)
0°
−10°
−20°
−30°
−40°
−50°
−60°
50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180° −170° −160° −150°
1010
1014
1018
1022
1006
1002
998
994
990
986
982
−6 −4 −2 0 2 4 6
(B)
−10°
−20°
−30°
−40°
90° 100° 110° 120° 130° 140° 150° 160° 170°
2
6
10
−4
−8
−12
−16
−80 −60 −40 −20 0 20 40 60 80

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/ depth (m)	No. of grains measured	No. of grains accepted	CAM D_e (Gy)	CAM overdispersion (%)	**Finite Mixture Model results**			
					No. components fitted	Overdispersion (%)	Propotion of grains in major component (%)	Major component 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/ depth (m)	Field water content (%)	External dose rate (Gy/ka)			Internal dose rate (Gy/ka)	Total dose rate (Gy/ka)	De (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/ depth (m)	Sample No.	Field water content (%)	Temp. Plateau Region (° C)	U + Th Specific Activity (Bq/kg)	K (%) ± 0.05	Total dose (Gy/ka)	De (Gy)	Age (ka)	Age (CE)
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 (242 ± 27)	-

Sample W4442 was analysed using the 90 – 125 μm quartz

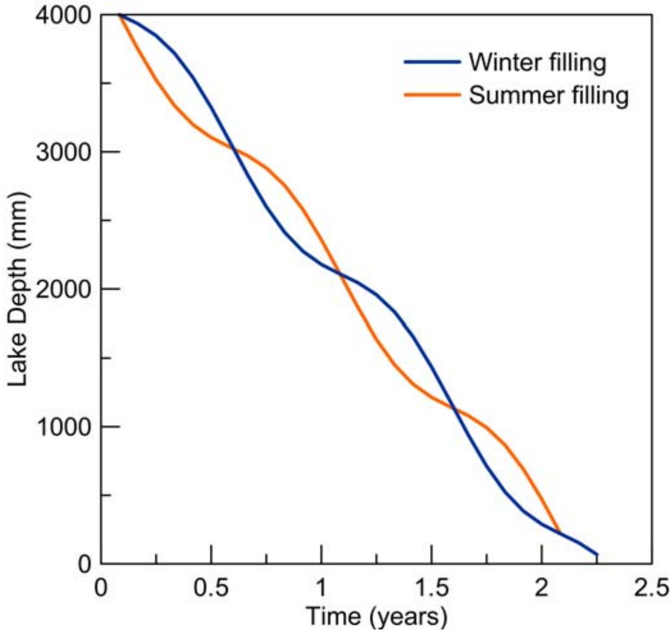
Sample W4443 was analysed using the 1- 8 μm polymineral grain fraction. Bracketed age includes a fading factor measured after 14 days storage at 80° C.

Supplementary Table 5 AMS ^{14}C measurements - All errors are 1σ for measured radiocarbon ages but 2σ

Sample/ depth (m)	Lab Code	Sample material	δ (^{13}C) per mil	Measured radiocarbon age (BP)	Calibrated radiocarbon age (cal. BP) 2σ	Age (CE) 2σ
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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Tetzlaff, G., Bye, J.A.T., 1978. Water balance of lake eyre for the flooded period January 1974 - June 1976. Transactions Royal Society South Australia 102(4), 90-96.