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Late Quaternary evolution of a playa margin at Lake Frome, South Australia

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Publication Details

May, J. -H., Barrett, A., Cohen, T. J., Jones, B. G., Price, D. & Gliganic, L. A. (2015). Late Quaternary evolution of a playa margin at Lake Frome, South Australia. *Journal of Arid Environments*, 122 93-108.

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Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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Late Quaternary evolution of a playa margin at Lake Frome, South Australia

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Abstract

Playa margins are often characterised by a wide spectrum of landforms, which provide links between major lake stands, as recorded by beach ridges, and the detailed stratigraphic and paleoenvironmental information stored in lacustrine sediments. We mapped playa marginal geomorphology at Lake Frome, South Australia, documented the sedimentary characteristics, and analysed microfossil assemblages in selected sediments. Using a luminescence based approach, the sediments were summarised in four main stratigraphic units. During the later stages of Marine Isotope Stage (MIS)5 fluvio-deltaic sediments were deposited (Unit 1), indicating significant runoff from the adjacent Flinders Ranges into partly freshwater-dominated lakes. No sediments were dated between ~70 and 25 ka, but renewed sediment delivery from the Flinders Ranges and re-deposition characterised the playa margin LGM and the early Holocene (Unit 2). The most recent phase of depositional activity is reflected by source-bordering dunes and lake marginal spit formation (Unit 3). Short-lived flooding events in the late Holocene are recorded by lake floor sediments and terminal splays (Unit 4). Our findings outline a dynamic late Quaternary playa margin, and highlight the complementary role which playa marginal landforms and sediments may play for the interpretation of runoff, sedimentary dynamics and paleoenvironments related to high regional lake levels.

Keywords: Playa lake, shoreline, stratigraphy, Lake Frome, late Quaternary, paleoenvironment

1. Introduction

Lakes are sensitive archives for the reconstruction of paleoenvironments and hydrology, and can thus provide crucial data for an improved understanding of past regional to global-scale changes in atmospheric circulation systems in the Quaternary (Harrison, 1993; Street-Perrott and Harrison, 1985). In Australia, the large endoreic playa lake systems of lakes Eyre, Frome, Callabonna, Blanche and Gregory are situated in the arid interior of the continent, and have played a central role in reconstructing regional-scale changes in paleoenvironments and hydrology (Nanson and Price, 1998). Early studies made use of discontinuous lacustrine sedimentary archives in the central parts of the lake basins to infer changes in depositional environments over time (Bowler et al., 1986; Magee et al., 1995). The chronology and sedimentology of shoreline, fluvial and aeolian sediments has been used to indicate that these dry playa lakes in the now arid centre of Australia had repeatedly filled to form a continuous water body or mega-lake with a maximum extent of nearly 35,000 km² (DeVogel et al., 2004; Leon and Cohen, 2012; Magee et al., 2004).

More recently, the detailed survey of the lake floor topography (Leon and Cohen, 2012) and shoreline geomorphology (Nanson et al., 1998) in combination with the increasing availability of chronological data from beach ridges around these mega-lakes (Cohen et al., 2015; Cohen et al., 2012; Cohen et al., 2011) have placed new constraints on both timing *and* magnitude of peak lake levels and volumes during these mega-lake events. Peak highstands with maximum water depths of ~20-25 m and >15 m at Lake Eyre and Lake Frome/Callabonna, respectively, occurred exclusively in the first half of the last glacial cycle prior to ~50 ka (Cohen et al., 2012; Magee et al., 2004), while no significant evidence for filling events has been reported from Lake Eyre during the last 45 – 50 ka (Cohen et al., 2015; Magee and Miller, 1998; Magee et al., 2004). In contrast, successively younger and lower lake levels are recorded around the southernmost internally draining playa lakes Frome and Callabonna during the same time (Cohen et al., 2012; Cohen et al., 2011), raising the question if this divergence could result from regionally differing responses to lake-specific hydrologic boundary conditions and thresholds (Benson and Paillet, 1989; Cohen et al., 2012), or may in fact reflect significant changes in runoff and/or precipitation sources related to large-scale shifts in atmospheric circulation pattern (Cohen et al., 2012).

To answer these questions, a more comprehensive understanding of the lake history is required, which could be achieved by combining existing shoreline data with sedimentary and stratigraphic records (Wohl and Enzel, 1995). While the information stored in shoreline records such as beach ridges is generally restricted to the major lake stands (Burrough and Thomas, 2009; Sack and Álvarez, 2001), playa marginal settings provide valuable complementary information on changes in local-scale sedimentary environments during transgressive, regressive and low-stand episodes. This is particularly obvious when considering the wide range of landforms such as aeolian dunes, coastal spits and bars, or terminal fan-delta and splay systems around the modern day margins of the dry playa lakes in Central Australia (Ainsworth et al., 2012; Callen and Tedford, 1976; Croke et al., 1996; Draper and Jensen, 1976; Fisher et al., 2008; Lang et al., 2004). This study presents an overview of these diverse playa marginal landforms, sediments, stratigraphy and chronology in the vicinity of the Balcanoona Creek terminal splay on the western shore of Lake Frome with the objectives of (i) evaluating the potential of playa margins to provide complementary information to link existing shoreline

records and lacustrine sediments, and (ii) contribute new data towards linking major changes in regional fluvial activity *and* lake environments over the late Quaternary.

2. Regional Setting

The Lake Eyre Basin occupies a structural depression in the centre of Australia and drains an area of approximately 1.12 million km², where rainfall and runoff ranges are highly variable (Alley, 1998; Habeck-Fardy and Nanson, 2014; Magee et al., 1995). In the southern basin, Lake Frome is an ephemeral salt lake or playa located between ~30-31°S, and 139.5-140°E (Fig. 1a, b). With a total area of ~2,700 km² at an average elevation close to sea level, it is the most southerly playa in an arc of ephemeral lake bodies around the northern Flinders Ranges. While these lakes are separated from Lake Eyre by an overflow (the Warrawoocara sill; Nanson et al., 1998) at ~15±2 m AHD (Australian Height Datum), Lake Frome and Lake Callabonna connect via the Salt Creek sill situated at ~5±2 m AHD (Bowler et al., 1986; Cohen et al., 2012; Nanson et al., 1998). Around its eastern and north-eastern margin, Lake Frome is bounded by a complex array of longitudinal dunes as well as transverse and source-bordering dunes of the Strzelecki Desert (Fitzsimmons, 2007; Fitzsimmons et al., 2009). To the west, large alluvial fans descend from the Flinders Ranges in the west (Bowler et al., 1986; Draper and Jensen, 1976). Their sediment is mainly of coarse-grained fluvial-alluvial origin, comprising Tertiary and Pleistocene formations characterised by lithologies reflecting their provenance from the highly folded Flinders Ranges where Proterozoic metasediments, granitoids, volcanic and sedimentary rocks overlie a crystalline basement (Callen and Tedford, 1976; Sheard, 2009).

The Lake Frome catchment encompasses an area of around 63,000 km² with approximately half of this area corresponding to ephemeral creeks draining the eastern Flinders Ranges to the west of the lake (Cohen et al., 2012; De Deckker et al., 2011). The larger creeks such as Munyallina, Balcanoona and Big John Creeks have headwaters in the Flinders Ranges, where average rainfall is higher (~300 mm/a) than in the surrounding plains (100-300 mm/a). Consequently these creeks currently form the main source of intermittent runoff to the lake, even though Lake Frome can receive inflow from Cooper Creek via Strzelecki Creek, Lake Callabonna and Salt Creek to the north (Fig. 1b; (Draper and Jensen, 1976; Nanson et al., 1998). Creek channels running from the Olary Ranges in the south also drain towards Lake Frome but under the present climatic conditions these channels seldom carry water to the lake (Draper and Jensen, 1976; Singh, 1981). Since the time of European settlement, reports of significant runoff reaching Lake Frome are rare, and despite the existence of shallow surface water it has historically not exceeded the area achieved during the 1974 floods when it filled to ~75% of its size (Fig. 1c; (Draper and Jensen, 1976). Even though lakes farther north (Lakes Gregory, Blanche and Callabonna) received water from Strzelecki Creek at that time (De Deckker et al., 2011) which at least partly overtopped the Salt Creek sill (Fig. 1c), water held in Lake Frome in 1974 mostly resulted from a combination of runoff from the Flinders Ranges and groundwater discharge (Cohen et al., 2011; Nanson et al., 1998). The prevailing winds in the Lake Frome region are southerly winds, but westerly winds become more pronounced during the winter months (Sprigg, 1982).

Around the margins of the dry lake of today (Fig. 1b-d), raised and abandoned shorelines with beach ridges are found at several elevations up to ~15 m AHD providing geomorphic and sedimentary evidence for increased lake levels in the past (Cohen et al., 2011; De Deckker, 1983;

Nanson et al., 1998). Numerous islands, mostly composed of gypsiferous clay and sand, are scattered in the deepest part of the lake and have been interpreted to reflect episodes of lake floor deflation (Callen, 1984). The boundary between lake floor and the modern shoreline of Lake Frome is roughly defined by the salt tolerating species. Below this, elevation slowly drops to approximately -2 m AHD in the deepest part of the lake at its southern end (Draper and Jensen, 1976), but very few data exist with regard to accuracy and spatial variability of the lake floor topography.

Our study site is located along the western shoreline of the playa lake immediately to the northeast of the terminal splay associated with the ephemeral Balcanoona Creek. It comprises parts of the lake floor and a complex array of shoreline forms between ~1-5 m AHD including embayments, an elongate landform resembling a coastal spit (hereafter called a spit), aeolian dunes, and terminal splays (Fig. 2).

3. Methods

3.1 Geomorphology and topography

The geomorphology of the study area was visually interpreted from colour, density and texture patterns in the high-resolution satellite imagery in Google Earth and mapped in ArcGIS 10.0 (Fig. 2; (Verstappen, 1977). Contour lines and mean elevations for some of the mapped landforms were derived from a one arcsecond (~30 m) digital elevation model (Fig. 3; (Gallant et al., 2011). Most field work was conducted during the dry season of 2011, and complemented by high-resolution topographic measurements in 2012. Firstly, a hand-held Trimble GeoXH geographical positioning system (GPS) was used for general geomorphic reconnaissance and mapping. Then, stratigraphic and sedimentary profiles were documented at 24 sites along three transects (TA-TC, Fig. 2, 4). Transect locations were chosen to provide coverage across the main mapped playa marginal landforms. Most profiles are a combination of trenches excavated by hand to a depth of ~0.5-1 m, complemented by hand augering with a 75 mm diameter head. At five sites additional sediment cores were collected in 75 mm closed aluminium vibracores.

GPS coordinates for each sample location were collected, and elevations were taken using a laser theodolite with all positions corrected to the Australian Height Datum (AHD) using a Trimble RTK DGPS with the online GPS post-processing and correction service, AUSPOS on the static base station.

3.2 Sedimentary analysis

All sedimentary profiles were described in the field with regard to texture, main stratigraphic boundaries, chemical precipitates such as gypsum, or carbonate, and the occurrence of other sedimentary structures. Carbonate content was tested by applying 10% HCl to the sediment. Approximately 350 samples of ~25-50 g were taken from representative sedimentary layers and horizons for further analysis in the laboratory. Colour was determined with a Munsell Colour Chart on wet and dry sediment. Grain size analysis of the clay, silt and sand fractions (to a maximum length of 2mm) was carried out using a Malvern Mastersizer 2000 Laser Diffraction Unit with one minute of ultrasonic dispersion in water. Based on these data, sediment textures were classified following the US Department of Agriculture classification scheme (USDA).

3.3 Microfossils

Horizons of fine-grained sediment were selected from five cores and pits on the lake floor (P2, 3, 13, 18, 27) to be analysed for microfossil content (Fig. 4). Between 5 and 25 g of sediment was soaked in distilled water for 24 hours to allow the silt and clay content to soften before sieving the sediment with a 125 μm sieve to separate the microfossils from finer sediment. Microfossil content was dominated by Ostracoda (phylum; Arthropoda, sub-phylum; Crustacea) which were found to be present in the sediment. Valves of all genera present were picked and identified following existing studies on macrofossils in South Australian salt lakes (De Deckker, 1983; De Deckker, 1988a; De Deckker, 1988b; De Deckker et al., 2011). The number of valves, life stage details and the state of preservation of the valves were noted.

3.4 Chronology

Three different dating methods were applied in this study, comprising 19 samples for thermoluminescence (TL) dating, four samples for optically stimulated luminescence (OSL) dating, and two samples for radiocarbon analysis (^{14}C). Luminescence ages are calculated by dividing an estimate of the amount of radiation that quartz grains were exposed to during burial (equivalent dose, D_e) by the rate at which the grains were exposed to naturally occurring radiation in the natural environment (dose rate). A variety of differing luminescence techniques have been applied in dating aeolian, fluvial, littoral, and lacustrine sediments in arid Central Australia (e.g. Nanson et al., 1998; Magee et al., 2004; Cohen et al., 2011; Cohen et al. 2012). A recent inventory of OSL and TL ages from Central Australia (Cohen et al., 2015) shows that there are no systematic differences with regard to absolute and relative standard errors between the two methods ($n=130$), and there is very good agreement between duplicate TL and OSL samples ($n=20$). This demonstrates that the use of TL generally warrants both accurate and precise chronologies in the Central Australian setting. In this study, TL has therefore provided a time- and cost-efficient means for stratigraphic and chronological exploration. In order to further test the validity of our TL chronology in the specific playa marginal setting at Lake Frome, we additionally analysed four paired samples from different sedimentary environments with single grain OSL techniques. Overall, the good agreement between both techniques suggests that our largely TL based chronological framework is reliable

TL dating was conducted at the University of Wollongong, and used a combination of the regeneration and the additive dose methods following the procedure described in Shepherd and Price (1990). Samples were wet sieved to separate the 90–125 μm quartz grain size fraction which was chemically treated in dilute HCl and etched in HF to remove the outer grain coating as well as other material containing TL created by short range alpha particles. Then, heavy minerals were removed from the remaining grains by heavy liquid separation. A total of 28 aliquots were prepared and analysed per sample with a mask diameter of 10 mm. More specifically, 14 aliquots (retaining naturally accumulated signal) were prepared along with another 14 aliquots composed of grains that had been subjected to a minimum of 24 h exposure beneath a laboratory ultraviolet lamp (Philips MLU 300 W) to reset any natural TL signal. The bleached aliquots were given a range of doses with a calibrated ^{90}Sr plaque radiation source and the resulting TL was measured and used to construct a growth curve. The amount of radiation absorbed by the grains since deposition (i.e. D_e) was determined by fitting the TL measured

from the unbleached aliquots to the constructed glow curve. All first glow TL outputs are normalised using a second glow procedure (i.e. given a second irradiation and glowed out) at the analysis temperature. In this study the method for determining the final D_e is a modified regenerative procedure (Readhead, 1988), providing a means of checking for change in TL sensitivity. For dose rate determination, a portion of the sample was weighed, dried and weighed again to measure moisture content. It was then ground to a powder like consistency, for X-ray fractionation (XRF) or Atomic Emission Spectroscopy in order to determine the quantities of potassium and rubidium in each sample, whilst the annual radiation dose delivered by uranium and thorium was measured by thick source alpha counting (TSAC) procedure. Annual radiation dose rate was calculated following the procedure described by Aitken (1985). Uncertainties indicated for the final TL ages are at the one standard deviation level.

Samples for OSL dating were prepared in the laboratory using standard techniques (Wintle, 1997). Sediment samples were wet sieved (retaining grains of 180–212 μm diameter), soaked in hydrochloric acid and hydrogen peroxide, sorted by density using a sodium polytungstate solution (retaining 2.62–2.70 g/cm^3 as quartz) and soaked in hydrofluoric acid and hydrochloric acid. Single quartz grains were loaded into a Risø TL/OSL reader and were stimulated, measured and irradiated as reported by Gliganic et al. (2012). Equivalent dose values were determined using a modified single-aliquot regenerative-dose (SAR) procedure (Murray and Wintle, 2000) using regenerative and test dose preheats of 200°C for 10 s and 160°C for 5 s, respectively. Standard tests of SAR suitability were performed for each grain including a recycling ratio test, recuperation test (Murray and Wintle, 2000) and an OSL-IR depletion ratio test (Duller, 2003). Single-grain D_e distributions were analysed using the central age model (CAM; Galbraith et al., 1999) and the finite mixture model (FMM; Roberts et al., 2000). The FMM was fitted following Gliganic et al. (2015) to determine the most appropriate burial dose estimates. The environmental dose rate was determined using a range of techniques. The cosmic-ray dose rate was calculated following Prescott and Hutton (1994). The beta dose rate contribution was measured using a GM-25-5 beta counter (Bøtter-Jensen and Mejdahl, 1988) and a correction was made for grain-size attenuation (Mejdahl, 1979). Gamma dose rates were measured using thick-source alpha counting. Dose rates were calculated using the conversion factors of Guerin et al. (2011) and corrected for attenuation due to moisture.

For radiocarbon analysis, organic-rich sediment collected at P27 was sieved (150 μm sieve) to separate woody remains, which were submitted for AMS radiocarbon dating at Beta Analytics, USA. In addition, ostracods were extracted from a sample in P3 and submitted for AMS radiocarbon dating at the Australian Nuclear Sciences and Technology Organisation (ANSTO). The results were calibrated to calendar years using Calib 7.0 software and the SHcal13 calibration curve (Hogg et al., 2013; Stuiver and Reimer, 1993).

4. Results

4.1 Playa margin geomorphology

Our study area is located at the interface between the lowermost footslopes of large pediments and alluvial fans descending from the Flinders Ranges, and the playa floor of Lake Frome separated by the modern shoreline (Figs. 1, 2). Based on our topographically corrected DGPS measurements the lake floor in the immediate vicinity of the shoreline and at the spit is ~1.2 m

AHD (Fig. 3), and the geomorphology on both sides of the shoreline shows considerable variability. Most of the northern and northwestern portions of the study area resemble relatively flat, but gently dipping surfaces. Four surfaces ("alluvial"; A0-A3) were distinguished based on differences in elevation (Fig. 3) and surface expression, e.g. small-scale topography, patchiness and variability of surface material and vegetation (Suppl. Fig. 1). The highest of these surfaces (A0) occupies the northwestern corner of the study area at 13.9 ± 1.6 m, and has beach ridges and frequent longitudinal dunes (Suppl. Fig. 1a) formed on it. Based on SRTM elevation data, two successively lower surfaces (A1 and A2; Suppl. Fig. 1a, b) occupy elevations around 9.0 ± 1.6 m and 7.3 ± 1.5 m, respectively, and locally exhibit remnants of paleochannel morphology (Suppl. Fig. 1c). A0-A2 have strong reddish-brown surface colour pointing to significant weathering and the existence of well-developed surface soils. In contrast, the lowermost surface above the shoreline (A3) is located at an elevation of 5.7 ± 1.5 m and appears generally brownish (Suppl. Fig. 1d). It is related to the modern creek mouths, forming a loosely triangular shape resembling an embayment, and is overlain by active and inactive dunes and sand sheets (Figs. 2, 4). In the southwestern part of our study area, two anabranches of Balcanoona Creek debouche onto the floor of Lake Frome, forming a very low gradient radial terminal splay at 2.9 ± 1.2 m. Whereas the northern splay is characterised by an active network of narrow and shallow drainage channels (S1; Suppl. Fig. 1e), no active channel network is developed on the southern half of the splay (S2; Suppl. Fig. 1f). To the north, a further creek terminates in a minor floodout. Downstream of this floodout no drainage channels are recognised in the imagery but field reconnaissance suggests that discharge occasionally reaches the shoreline and lake floor via sheetflooding processes. Most of the shoreline is characterised by active and inactive aeolian dunes (D; Fig. 4) of up to ~ 8 m height with crests oriented in a northeastern direction. Dunes border the downwind creek banks or terminal splay margins but also occupy the shoreline away from obvious sediment source areas (Fig. 2). Eroded remnants of paleodunes ("yardangs"; Fig. 5a) are mostly aligned to the main wind direction. Gravel platforms (GP; Fig. 5b) and a spit (GS) have developed along the shoreline (Figs. 2, 3). Gravelly platforms form small-scale near-horizontal benches at ~ 3.5 -4 m AHD along the shoreline (Fig. 3). They drop off steeply to the lake floor and thus imply some degree of lateral erosion by fluvial or wave processes. The ~ 800 m long and ~ 3 m high spit is characterised by an irregular surface topography with a maximum elevation of ~ 3.8 m AHD but decreasing down spit (Fig. 3). Similar to other spits along the western margin of Lake Frome (referred to as pseudo-spits by Draper and Jensen, 1976), it exhibits an almost rectangular or cusped morphology, pointing to a strong relationship with sediment delivery from the creek mouth. The lake floor (F) occupies elevations below ~ 1.2 m AHD in the immediate vicinity of the shoreline and embayment (Fig. 3). Here, the lake floor mostly appears as homogenous cover of aeolian sand (F1; Suppl. Fig. 1g) whereas otherwise it is characterised by markedly heterogeneous surface patterns (F2; Fig. 4, Suppl. Fig. 1h). Farther towards the centre of the lake, the lake floor is more homogenous, and very gently drops with an average slope of 0.024%. The water line immediately after the 1974 peak filling event as mapped from satellite imagery (Fig. 1c) has an elevation of ~ 0.9 -1.0 m AHD, and the lake floor ~ 5 km distance from the shoreline is ~ -0.1 m AHD (Fig. 3).

4.2 Landforms and surface sediments

Based on detailed field reconnaissance, the sedimentary and pedogenic surface characteristics show marked variation across the different landforms in the study area (Figs. 4, 5). While dunes, paleodunes and yardangs are characterised by loose and unweathered surface sand, most of the

lake floor in vicinity of the shoreline shows a well developed vesicular horizon under a thin layer of salt at the surface (Fig. 5c), pointing to the salt-driven accretion of aeolian material on this part of the lake floor. In contrast, numerous patches of residual gravel are found at the surface of the lake floor, exhibiting evidence for salt heave and/or deflation of the fine-grained matrix around the clasts (Fig. 5d). In addition, dispersed wooden debris is found on the lake floor along much of the shoreline downstream of the terminal splay.

Active wind-driven erosion is also evident from yardangs, which are generally composed of well-sorted, yellowish to reddish medium sands. Their base is formed by whitish grey sands (Fig. 5a), and they rest on reddish and more resistant poorly sorted sandy to gravelly sediment with signs of strong post-depositional pedogenic overprinting in the form of carbonate cementation, patches (Fig. 5e) and coatings (Fig. 5f). Along corridors of preferential aeolian erosion the surface shows evidence for wind abrasion (Fig. 5g) partly overlain by mobile sheets of granules and carbonaceous root tubules (Fig. 5h). Otherwise, a well-sorted gravel pavement covers gravel platforms, while much of the spit shows a very variable surface morphology ranging from aeolian sands and loose lag of granules to a well sorted pebble pavement (Fig. 5i).

4.3 Sediments and Stratigraphy

A total of 12 hand excavated pits and 12 cores provide a first overview of the main subsurface sedimentary and pedogenic characteristics of the different landforms along the three topographic transects. Depending on surface topography, material compactness, and groundwater levels, the profiles range between ~0.4 m and >6 m depth. Sediments exposed in pits and in cores show large variability in terms of grain size, colour, and to a lesser extent bedding structure, bedding planes and the presence of salt precipitates such as gypsum, and carbonate (Fig. 6). Table 1 provides a summary description of the main sedimentary characteristics that make up each of the four main stratigraphic units at the study site, which form the base for the interpretation of depositional environments.

- **Unit 1** comprises the subsurface lacustrine and fluvio-deltaic sediments found in the basal parts of lake-floor cores and pits, and is subdivided into three subunits (1a-c) based on differences in dominant structure, bedding, colour and grain size. The basal Unit 1a consist of compact and massive beds of silt, clay (up to 80-95% silt and clay) and sand with occasional discontinuous beds of sand, granules and pebbles. Unit 1b is generally characterised by horizontally laminated fine sands, silts and loams of very variable colour ranging from olive brown to greenish grey. In contrast to Units 1a and b, Unit 1c consists of mostly brownish sands, pebbles and gravels with an erosive basal unconformity, and restricted to an area around the spit, while Units 1a and b seem to extend beneath the entirety of the study site (Figs. 6, 7).
- **Unit 2** comprises fluvio-deltaic sands, pebbles and granules which are often floating in a poorly sorted massive sandy matrix without further evidence of bedding. It builds up parts of the spit shoulder and the surface underlying the paleodunes. The unit is subdivided by the presence of a paleosol into a more reddish brown, lower (2a), and a more light brownish and less carbonaceous upper (2b) subunit.
- **Unit 3** describes the sediments building up the dominant playa marginal landforms, i.e. aeolian dunes, paleodunes and yardangs consisting of well-sorted medium sand (3a), and the poorly sorted, massive medium to coarse-grained sands of the spit landform (3b). The latter

unit is characterised by the presence of floating pebbles and scattered concentrations of granules, and can also contain lenses of sub-rounded to sub-angular pebbles (60 mm b-axis).

- **Unit 4** comprises the uppermost lake floor sediments in the embayment and distal terminal splay. In the embayment framed by the spit, they consist of highly oxidised reddish brown laminated fine sands, silts and clay often interspersed and capped by abundant salt and displacive seed gypsum.

4.3 Microfossils

Samples corresponding to Units 1 (a and b) and 4 were analysed for ostracods and other microfossils, and counts are summarised in Table 2. The numbers of ostracod valves or carapaces found in Unit 4 in the distal portion of the active terminal splay (S1) were very low compared to the stratigraphically lower units from cores in the lake floor and embayment (F1). More specifically, the ostracod populations from S1 are dominated by *Diacypsis dietzi* with lesser numbers of *Reticypsis sp.* and *Platycypsis baueri*, and at least one intact carapace of the very fragile *Platycypsis baueri* species was found in this unit. In contrast, low numbers of exclusively *Reticypsis sp.* were found in the oxidised silts and sands in the upper lake floor sediments (F1) of Unit 4.

Dominant ostracod species in the laminated silts and clays from Unit 1b were *Reticypsis sp.* and *Diacypsis dietzi* with minor numbers of *Mytilocypsis sp.* and a few *Diacypsis spinosa*. A large percentage of *Reticypsis sp.* was also found as articulated carapaces in this unit. Ostracod populations from the basal Unit 1a are described from only one sample, possibly in relation to the oxidised character of the sediment resulting in poor ostracod preservation in this unit. The sample is dominated by juvenile *Diacypsis spinosa* valves. A very small number of the highly saline tolerant species *Diacypsis whitei* were also found within this horizon but nowhere else in the embayment sediment. A range of juvenile *Diacypsis spinosa* occurs in abundance in the sediment from this unit, but no adults were identified (Fig. 5j). *D. spinosa* adults measure up to at least 0.99 mm but the largest of the species found in the sediment from this unit were only around 0.5 mm (De Deckker, 1981). Also, bore-hole predation marks were found on *Reticypsis sp.* carapaces (Fig. 5k) which were not observed in any other unit. In addition, charophyte oogonia are present in Unit 1a (Fig. l), but skeletal fish remains were not preserved well enough to enable identification.

4.4 Chronostratigraphy

In order to establish a chronological framework for landforms, sediments and stratigraphic units in the study area 25 ages are available, including 19 TL (Table 3), four single grain OSL (Table 4; Suppl. Fig. 2) and two ¹⁴C (Table 5) ages. Overall, the ages range from ~0.65 - 110 ka, and are generally stratigraphically coherent (Fig. 7). Particularly good correspondence exists between the single grain OSL and TL results, which overlap within 2σ uncertainties for three out of four comparative samples from Unit 1 and Unit 4 (e.g. P19, P31-20; Fig.7).

Ages for the lacustrine and fluvio-deltaic Unit 1 are between ~70 and 110 ka, and generally point to deposition during MIS5. More specifically, however, the oldest obtained age of 110±5 ka from Unit 1a falls into MIS 5d, while all remaining ages (~70 - 92 ka) in the near-shore lacustrine and fluvio-deltaic sediments of Unit 1b fall into MIS5a/b, potentially suggesting that

both sub-Units 1a and 1b may be separated chronologically. A radiocarbon age from Unit 1b yielded ~ 35 cal ka BP and indicates some degree of contamination with younger carbon introduced by recrystallization on the ostracod shells which were used for dating.

Three ages are available for the proximal fluvio-deltaic and/or near-shore sediments summarised in Units 2a (MIS2: 16.7 ± 0.9 and 25.6 ± 2.0 ka) and 2b (earliest Holocene: 11.5 ± 0.7 ka). The overlying and stratigraphically younger dune sands of Unit 3a date to $\sim 6-7$ ka (Fig. 7). The overlying sediments which build up the spit landform (Unit 3b) yielded mid Holocene ages (4.2 ± 0.3 to 6.1 ± 0.4 ka). More specifically, one comparative OSL age from the spit overlaps the TL age within 2σ uncertainties, while the other yielded a significantly older TL age compared to the single grain OSL result (P31-20, Fig. 7), but still Holocene in age. In this case, the high single grain overdispersion of $\sim 80\%$ suggests an offset of several thousand years in the TL data, e.g. resulting from incomplete bleaching or dose rate related issues. In particular the younger, Holocene TL ages are therefore considered as maximum age estimates. For samples from older units, however, this effect is probably negligible given the proportionally larger errors, and thus likely does not significantly affect the validity of our Pleistocene TL chronology. The upper lake floor deposits (Unit 4) yielded TL ages of 5.5 ± 0.5 and 0.65 ± 0.08 ka in the embayment (P1, P18; Fig. 7). In addition, a radiocarbon age of ~ 2.8 cal ka BP was obtained from plant remains associated with a flood sediment layer in Unit 4 on the distal terminal fan on the lake floor (P27, Fig. 7).

5. Interpretation and discussion

In combination, our geomorphological, stratigraphic, macrofossil and chronological data provide the first record for the evolution of the Lake Frome playa margin over at least $\sim 90-110$ ka, providing the base for the interpretation of types and temporal changes of fluvial, aeolian, lacustrine and coastal processes at the dynamic interface of the shoreline, and the discussion of their paleoenvironmental significance.

5.1 Sedimentary processes and depositional environments along the playa margin

The basal **Unit 1a** mostly consists of compact, massive beds of silt, clay and some sand, suggesting relatively continuous deposition in a near-shore lacustrine environment. The abundance of small (~ 250 μm) selenite crystals corroborates this scenario as they form under relatively stable lacustrine conditions (Magee, 1991). Occasional discontinuous beds of sand, granules and pebbles in this unit point to some degree of variations in lake level and/or a source of coarse sediment in relatively close proximity. Microfossils in Unit 1a are only described from one sample - possibly due to the oxidised character of the sediment and poor ostracod preservation - showing dominantly juvenile *Diacypris spinosa* valves which are commonly found in waters far below 20‰ salinity levels (De Deckker, 1981; De Deckker et al., 2011). In addition, charophyte oogonia are present in Unit 1a (Fig. 5) and indicate that concentrations of salinity were less than 69‰ (Burne et al., 1980) with water levels of ~ 2 m or less at the time (De Deckker, 1988a). In summary, the basal Unit 1a provides the most diverse range of microfossils and the highest order of microfossil diversity as additionally shown by bore-hole predation marks which were found on *Reticypris* sp. carapaces (Fig. 5). This generally points to the presence of a relatively deep and fresh water body in agreement with the sedimentary findings. However, the marked abundance of juvenile *Diacypris spinosa* and small numbers of *Diacypris*

whitei suggest that rapid changes in the lacustrine environment may have also occurred after a freshwater incursion, perhaps due to oscillations in lake level or temperature, or rapid escalations in salinity from the dissolution of surface salts (De Deckker, 2002). The highly oxidised nature of the upper parts of the unit suggests that the lake bed was subaerially exposed prior to the deposition of Unit 1b. This could also explain the presence of carbonate in this unit. Even though uncertainties are comparatively large in this age range, an age of 110 ± 5 ka from Unit 1a contrasts with the 70-92 ka ages in the overlying Unit 1b, and thus implies a prolonged phase of soil formation separating Unit 1a and 1b between ~95-110 ka.

The laminated, mostly reduced gray-green lacustrine sands, silts and clays of the extensive **Unit 1b** are interpreted to represent fluctuations related to discharge and sediment delivery in a near-shore fluvio-deltaic environment during MIS5a and b. Again, selenite corroborates the scenario of subaqueous deposition within a relatively long-lived water body, and additional angular gypsum rosettes may have formed subsequently upon desiccation. The base of this unit is often characterised by the presence of discontinuous basal gravel lenses which could imply that increasing lake levels were preceded by the progradation of fluvial deposition into the lake. In contrast, Unit 1c is very localised and is mostly sandy with erosional boundaries and rip-up clasts. It may thus represent a feeder channel of the active fan delta responsible for Unit 1b deposition. In fact, the available ages suggest that Units 1b and 1c are synchronous within the chronological resolution given by TL and OSL. The ostracods found in Unit 1b are dominated by *Reticypris* sp. and *Diacypris dietzi* with minor numbers of *Mytilocypris* sp. and a few *Diacypris spinosa*. This assemblage of ostracods species indicates a very broad level of salinity tolerance extending from 4-141‰, but the presence of a very small number of *Diacypris spinosa* within this unit also indicates sufficient input of fresh water at times to provide a habitat for this species (De Deckker and Geddes, 1980). A large percentage of *Reticypris* sp. were also found as articulated carapaces in this unit. It has been noted by De Deckker (2002) that the presence of intact carapaces indicates a fatal environmental change followed by rapid sedimentation to preserve the carapaces. These observations therefore agree well with repeated pulses of sediment and freshwater input in a near-shore deltaic environment, possibly going along with some oscillations in lake level.

The general lack of microfauna or sedimentary bedding in the late Pleistocene to early Holocene **Unit 2** complicates the interpretation of depositional environments for this unit. The poor sorting of the sand, the presence of floating pebbles, and the lack of beach detritus may suggest an alluvial, proximal fluvio-deltaic or even coastal origin in relation to a nearby lacustrine fan delta (e.g. Horton and Schmitt, 1996; Olariu and Bhattacharya, 2006; Postma, 1990; Smith, 1991). In this context, the surfaces A0-A3 may represent the remnants of "alluvial" deposition adjusted to successively lower lake stands, but so far no field data are available to confirm this interpretation. Morphologically, Unit 2 builds up a pebbly to gravelly, and cliffed platform at ~3 m (**Unit 2a**) to ~4 m (**Unit 2b**) AHD, ~ 3 m above the modern lake floor. This implies post-depositional and possibly wave-driven erosion during successively lower lake levels in the mid-to late Holocene. In any case, the deposition of coarse-grained sands and pebbles at ~3-4 m AHD clearly suggests a proximal sediment source - likely related to active sediment supply and runoff from the nearby creeks - and a lake level probably not significantly higher than ~3 and ~4 m AHD around 26-17 ka and 11 ka, respectively. In addition, Unit 2a shows good evidence for prolonged subaerial exposure and pedogenic overprinting, which would explain the relative resistivity to erosion and cliffed morphology (Figs. 2, 4). Based on our chronology, subaerial

exposure at ~3 AHD would have commenced after 25 ka, or even 16 ka, and before ~11 ka. This implies the co-existence of low to intermediate lake levels (<3 m AHD) during or immediately after the LGM, and environmental conditions sufficiently wet to provide moisture for pedogenic processes such as reddening and carbonate translocation.

Dunes and paleodunes of **Unit 3a** (D, Figs. 2, 4, 7) rest on the gravel platforms of **Unit 2** above ~3-4 m AHD, and were dated to 6-7 ka. They thus provide clear evidence for sustained sediment supply from the nearby creeks and/or active beach processes. This implies that lake levels during this time were predominantly (or exclusively) below ~3-4 m AHD. The mid to late Holocene deposits forming **Unit 3b** constitute the lake marginal spit (GS, Figs. 2, 4, 7). Similar to Unit 2, these sands and gravels are poorly sorted and contain floating pebbles, and even thick pebble lenses, generally pointing to fluvial or proximal fluvio-deltaic origin of the sediment. In this scenario the spit could be regarded as an erosional remnant of a previously more extensive body of fluvial and/or fluvio-deltaic sediment. However, the planform morphology is typical for coastal spits (e.g. Bird, 2000) and rather suggests an origin related to alongshore sediment transport by wind and wave dynamics. Given the lack of sedimentological evidence of beach ridge detritus or bedding which could corroborate lateral accretion in the swash zone, Unit 3b - and the spit landform in general - may thus be the result of sediment accretion on a submerged bar immediately downstream of an active deltaic sediment source such as Balcanoona Creek. In either case, the deposition of coarse-grained sands and pebbles between ~1-3 m AHD clearly implies a lake level probably not significantly higher than ~3-4 m (AHD) between ~4.2-4.9 ka.

The uppermost sediments of the lake floor in the embayment (F1-3, Figs. 2, 4) and on the distal terminal splay (S1, Figs. 2, 4) are included in **Unit 4**. In general it consists of fine-grained, highly oxidised red-brown sands with some silt and clay. Except from splay deposits, horizontal laminations have are absent elsewhere in the uppermost lake floor sediments, probably partly due to the growth of displacive seed and discoidal gypsum between sediment grains close to the surface. In this regard, the uppermost sediments and surface expression of this unit have most likely been significantly altered by salt dynamics typical of playa mudflats, or the salt aided accretion of aeolian sand as observed in parts of the lake floor (e.g. D, F1, Fig. 4). However, a few preserved silt lenses and salt layers indicate intervals of more lacustrine conditions. Only low numbers of exclusively *Reticypris* sp. were found, reflecting low species diversity in this unit, at least outside of the influence of terminal splay processes. In contrast - and by analogy with the historically largest flood event in 1974 (Fig. 1) - the well-developed bedding in the distal terminal splay deposits (e.g. P27) and wooden debris in vicinity to the shoreline reflect repeated but discrete depositional and discharge events on the terminal splay and the adjacent lake floor in the late Holocene since at least 2.8 cal ka BP. Its oxidised, reddish colour provides evidence that these depositional events were likely short-lived flooding episodes, which either filled the lake to a minor lake level (i.e. below ~1.2 m AHD) or were too short to modify the shoreline. These scenarios agree with the ostracod populations in the distal splay sediments underlying the lake floor (F2, Fig. 4) with dominant *Diacypris dietzi* and lesser numbers of *Reticypris* sp. and *Platycypris baueri*, indicating the likelihood of water salinity greater than 70‰ (De Deckker, 1982). At least one carapace of the very fragile *Platycypris baueri* species was found in this horizon. Intact carapaces of this very thin and fragile valved species indicate fluctuating water conditions because *Platycypris baueri* is known to burrow millimetres into the sediment to avoid desiccation. In combination, this suggests the presence of surface water remaining in the

lake for short durations only as the result of high-magnitude but low-frequency flood events since the mid Holocene (i.e. TL age of 5.5 ka).

5.2 Significance for the late Quaternary evolution of Lake Frome

In summary, the sedimentary and stratigraphic architecture of the playa margin reflects a gradual change from lower-energy lacustrine and subaqueous fluvio-deltaic deposition to higher energy fluvial, near-shore, beach and aeolian processes, and ultimately distal terminal splays along the modern shoreline. On a larger spatial and temporal scale, this transition therefore identifies the shift from distal to proximal depositional environments, related to successively lower lake levels over the course of the last 110 ka, causing the overall progradation of the fluvial-lacustrine interface (Myers and Milton, 2009) and thus a lake-ward shift of the playa margin.

5.2.1 Pleistocene Mega-Lakes

MIS 5d-a lacustrine and fluvio-deltaic sediments (Unit 1) are in good agreement with previous research on the late Quaternary history of Lake Frome (or Mega-Lake Frome; Fig. 8). The two lacustrine events represented by Units 1a and 1b-c, respectively, are also reflected in luminescence ages between ~110 - 85 ka from beach ridges at ~15 m AHD at Lake Frome (Fig. 8; Cohen et al., 2012). Our sedimentary, microfossil and chronological data indicate two lake events separated by an interval of weathering and subaerial exposure, which is not evident in the beach ridge data (Cohen et al., 2012; Cohen et al., 2011). However, a lacustrine phase followed by significant pedogenesis is also documented in the basal part of sedimentary cores from the centre of Lake Frome (Bowler et al., 1986; De Deckker et al., 2011). By correlation to our Unit 1b, this may suggest MIS5d ages for the basal weathered sediments in these cores followed by an episode of subaerial exposure in MIS5c, but more detailed chronological data are required to confirm this scenario.

Unit 1b corresponds to a distinct phase of lake highstands evident from beach ridges around Lake Frome and Callabonna dated to 80-100 ka (Cohen et al., 2012). At this time, lakes were freshwater dominated, reached a depth of ~15 m, and were most likely overflowing into Lake Eyre. Consequently, the coeval deposition of fluvio-deltaic sediment at ~1 m AHD (i.e. 14 m below maximum lake level) suggests that lake depth must have fluctuated at rates beyond the resolution of our chronology. Alternatively, all fluvio-deltaic sediments in this unit could reflect a lake level during a regressional phase after ~90 ka, which may be corroborated by the coarse-grained and channelized character of Unit 1c. Either scenario would imply strong changes in water salinities as expressed by microfossil assemblages in this unit. Importantly, the coincidence of freshwater dominated lakes and active sediment transport and deposition from the Flinders Ranges is a clear indication that significant runoff was produced locally during this interval. This provides further evidence for the notion of generally enhanced precipitation and runoff regimes during the waning stages of MIS5 (Nanson et al., 2008), and shows that playa marginal sediments contain important information towards disentangling the regional variations in sediment flux and runoff (e.g. Cohen et al., 2012).

No further sediments were dated to the time between ~70-25 ka at our study site (Fig. 8a), even though at least three MIS 3 and 4 lake stands are reflected in the 10-15 m AHD beach ridges

(Cohen et al., 2012). These lakes would have submerged the modern shoreline in the study area by more than 9 m of water, but no fine-grained lacustrine or near-shore sediment of this age is found in the study area, where the oldest sediment directly overlying Unit 1 is of MIS 2 age. While this may be the result of low local sedimentation rates after ~70 ka, it could also reflect a phase of erosion sometime before ~25 ka. In fact, playa and lacustrine deposits in the centre of the lake radiocarbon dated to ~42-30 ka (De Deckker et al., 2011) are overlying a disconformity, which has been interpreted to reflect a period of previous lake floor deflation (Bowler et al., 1986), but contrasts with evidence from the beach ridges for intervals of high lake levels ~60, 45 and 33 ka (Cohen et al., 2012). Sedimentary and chronological data from surfaces A1 (~9 m AHD) and A2 (~7.3 m) will be required to test if these surfaces could be the result of at least periodically significant runoff and sediment delivery from the Flinders Ranges, and fluvio-deltaic and/or near-shore deposition related to lake stands and deep water conditions during MIS 3 and 2 (Fig. 8a). In contrast, pedogenic overprinting of Unit 2a must have occurred after 25 ka or 16 ka, and before ~11 ka. This implies low to intermediate lake levels (< 3 m AHD) and environmental conditions sufficiently wet to provide moisture for noteworthy pedogenesis when Lake Frome seems to have undergone a major change towards fluctuating but more ephemeral and saline environments during or immediately after the LGM (De Deckker et al., 2011).

5.2.2 Lake Frome in the Holocene

Deposition of Unit 2b around ~11 ka at ~4 m AHD is likely related to a lake transgression as recorded by beach facies in a prominent beach ridge between ~5-7 m AHD at Lake Callabonna (Cohen et al., 2012), and supports the notion of locally wet conditions during the Pleistocene-Holocene transition as seen in other regional studies around Lake Frome (De Deckker et al., 2011; Gliganic et al., 2014; Quigley et al., 2010). A detailed comparison of all younger, Holocene ages with existing chronologies from beach ridges (Fig. 8b) shows that the evidence for sedimentary dynamics in relation to Holocene lake highstands is restricted to elevations below ~2.5 m AHD at our Lake Frome study site. This is below the possible elevation range for a connected and single water body across both lakes as dictated by the Salt Creek sill at 5 ± 2 m AHD, and contrasts with beach deposits and beach ridges at ~5 m AHD dated to ~3.5-5.6 ka at Lake Callabonna (Cohen et al., 2012; Gliganic et al., 2014). So far, no beach ridges or other sedimentary evidence for lake levels at this elevation have been documented or dated around Lake Frome, even though samples from sandy clays in the upper metre of sediment in the lake centre yielded Holocene radiocarbon ages of ~3.4 and 4.6 cal ka BP (De Deckker et al., 2011; Draper and Jensen, 1976). In the absence of more detailed topographic and stratigraphic constraints from the Salt Creek sill, the apparent contrast with lake levels at ~5 m AHD at Lake Callabonna during the same interval might imply hydrologically disconnected water bodies of different depths during the mid-Holocene. Alternatively, it may suggest higher lake levels at Lake Callabonna relative to Frome, ultimately reflecting inverse overflow directions from the north compared to the MIS5 and 4 mega-lake system. Combined with our results of dune and spit formation, the existing data clearly imply active sediment supply from the Flinders Ranges at ~6-7 ka leading towards peak mid Holocene lake levels of ~3-4 m AHD at Lake Frome with the formation of the spit shortly after 5 ka. This scenario is in general agreement with other proxy records from around the Flinders Ranges documenting wet conditions between ~7 and 3 ka (Gliganic et al., 2014; McCarthy and Head, 2001; Quigley et al., 2010).

In analogy to the modern situation, late Holocene conditions were characterised by generally dry and locally deflating playa margins, interrupted by sporadic flooding events, depositional activity on the terminal fans and some dunes, and short-lived inundation of the lake floor. In this context, the good agreement of a 2.8 ka radiocarbon age in the active Balcanoona Creek terminal splay and the construction of a beach ridge at Lake Callabonna at ~2.7 ka (Glignani et al., 2014) implies that these events were short-lived, not enabling significant sediment delivery to the lake floor and limiting modifications to the playa marginal shoreline.

Conclusions

This combined geomorphic, sedimentary, microfossil and chronological dataset has enabled the first reconstruction of the late Quaternary evolution of the western playa margin of Lake Frome. As such, it provides new data towards an improved link between previously published records of lake stands as expressed by beach ridges along the western shores of Lake Frome and Callabonna (Cohen et al., 2012; Glignani et al., 2014), and the detailed sedimentary, paleoenvironmental and geochemical records from cores in the lake centre (Bowler et al., 1986; De Deckker et al., 2011; Draper and Jensen, 1976; Singh, 1981). This link is expressed by (i) the good chronological overlap between the stratigraphic units in our study area and previously published lake stands as expressed by beach ridges. Even though not all lake stands are also reflected in our sedimentary records, (ii) there is some topographic correspondence between mapped surfaces to the west of the modern shoreline and published elevations of beach ridges, tentatively suggesting the aggradation of lake marginal floodplains or deltas in response to increased lake levels and intensified sediment supply from the Flinders Ranges. In addition, the sedimentary units in our study area interpreted as distal fluvio-deltaic contain lacustrine microfossil assemblages, and thus allow direct comparison to paleoenvironmental records from the lake centre (De Deckker et al., 2011). The presence of these sedimentary units also provides evidence for active local fluvial systems, and thus plays an important role for the interpretation of local vs regional scale contribution of streamflow and sediment during the respective highstands - an issue which may ultimately help to unravel tropical from westerlies dominated precipitation sources (Cohen et al., 2012). So far, however, the marked lack of dated sediments between ~70-25 ka in our data may be interpreted as the result from discrete periods of erosion along the playa margin (e.g. deflation), changes in the spatial patterns in sediment delivery between the successive lake stands, or the laterally active nature of avulsive deltaic systems not captured by the limited extent of our stratigraphic transects. Additional sedimentary cores are needed to clarify this issue.

This study has demonstrated the highly dynamic nature of the longer-term, late Quaternary evolution of a playa margin, which is expressed by the variety of small- and medium-scale depositional and erosional landforms. While this may complicate the use of playa marginal records as linking elements between shoreline and lacustrine records, these archives - in particular over the Holocene - potentially allow a detailed reconstruction of the interaction between fluvial, lacustrine, shoreline and aeolian processes which is required to understand the link between hydroclimate and sediment transport on the one hand, and magnitude or duration of lake highstands on the other hand.

Acknowledgements

The authors would like to thank the Department of Environment and Natural Resources, Government of South Australia, for providing a research permit (Y-25926-1) for field work at Lake Frome. Funding was provided to TJC and BGJ by an ARC Discovery Grant (DP 1096911).

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Fig. 1: Geographical setting of Lake Frome study area. a) Location in Australia. b) Main topographical features in the Lake Frome and Callabonna area; lake area as defined by modern shoreline in light blue, area of maximum late Quaternary lake highstand as defined by 15 m contour line in dark blue. Lake bathymetry is illustrated with white contour lines below 0 m AHD spaced at 0.5 m intervals (adapted from Draper and Jensen, 1976). White circles mark locations of dated beach ridges (Cohen et al., 2011 & 2012; Gliganic et al., 2014), grey circles mark locations of dated lacustrine records (e.g. Bowler et al., 1986; Singh, 1981; De Deckker et

al., 2011). Dune ridges around the lake margins are illustrated by grey lines, main creeks are dotted lines. c) Landsat TM image (band combination 3-2-1) at the end of the dry season 2011 illustrating the high reflectivity (white colour) of salts at the surface of Lake Frome. d) Landsat image (band combination 3-2-1) at the end of the wet season during the largest historically reported filling event in 1974 with approximately 90% of the lake floor covered by water. Note plumes of fine-grained sediment entered the lake from the Flinders Ranges.

Fig. 2: Geomorphological overview of the Lake Frome shoreline study area (see text for details). Contour lines are space at 2m intervals and are derived from 1 arcsec SRTM elevation data. Depositional surfaces are labelled A0-A3 with hashed pattern indicating the presence of a well-developed soil at the surface. GP denotes gravel platforms, GS is the spit landform, and D denotes dunes and paleodunes. S denotes terminal splays (S1 has active channel network, S2 is inactive), and F denotes the playa lake floor (F1 with sand cover, F2 heterogenous surface pattern, F3 homogeneous surface with salt crust). TS, TA, TB and TC refer to the topographic transects in Fig. 3, 4 and 7.

Fig. 3: Topographic transects based on 1 arcsec SRTM data (Transect S, black line) and combined DGPS and theodolite data (Transects A-C, red line). Landforms are indicated by letters above transect (refer to Fig. 2 for further information and transect locations).

Fig. 4: Google Earth caption of main geomorphological features in the Lake Frome shoreline study area. Black crosses mark DGPS readings, numbered red dots mark locations of sediment cores and pits in Fig. 6. Note reddish surface appearance on spit shoulder around point 25, and dark grey gravel patches on the lake floor (e.g. adjacent to point 33).

Fig. 5: Field photographs of key sedimentary and surface features, and macrofossils. a) Yardang. b) Cluffed gravel platform. c) Vesicular surface on lake floor (F1). d) Elevated pebbles from salt heave processes. e) Reddish sand with carbonate concretions overlain by gravel lag. f) Gravel with well-developed carbonate coatings. g) Wind abraded surface. h) Lag deposit of pebbles, sand and carbonate tubules. i) Sandy (above) to pebbly (below) surface sediment along the spit (GS). j) Juvenile *Diacypris spinosa*. k) Predator hole in *Reticypris* sp. carapace. l) Charophyte oogonia.

Fig. 6: Sedimentological and stratigraphical profiles of all cores and pits along transects A, B and C (see Fig. 2 for location).

Fig. 7: Stratigraphic interpretation, correlation of sedimentary profiles and stratigraphic units, and chronology along transects A, B and C (see Figs. 2 and 3 for locations).

Fig. 8: Summary plot of chronological information and geomorphic observations in this study in compared with existing beach ridge data from the Lake Frome and Callabonna system (Cohen et al., 2012, Gliganic et al., 2014).

Suppl. Fig. 1: Google Earth captions of the main geomorphic units mapped in the study area. a) Depositional surfaces A0 and A1. b) Depositional surfaces A2 and A3 (dotted line marks boundary between them). c) Close-up of interpreted paleochannel remnants in A2 (dotted line). d) Interface between depositional surface A3 and dunes/paleodunes along the shoreline (dotted line marks boundary between them). e) Inactive terminal splay S1. f) Active and channelized terminal splay S2. g) Contrasting pattern of the lake floor with F1 showing evidence for a pre-

existing network of paleochannels, and F2 reflecting a thin surface cover of aeolian sands (compare Fig. 5c). h) Close-up of lake floor F2 in g)

Suppl. Fig. 2: Radialplots of single grain D_e distributions (see text and Table 4 for details)

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Table 1: Summary of the main sedimentary characteristics of the stratigraphic units in the study area

Unit	Dominant Textures (most abundant to least)	Typical Thickness	Dominant Colours Munsell	Gypsum and Carbonate	Bedding structures	Associated Landforms (Fig. 2)	Depositional Environment
1A	Silt & clay Very fine to fine sand Granules & pebbles at base	~0.5-1.5m	Yellowish red Strong brown Light olive gray	Selinite Carbonate	Massive silt & clay beds, sand layers, pebbles in sand and in clay	No surface expression	Lacustrine (weathered / paleosol)
1B	Very fine to fine sand, silt & clay Granules & pebbles	~1m	Light olive brown Brown Greyish brown Pale olive Greenish gray	Angular roses Selinite	Horizontal laminations	Lake Floor Alluvial Surfaces	Near-shore lacustrine Fluvio-Deltaic (Non-Channelized)
1C	Very fine to medium grained sand Granules & pebbles Rip-up clasts Laminations of silt	~0.5-3m	Strong brown Light brown Brown	-	Massive Horizontal laminations Erosional lower contacts	No surface expression	Fluvio-Deltaic (Channelized)
2A	Very fine to medium grained sand Granules & pebbles	~0.35-2m	Reddish brown Reddish yellow Yellowish red	Carbonate	Massive	Gravel Platforms (Alluvial Surfaces) (Pseudo-)Spit	Fluvio-Deltaic Beach (weathered / paleosol)
2B	Very fine to medium grained sand Granules & pebbles	~1-2m	Reddish yellow Yellowish red	Minor Carbonate	Massive	Gravel Platforms (Alluvial Surfaces) (Pseudo-)Spit	Fluvio-Deltaic Beach
3A	Fine to medium sand	~2-4m	Yellowish red Reddish yellow	Minor Cementation (CaCO ₃)	Cross-bedding	Aeolian Dunes Yardangs	Aeolian
3B	Very fine to medium grained sand Granules & pebbles (floating and lenses)	~ 2m	Reddish yellow Yellowish brown		Massive	(Pseudo-)Spit	Fluvio-Deltaic Beach
4	Fine sand, silt & clay	~0.15-2m	Reddish brown Yellowish brown	Displacive gypsum	Massive Horizontal laminations	Embayment, Proximal Lake Floor Terminal splay	Ephemeral lacustrine / deltaic Aeolian

Table 2: Ostracods and macrofossil counts in selected sediment samples from the study area

Hole	Depth [cm]	Sediment	Unit	Microfossil type	Reticypis sp. [#]	Diacypis dietzi [#]	Diacypis whitei [#]	Diacypis spinosa [#]	Mytilocypris sp. [#]	Platycypis baueri [#]
27	37	Active Terminal Splay	4	Ostracoda	12	> 25				10
18	20	Surface sands	4	Ostracoda	2					
18	40	Oxidised silt	4	-						
18	60	Oxidised silt	4	Ostracoda	17					
18	70	Oxidised silt	4	Ostracoda	11					
3	19	Laminated	1 B	Ostracoda	-			1		
3	25	Laminated	1 B	Ostracoda	> 30-40	6				
3	37	Laminated	1 B	Ostracoda	17	5				
3	42	Laminated	1 B	Ostracoda	> 115-120	1				
3	50	Laminated	1 B	Ostracoda	> 65-70	7				
3	58	Laminated	1 B	Ostracoda	> 125-130	1			1	
3	63	Laminated	1 B	Ostracoda	> 105-110	4		1	2	
3	100	Laminated	1 B	Ostracoda	> 65-70				2	2
18	92	Laminated	1 B/C	Ostracoda	> 85-90	1		4	3	
18	97	Laminated	1 B	Ostracoda	> 35-40	1				
18	100	Laminated	1 B	Ostracoda	> 75-80	30		1		
18	106	Laminated	1 B	Ostracoda	> 100-105	2		6		
18	142	Laminated	1 B	Ostracoda	> 30-35	1			1	
18	243	Oxidised basal	1 A	-						
2	250	Oxidised basal	1 A	-						
2	300	Oxidised basal	1 A	Fish skeleton?						
13	585	Oxidised basal	1 A	-						
13	600	Reducing basal	1 A	Oogonia / Ostracoda	25-30	9	2	> 120		

Table 3: Thermoluminescence dating results

Sample [Lab #]	Sample Name	Type	Plateau Region [°C]	Analysis Temp. [°C]	Palaeodose [Grays]	K Content [XRF %]	Rb Content [XRF ppm]	Moisture [% by weight]	Specific Activity [Bq/kg U+Th]	Cosmic Contribution [μGy/yr assumed]	Annual Radiation Dose [μGy/yr]	TL Age [ka]
W4573	TL1@15cm	Trench	275-400	350	1.2 ± 0.2	0.610 ± 0.005*	50 ± 25**	15.2 ± 3	61.2 ± 2.0	185 ± 25	1803 ± 33	0.65 ± 0.08
W4450	TL3@0.35m	Trench	300-500	375	159 ± 10	0.95 ± 0.05	38 ± 4	20.9 ± 3	62.0 ± 1.8	150 ± 25	1970 ± 52	80.8 ± 5.4
W4406	LF14@0.5m	Trench	275-500	375	25.8 ± 1.4	0.86 ± 0.05*	100 ± 25**	2.5 ± 3	58.3 ± 1.6	165 ± 25	2241 ± 62	11.5 ± 0.7
W4407	LF14@1.2m	Trench	275-500	375	53.1 ± 2.6	1.46 ± 0.05*	100 ± 25**	3.0 ± 3	75.3 ± 1.9	155 ± 25	3180 ± 63	16.7 ± 0.9
W4577	TL16@220cm	Core	300-450	375	117 ± 6	0.460 ± 0.005*	50 ± 25**	10.8 ± 3	38.1 ± 1.2	150 ± 25	1276 ± 28	92.0 ± 5.0
W4452	TL16@2.37m	Core	300-500	375	104 ± 5	0.53 ± 0.05	22 ± 2	18.3 ± 3	31.1 ± 0.9	147 ± 25	1121 ± 50	92.4 ± 6.2
W4576	TL16@295cm	Core	300-500	375	156 ± 12	0.715 ± 0.005*	50 ± 25**	7.3 ± 3	45.5 ± 1.4	140 ± 25	1708 ± 30	91.1 ± 7.3
W4488	LFC18@0.50m	Core	275-500	375	18.8 ± 1.5	1.570 ± 0.005	69.2 ± 5	10.5 ± 3	93.3 ± 2.7	180 ± 25	3382 ± 42	5.5 ± 0.5
W4489	LFC18@2.28m	Core	300-500	375	153 ± 9	0.610 ± 0.005	22.3 ± 5	17.4 ± 3	41.9 ± 1.3	146 ± 25	1389 ± 27	110 ± 5
W4490	LFC19@2.05m	Core	300-500	375	145 ± 11	0.820 ± 0.005	30.4 ± 5	17.7 ± 3	54.4 ± 1.5	150 ± 25	1782 ± 28	81.1 ± 6.4
W4599	LFP20@0.40m	Trench	275-425	375	10.5 ± 1.1	0.430 ± 0.005	22 ± 2	1.2 ± 3	30.6 ± 1.0	180 ± 25	1258 ± 29	8.3 ± 0.9
W4600	LFP20@1.35m	Trench	275-500	375	9.3 ± 0.5	0.815 ± 0.05	41 ± 2	17.8 ± 3	59.8 ± 1.6	143 ± 25	1868 ± 53	5.0 ± 0.3
W4574	TL23@70cm	Trench	275-500	375	8.7 ± 0.6	0.330 ± 0.005*	50 ± 25**	1.1 ± 3	44.8 ± 1.4	150 ± 25	1415 ± 32	6.1 ± 0.4
W4486	LF23-L@1.10m	Trench	275-500	375	7.9 ± 0.7	0.730 ± 0.005	30.4 ± 5	8.4 ± 3	38.5 ± 1.2	150 ± 25	1572 ± 28	5.0 ± 0.4
W4487	LF25F@0.50m	Trench	300-500	375	45.6 ± 3.5	0.740 ± 0.005	33.1 ± 5	6.8 ± 3	47.1 ± 1.4	150 ± 25	1782 ± 30	25.6 ± 2.0
W4449	TL25@3.7m	Core	275-500	375	14.6 ± 1.1	0.91 ± 0.05	41 ± 4	5 ± 3*	54.4 ± 1.7	140 ± 25	2120 ± 61	6.9 ± 0.6
W4451	TL26@0.20m	Trench	275-500	375	11.3 ± 0.9	0.70 ± 0.05	31 ± 3	3.3 ± 3	48.2 ± 1.6	150 ± 25	1829 ± 61	6.2 ± 0.5
W4453	TL30@2.77m	Core	300-500	375	118 ± 7	0.61 ± 0.05	24 ± 2	19.0 ± 3	43.4 ± 1.3	140 ± 25	1399 ± 52	84.7 ± 5.6
W4575	TL30@293cm	Core	300-500	375	107 ± 5	0.475 ± 0.005	50 ± 25**	9.7 ± 3	42.0 ± 1.3	140 ± 25	1366 ± 29	78.6 ± 4.2

* measured by Atomic Emission Spectroscopy

** assumed values

Table 4: Optically stimulated luminescence results

Sample	n*	water content (%)	Gamma (Gy/ka)	Beta (Gy/ka)	Cosmic (Gy/ka)	Total Dose Rate (Gy/ka)***	Over-dispersion (%)****	De (Gy)	Age model	Age (ka)
LF19C_58	53/800	17±3	0.53 ± 0.02	0.67 ± 0.05	0.14 ± 0.01	1.37 ± 0.08	41 ± 6	111.6 ± 5.4	FMM	81.4 ± 6.3
LF19C_148	53/800	17±3	0.55 ± 0.02	0.72 ± 0.05	0.13 ± 0.01	1.43 ± 0.09	84 ± 9	100.3 ± 5.2	FMM	70.2 ± 5.8
LF20_40	79/800	2±1**	0.42 ± 0.02	0.51 ± 0.03	0.20 ± 0.02	1.16 ± 0.05	27 ± 3	5.7 ± 0.2	FMM	4.9 ± 0.3
LF20_135	94/800	2±1**	0.65 ± 0.02	0.92 ± 0.05	0.17 ± 0.02	1.77 ± 0.08	80 ± 6	7.8 ± 0.3	FMM	4.4 ± 0.3

* Number of grains accepted/ measured

** Measured water content is 0.7%

*** Includes an internal dose rate contribution of 0.03±0.01 based on previous studies of Australian quartz (Bowler et al., 2003)

**** Overdispersion calculated using the Central Age Model

Table 5: Radiocarbon dating results

Sample Name	Lab Code	Sample Type	d13C	pMC	±	14C Age	±	cal a BP *
LF 3 @ 0.42	OZQ395	Ostracods	-	1.96	0.2	31600	830	33932 - 37585
LF 27 @ 0.35	Beta-300466	Plant Remains	-25.6	-	-	2770	30	2756 - 2920

*2 sigma, calibrated with SHcal13 calibration curve