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Late-Holocene climatic variability indicated by three natural archives in arid southern Australia

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Abstract

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Keywords

southern, arid, archives, natural, three, australia, indicated, late, variability, climatic, holocene, GeoQuest

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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Late Holocene climatic variability indicated by three natural archives in arid southern Australia

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Abstract

Three terrestrial climate proxies are used to investigate the evolution of Holocene palaeoenvironments in southern central Australia, all of which present a coherent record of palaeohydrology. Single-grain optically stimulated luminescence from sediments supplemented by ^{14}C from charcoal and lacustrine shells were obtained to date shoreline deposits (Lake Callabonna) and the adjacent Mt Chambers Creek alluvial fan. Our findings are complemented by a U/Th based record of speleothem growth in the Mt Chambers Creek catchment, which we interpret to reflect increased precipitation. Together, these archives shed light on the timing of, and possible sources of water for Holocene pluvial intervals. We identified several phases of elevated lake levels dated at ~5.8–5.2, 4.5, 3.5–2.7, and 1 ka, most of which correspond to fluvial activity resulting from increased precipitation in the adjacent ranges. The enhanced hydrology during phases of the late Holocene likely increased the reliability of resources for regional human populations during a time of reduced winter rainfall. When considered within the framework of the current understanding of Holocene palaeoclimate in central Australia, our data suggest that the pattern of landscape response was broadly synchronous with larger scale climatic variability and punctuated by pluvial periods greater than today.

Keywords: late Holocene, Flinders Ranges, Lake Callabonna, environmental variability, archaeology, arid Australia

1.0 Introduction

The Holocene is of crucial importance for understanding the controls on Earth's climate under comparatively stable boundary conditions (Mayewski et al., 2004; Wanner et al., 2008), and the anthropogenic role in modifying the climate system has recently become the major issue in the ongoing debate of global change (IPCC, Steffen et al., 2004). In turn, a growing number of studies provide manifold examples of human cultural adaption to changing environmental and climatic conditions (DeMenocal, 2001; Haberle and David, 2004; Anderson et al., 2007). Consequently, the investigation of the nature, complexity and spatial dimensions of human-environmental interactions has become a main focus of Holocene research (Mayewski et al., 2004; Dearing, 2006). In this context, the reconstruction of environmental changes from multiple, terrestrial datasets provides a robust basis for assessing the impact that hemispheric or global Holocene climate variability may have had on regional-scale landscapes and resources (Wanner et al., 2008).

In the Southern Hemisphere, recent compilations have suggested that substantial changes in the pattern and spatial distribution of westerly-driven precipitation after ~5 ka (Fletcher and Moreno, 2012) are related to the onset of increased El Niño Southern Oscillation (ENSO) variability post 6–5 ka (Shulmeister, 1999; Moy et al., 2002). The exact mechanisms and timing behind the temporal and spatial shifts of these large-scale atmospheric systems, as well as the resulting regional variations in climate, environmental conditions, and their impact on human populations, however, still remain unresolved for many parts of the world. In Australia, the middle and late Holocene was a time of substantial changes in human demographics (Smith et al., 2008; Johnson and Brook, 2011) and technology (Hiscock, 1994, 2002; Attenbrow et al., 2009; Veth et al., 2011). For example, radiocarbon time series-based records of population expansions and contractions suggest a possible link to environmental changes associated with ENSO driven climatic variability (Smith et al. 2008). Also, certain tools (e.g., tulas, bifacial points and backed artefacts) were produced at higher rates after ~4 ka because their standardised and multi-functional nature reduced foraging risks by being reliable and easily repairable in an increasingly variable environment (Hiscock, 1994, 2002; Attenbrow et al., 2009; Veth et al., 2011).

A suite of palaeoclimate records for the Australasian region indicate warmer and wetter conditions in the early to middle Holocene (following terminology of Walker et al., 2012) with increasing variability and enhanced dry intervals related to a more pronounced El Niño mode of ENSO through the late Holocene (see Reeves et al., 2013). However, high-resolution records from the desert interior, where

the interaction between circulation patterns is complex, remain unrepresented with respect to more tropical and temperate regions. That said, a growing number of discontinuous climate records have been obtained from sedimentary archives (fluvial, aeolian, lacustrine; Nanson et al., 2008; Cohen et al., 2011, 2012a,b; Fitzsimmons et al., 2013), pollen and other biological proxies (e.g., Singh and Luly, 1991; McCarthy and Head, 2001), dust (Marx et al., 2009) and speleothem investigations (Quigley et al., 2010). Based on these records, the prevailing palaeoclimate interpretation for the southern arid zone is for a wetter than present early to middle Holocene, followed by a shift to a drier and more variable climate after 5 ka. The existence of wet intervals in the late Holocene, producing phases of standing water in the otherwise dry Lake Callabonna (Fig. 1), is attributed to shifts in the intensity and position of summer-dominated tropical vs winter-dominated westerly derived rainfall (Cohen et al., 2012a). Determining the exact synoptic drivers in southern central Australia is complicated by the fact that the playa lakes can receive local runoff derived from the Flinders Ranges as well as runoff via Cooper and Strzelecki creeks. With new regional records emerging in the winter-dominated rainfall zone of southern Australia (e.g., Wilkins et al., 2013), more studies from arid and semi-arid areas are required to resolve both the extent of, and the terrestrial responses to, climate changes.

Here we aim to (i) establish a detailed chronology for three coupled proxies that preserve a record of hydrological activity (shorelines, alluvial fans, speleothems) around the eastern Flinders Ranges using multiple geochronological techniques (single-grain optically stimulated luminescence (OSL), ^{14}C , and U/Th), (ii) test if Holocene lacustrine phases correlate with precipitation and fluvial activity derived from the Flinders Ranges to constrain one of the possible sources of water entering the lakes, and (iii) use these archives to assess the landscape-scale hydrological and environmental response to climate variability over the Holocene. Our multi-proxy data provides new insights into the middle to late Holocene environmental and climatic variability in southern central Australia and contributes to the ongoing discussion of the nature and causes of Holocene climate change and resultant human responses.

2.0 Background

2.1 Regional Setting

Our study setting in southern central Australia is comprised of two contrasting landscapes: the Flinders Ranges and surrounding lowland playas. The Flinders Ranges consist of deformed Palaeoproterozoic metasediments, Mesoproterozoic granitoids, and volcanics, with folded

Neoproterozoic rocks overlying crystalline basement (Sheard, 2009). The ranges rise to an elevation of 1165 m, and extend ~700 km from Adelaide in the south to the Lake Eyre Basin in the north. They are flanked by colluvial and alluvial sediments that feed into internally draining playa lakes on the eastern, northern, and western margins, including lakes Frome, Callabonna, Gregory, Blanche, Eyre, and Torrens (Fig. 1). Bedrock and gravel bed streams carry runoff from the ranges to the modern lakes, which can also be filled by floodwaters delivered to lakes Blanche and Callabonna via Strzelecki Creek, a distributary of Cooper Creek, which drains the subtropical north-east sector of the Lake Eyre Basin. Thus, the hydrological record of these lakes reflects a record of subtropical or temperate rainfall, or some combination of both (Nanson et al., 1998; Cohen et al., 2012b).

Today, the region is arid to semi-arid: the lowlands receive ~150 mm/yr of rainfall and the ranges receive ~300 mm/yr. Potential evaporation (~2000 mm/yr surrounding the playas) exceeds precipitation significantly, accounting for the lack of permanent water bodies in the region. Two atmospheric systems deliver the majority of precipitation to modern southern central Australia: the Australian summer monsoon (ASM) and the southwest westerlies (SWW) (Sturman and Tapper, 2006). The SWW are a strongly zonal atmospheric circulation pattern affecting the climate of southern hemisphere landmasses below ~30°S, bringing cooler seasonal (winter) rain to southern Australia (Sturman and Tapper, 2006; Fletcher and Moreno, 2012). The frequency of ASM incursions into the region is related to the ENSO phenomenon, with La Niña conditions producing a more intense ASM that can cause heavy rainfall across the continental interior (Semenov et al., 2008), while El Niño conditions result in more arid conditions in the region (Dai and Wigley, 2000). Indeed, the wettest year on record in Australia (1974) was a La Niña year and resulted in substantial filling of lakes Eyre, Frome and Callabonna, the latter filling to a depth of ~1 m. Historically, widespread large-magnitude flooding has generally occurred across eastern and central Australia during La Niña phases, causing large flows in ephemeral streams within the Flinders Ranges (Quigley et al., 2010). Otherwise, the creek beds are dry throughout most of the year, although flow data is extremely limited and does not allow quantitative estimates of flood frequency and/or the relative contribution of westerly-derived frontal winter rainfall or summer rainfall to discrete flow events.

2.2 Existing Holocene palaeoenvironmental records from the Flinders Ranges region

Information on Holocene palaeoenvironments in the Flinders Ranges region is comparatively limited (Fig. 1). The Pleistocene-Holocene transition has been characterised as having increased hydrologic activity in southern central Australia. The Lake Torrens piedmont experienced a phase of calcareous soil formation (Motpena palaeosol), possibly associated with warmer subhumid conditions between 16 and 12 ka BP (Williams, 1973). Palaeoshorelines (Cohen et al., 2011, 2012b) and ostracods (De Deckker et al., 2010) indicate that Lake Mega-Frome was ~6–7 m deep at 13.2 ± 0.8 ka compared to the 0–1 m depth range (during extreme events) of the recent historical period. Analysing pollen from Lake Frome cores, Singh and Luly (1991) observed a rise in summer-rainfall zone vegetation between ~13 and 4 ka, and from this speculated that summer monsoon incursions increased and strengthened during the terminal Pleistocene and early and middle Holocene.

Subsequent studies have supported the results of Singh and Luly (1991), and a consensus currently exists that the middle Holocene was wetter than today. Quigley et al. (2010) estimated the growth rates of a speleothem from the northern Flinders Ranges and inferred greater precipitation between 8 and 5 ka, with the wettest interval between 7 and 6 ka. Plant and pollen macrofossils derived from stick-nest rat middens were used as proxies for palaeovegetation by McCarthy and Head (2001) who suggest that the plant communities identified in the 7 to 5 ka time slice are representative of a warmer, wetter, and more spatially homogenous climate relative to present. Marx et al. (2009) investigated Australian-derived dust records in New Zealand and showed that, unlike subsequent times, from 7.8 to 4.8 ka the Lake Eyre Basin was not contributing dust to the bulk continental long range dust transport. Collectively, these studies provide good evidence for significantly wetter conditions during the middle Holocene in central and northern Australia due to a more active/permanent monsoon.

The late Holocene in central Australia has generally been characterised as more arid and variable than the middle Holocene (Singh and Luly, 1991; McCarthy and Head, 2001; Marx et al., 2009; Quigley et al., 2010). Quigley et al. (2010) infer that the lack of growth of the Yudnamutana speleothem after 5.2 ± 1.0 ka (Fig. 1) represents a decrease in precipitation in the Flinders Ranges. This work also compared ^{14}C ages from Williams (1973) and a single OSL age (Quigley et al., 2007) to assemble a chronological framework for coarse-grained aggradational terraces at the apex of the Wilkatana alluvial fan (Fig. 1). Quigley et al. (2010) show that the frequency of terrace deposits increases after 5.9 ka ($n=5$), suggesting increased frequency of extreme rainfall events and associated floods. Wasson and Galloway (1986) document elevated sedimentation rates at 6–3 ka on the Mundi Mundi alluvial fan ~150 km southeast of

Lake Frome, after which four episodes of late Holocene high-magnitude flooding occurred in the Barrier Range, the largest between ~3.4 and 1.9 ka (Jansen and Brierley, 2004). McCarthy and Head (2001) report that between 4 and 2 ka, fossil pollen and plant macrofossil assemblages in the Flinders Ranges are dominated by chenopod shrubland with fewer herbaceous taxa, most likely indicating a shift to cooler, more arid, and more variable climatic conditions. This conclusion is consistent with the earlier work of Singh and Luly (1991) who interpret their post-4 ka Lake Frome pollen record to reflect a decrease in summer precipitation associated with a weakening monsoon. Marx et al. (2009) report that after 4.8 ka central Australian dust sources were active probably because of a more arid and variable climate due to a northward repositioning of the ASM. Based on these studies, the period following 5–4 ka is thought to be a time of either increased variability and/or a decrease in summer rainfall. This paper tests these climatic assertions for the early, middle, and late Holocene using three complementary proxies for hydrological activity.

3.0 Methods

3.1 Approach and sampling strategy

The hydrological regime of the Flinders Ranges landscape is characterised by highly episodic, infrequent rains capable of generating moderate to large runoff events which have high transmission losses as water is conveyed to the terminal playa lake systems (e.g., Lake Callabonna). The very high potential evaporation rates ensure that once water is available in the landscape, the surface water bodies and soil moisture stores are quickly depleted, meaning only the largest storms or a series of storms yield sufficient standing water that can remain for significant periods of time (e.g., 1974, 2011). Using this water balance as our conceptual framework, we have investigated three archives, each representing moisture storage and flux in different parts of the hydrological system: (i) a speleothem from a shallow cave in the upper Mt Chambers Gorge reflects the percolation of local precipitation through a fractured bedrock network; (ii) farther downstream, alluvial sediments from the Mt Chambers Creek fan provide evidence for fluvial activity resulting from storm events in the catchment; finally, (iii) relict shorelines of the adjacent Lake Callabonna preserve a record of standing water. The comparison of these three proxies should thus reveal a record of landscape-scale hydrological and environmental dynamics in the study area.

The Flinders Ranges contains a variety of caves formed in the Proterozoic to early Palaeozoic carbonate rocks (Hamilton-Smith and Finlayson, 2003), but they remain virtually untapped sources of palaeoenvironmental information. Quigley et al. (2010) recovered a 40 mm thick flowstone from the ~10 m deep Yudnamutana Cave in the northern Flinders Ranges, and established a U/Th based chronology for growth rates coupled with measurements of isotopic variations in carbon and oxygen. Similar small caves have been reported around Mt Chambers Gorge (Fig. 2a; Medlin, 1993; McCarthy and Head, 2001; Mahoney et al., 2008), and field reconnaissance confirmed the presence of cm-scale stalactites in at least one of the caves (Fig. 2b, 3).

The Mt Chambers Creek alluvial fan has formed where flow exits the Flinders Ranges from Mt Chambers Gorge at ~100 m AHD and terminates 27 km downstream on the margin of Lake Frome at ~0 m AHD (Fig. 4). The fan surface exhibits a complex pattern of Holocene palaeochannels, sand and gravel lobes, and fine-grained floodouts (Fig. 2c, d) overlying Pleistocene alluvium and well-developed palaeosols (Coats 1973). The stratigraphy of the fan was investigated via river bank exposures (sites CF78, CF206, CF373) and trenches were excavated in gravel lobes and floodouts (sites CF95, CF96, CF97, CF344, CF383). At eight sites (Fig. 4), the sedimentology was documented and samples were collected for OSL and/or ^{14}C analysis in order to chronologically postulate intervals of flooding and overbank deposition.

Relict beach ridges (Fig. 2e) up to 15 m high preserved on the western margins of Lake Frome and Callabonna are evidence for intervals of large lakes and significantly different water balances over the last ~100 ka (Cohen et al., 2011, 2012a, b). We examined the stratigraphy of the lower shorelines with multiple excavations across three west-east transects (Lake Callabonna, Salt Creek, and White Dog; Fig. 5). Beach stratigraphy was documented (Fig. 2f), sediment samples were collected for OSL dating, and freshwater molluscs, snail shell, charcoal, and emu eggshell were collected for ^{14}C dating. The estimated palaeo-depths of the lake assume no significant deflation following shoreline development.

3.2 Optically stimulated luminescence

OSL dating is a technique that can be used to determine when grains of quartz were last exposed to sunlight and, thus, when they were deposited (Huntley et al., 1985; Aitken, 1998). After burial, electrons accumulate in the crystal lattice of quartz grains at a rate proportional to the flux of cosmic rays and ionising radiation from the surrounding sediment (the 'dose rate'). When grains are stimulated with

light in the laboratory, trapped electrons are released and some give rise to the OSL emission, which can be measured and used to calculate the equivalent dose (D_e) absorbed by the grain during burial. The burial age of a grain is calculated by dividing the D_e (Gy) by the dose rate (Gy/ka).

Samples were collected by hammering stainless steel tubes into exposed sedimentary sections. Quartz grains of 150–180 or 180–212 μm diameter were obtained from sediment samples under dim red-light conditions using standard procedures, which are described elsewhere (Gliganic et al., 2012a). Single quartz grains and multi-grain quartz aliquots were loaded into a Risø TL/OSL reader and were stimulated, measured and irradiated as reported by Gliganic et al. (2012a,b).

Equivalent dose values were obtained using a modified single-aliquot regenerative-dose (SAR) procedure (Murray and Wintle, 2000). Standard tests, including a recycling ratio test, recuperation test (Murray and Wintle, 2000), and OSL-IR depletion ratio test (Duller, 2003), were used to assess the suitability of the SAR procedure for each grain. Appropriate regenerative and test dose preheat combinations were empirically determined using dose recovery experiments (Roberts et al., 1999; Murray and Wintle, 2003), which also served to assess the suitability of the SAR procedure for accurate dose determination in representative samples (Table 1).

For most samples, individual quartz grains were measured to eliminate those with unsuitable OSL properties and allow the identification of incomplete bleaching and post-depositional sediment mixing prior to age calculation. Between 400 and 1100 grains were measured for each sample and a range of statistical models, including the Central Age Model (CAM; Galbraith et al., 1999), Minimum Age Model (MAM; Galbraith et al., 1999), Maximum Age Model (MAXM; Olley et al., 2006) and Finite Mixture Model (FMM; Roberts et al., 2000) were used to determine representative D_e values.

The total environmental dose rate for each sample is derived from cosmic rays and the flux of beta particle and gamma rays due to ^{238}U , ^{235}U , ^{232}Th (and their decay products) and ^{40}K . The bulk beta dose rate for each sample was measured using a GM-25-5 beta counter (Bøtter-Jensen and Mejdahl, 1988) and a correction was made for attenuation based on grain-size (Mejdahl, 1979). Gamma dose rates were measured using a field gamma spectrometer or by thick-source alpha counting (TSAC). Beta and gamma dose rates were calculated using the conversion factors of Adamiec and Aitken (1998). The cosmic-ray dose rate was calculated following Prescott and Hutton (1994). The measured water content was used $\pm 50\%$ uncertainty to allow for past variations in the moisture, so as to calculate dose rate attenuation by moisture for most samples (Table 2).

3.3 Radiocarbon dating

Samples for radiocarbon analysis were measured on an Accelerator Mass Spectrometer (AMS) at the Australian Nuclear Science and Technology Organisation or at Beta Analytic and all resulting conventional ages were calibrated using the SHcal04 curve (McCormac et al., 2004) in the CALIB program (Stuvier et al., 2005). Calibrated ^{14}C ages are reported as 2σ age ranges (Table 3). Dated material encompassed charcoal, shell fragments of terrestrial snails, bulk organics and emu shell, and may reflect a variety of post-depositional processes. Therefore, the resulting ages were carefully interpreted within the site-specific stratigraphic context and do not always necessarily reflect depositional ages for the surrounding sediment.

3.4 Speleothem analysis and U/Th dating

A ~9 cm long straw stalactite was recovered from an unnamed cave in the upper Mt Chambers Creek gorge (30.9594°S, 139.2477°E). It was sectioned into two halves and polished (Fig. 3a) in order to describe the internal layers and laminations of variable thickness, colour, and crystal morphology, and guide the interpretation of its growth history and micro-sampling for U/Th analysis.

Thirty laser ablation (LA)-ICPMS U/Th ages were measured at the Australian National University, along a 15 mm transect from the speleothem surface towards its centre (Fig. 3b). The analyses were carried out using a custom-built laser sampling system interfaced between an ArF Excimer laser (193 nm; Lambda Physik LPX120i) and a ThermoFisher Neptune multi-collector ICP-MS (Eggins et al., 1998a,b; Eggins et al., 2003; Eggins et al., 2005). In brief, it employs a single long working distance lens to project and demagnify (by a factor of 20) the image of a laser-illuminated aperture onto the sample surface, which enables a range of geometries to be ablated within bounding dimensions of between 1 and 400 μm . Laser pulse rates of 5 Hz were employed with a fluence of 10 J/cm² (power density 0.3 GW/cm²). Spot analyses (233 μm spot size) were carried out by drilling each hole for a period of 60 seconds and the signal was then averaged over a period of 60 seconds.

Measured $^{234}\text{U}/^{238}\text{U}$ and $^{230}\text{Th}/^{238}\text{U}$ isotopic ratios were corrected for elemental fractionation and Faraday cup/SEM yield by comparison with a 150 ka-old mollusc standard (S. Eggins; pers. comm.). ^{234}U and ^{230}Th were corrected for contribution of ^{238}U tail on masses 234 and 230, respectively. Mean background count rates measured with the 'laser off' were subtracted from all measured isotope

intensities. U and Th concentrations were calculated from repeated measurements of the NIST SRM610 standard. Ages were calculated with ($^{234}\text{U}/^{238}\text{U}$) and ($^{230}\text{Th}/^{238}\text{U}$) activity ratios using IsoPlot (Ludwig, 2003). Ratios were not corrected for detrital contamination as such contamination is expected to be negligible, based on ($^{230}\text{Th}/^{232}\text{Th}$) activity ratios >20 (Table 4). If implemented, detrital correction would yield activity ratios within analytical error of measured ratios. Based on these results, an age and growth model was constructed using the StalAge1.0 algorithm (Scholz and Hoffman 2011, Scholz et al. 2012).

4.0 Results

All OSL data, including water content, environmental dose rates, D_e values, age models and ages are presented in Table 2. Radiocarbon results are presented in Table 3 and LA-ICPMS U/Th data are presented in Table 4 and Figure 3.

4.1 Mt Chambers Gorge speleothem

None of the speleothems observed during field reconnaissance showed evidence for contemporary dripping. Some of them were partly broken and/or eroded and no corresponding stalagmites were preserved on the cave floor, probably due to recent disturbance.

The internal structure of our speleothem reveals an elongate, straw stalactite geometry. The hollow, inner part of the straw exhibits finely laminated deposits, with individual laminae of variable thickness and colour that are sometimes laterally discontinuous, probably indicating limited flow. At least four intervals of lamination are separated by more continuous and marked darker laminae (Fig. 3a, dashed lines) and/or growth of irregularly shaped, porous crystals, in combination likely due to a reduction in the rate of laminar calcite precipitation. The two inner intervals show an abrupt linear fracture (Fig. 3a), possibly indicating some loss of material. Brownish and porous crystals fill the remaining voids of the formerly hollow interior of the straw. This would have blocked further water flow and thus likely indicates the final stage of evolution.

From the set of 30 U/Th measurements, 28 yielded sufficiently high counts to allow for the calculation of ages (Table 4). ($^{230}\text{Th}/^{232}\text{Th}$) activity ratios range from 17 to 300 (Table 4), suggesting a minimal contribution from detrital thorium, hence no detrital correction was performed. Based on these U/Th results, an age and growth model (Fig. 3c) was established using the StalAge1.0 algorithm (Scholz and Hoffman 2011, Scholz et al. 2012). It suggests the onset of speleothem growth around 5.8 ka,

probably involving the initial growth and downward extension of a mostly hollow straw. In a second phase, the deposition of the laminar calcite layers began in the interior of the straw around 4 ka. At least two intervals of accelerated growth can be interpreted at around 3.5 and 2.5 ka, and speleothem growth seems to terminate shortly after 1.9 ka.

4.2 Mt Chambers Creek alluvial fan geomorphology and chronology

The alluvial fan has an overall longitudinal gradient of ~ 0.004 (Fig. 4). Remote sensing data and field reconnaissance show that much of the fan surface is covered by coarse gravel and pebble pavements. Based on their colour and texture, some differences can be discerned between older, reddish and well-developed gravel pavements developed on Pleistocene alluvium (the Pooraka Formation, Coats 1973), and younger alluvial loams, sands and gravels. The gravel deposits are aligned along palaeochannels that have well-preserved cross-section morphology, and terminate mid-fan in lobate gravel deposits up to several hundred meters in length (Fig. 2c, Fig. 4). Downstream of the terminal lobes the fan surface is mostly covered by loams, sands and occasional pebbles. In combination, the channels, gravel lobes and distal fine-grained sediments form floodouts similar in structure to the currently active floodout, and are typical for low-gradient alluvial systems in semi-arid and arid Australia (Gore et al., 2000; Tooth, 1999). At least four major floodout complexes can be distinguished (Fig. 4).

Ten OSL samples (Table 2) and seven ^{14}C samples (Table 3) were analysed to establish a chronology of depositional processes across the fan. For the OSL samples, post-depositional mixing was expected based on field observations such as root casts and dry cracks, and this was confirmed by the large spread in single-grain D_e data (i.e., high overdispersion values, $>20\%$). Consequently, the depositional OSL ages were calculated using the CAM (Galbraith et al., 1999) or the most populous component identified using the FMM (Roberts et al., 2000).

Two bank exposure sites in the modern channel (CF78, CF373, Fig. 4) demonstrate a similar stratigraphy comprising a unit of massive reddish-brown silty sands with occasional gravel lenses (Unit 6) overlying Pleistocene sediments that are capped by a well developed calcareous palaeosol. The silty-sands can be further subdivided into upper (6B) and a lower (6A) sub-units separated by a weakly developed palaeosol as indicated by more reddish colours, more frequent root casts and minor carbonate specs. At site CF78, the Unit 6A yielded an OSL age of 6.0 ± 0.3 ka. Unit 6B yielded a ^{14}C date of 4.71 ± 0.13 cal ka BP from ~ 65 cm depth, an OSL age of 3.7 ± 0.2 ka at ~ 35 cm depth, and a further ^{14}C date of

1.35±0.05 cal ka BP from ~30 cm depth. The discrepancy between radiocarbon and OSL ages from this unit is consistent with the inferred reworking and post-depositional mixing and thus supports our interpretation of the D_e datasets and OSL ages as indicative of deposition. At site CF373, Unit 6A yielded an OSL age of 4.2±0.2 ka and a ^{14}C age of 5.03±0.18 cal ka BP, while Unit 6B yielded an OSL age of 3.3±0.2 ka. Further downstream at site CF206, an inset bench within the modern channel yielded a ^{14}C age of 3.16±0.16 cal ka BP (Table 3).

The five pits excavated in the downstream end of the major floodouts show either imbricated channel gravel units up to 1.8m thick (CF95, CF96) or thin 10-40 cm lenses of sands and gravel overlying loams, typical of distal floodout environments (CF97, CF344, CF383). Pit CF383 (Fig. 4) comprises a lens of gravels extending from the surface to a depth of ~30 cm, which are underlain by massive sandy loams with floating pebbles, carbonate nodules, and charcoal. An OSL sample from 55 cm depth yielded a depositional age of 6.0±0.5 ka and a gastropod shell from 40 cm depth yielded a ^{14}C date of 4.37±0.13 cal ka BP (Fig. 4). Pit CF344 comprises 40 cm of massive structureless sands with occasional floating pebbles overlying 20 cm of imbricated gravels in a fine grained matrix, which unconformably overlies 115 cm of massive sandy loams resting on a well-developed carbonate-rich palaeosol. OSL samples were collected at 145 cm (11.0±0.8), 80 cm (6.7±0.4 ka) and 30 cm (3.3±0.3 ka). The timing of gravel deposition is more precisely bracketed by the MAM estimate of the underlying sample (5.1±0.4 ka) and the MAXM estimate of the overlying sample (4.2±0.4 ka).

Pits CF95, CF96, and CF97 are located along a series of palaeochannels and associated floodouts near the southern margin of the fan. Pit CF95 comprises 95 cm of semi-imbricated channel gravels with a silty to sandy matrix overlying an abrupt boundary with massive brown sandy loams. An OSL sample from 115 cm depth yielded a depositional age of 10.2±0.7 ka and a MAM age estimate of 7.6±0.7 ka, the latter of which is a minimum age for the deposition of the overlying gravels. Pit CF97 comprises massive sandy loams with floating pebbles and gravels. An OSL sample from 60 cm depth yielded an age of 11.9±0.7 ka. Pit CF96 comprises 140 cm of semi-imbricated channel gravels from which two broken gastropod shells yielded ^{14}C ages of 9.72±0.17 cal ka BP (85 cm depth) and 8.44±0.10 cal ka BP (65 cm depth). The stratigraphic coherence of the ^{14}C ages and the broken condition of the shells indicates that they are not intrusive and likely reflect the timing of deposition of the gravels.

These results indicate that the southern palaeochannel experienced repeated alluvial activity between ~11.9 and 7.6 ka, suggesting that it may have been a major channel during the early Holocene. A

pronounced phase of alluvial activity sometime between ~ 7.6 and 6 ka resulted in channel avulsion, causing the locus of fan deposition to switch from the southern to the northern segment of the fan. Pronounced phases of alluvial activity and deposition at ~ 6 ka, ~ 4.2 ka, and ~ 3.7 – 3.3 ka are indicated by the marked coincidence of depositional ages expressed along both the modern channel and at least one palaeofloodout.

4.3 Lake Callabonna shoreline stratigraphy and chronology

Three transects on Lake Callabonna record the Holocene history of lake-full phases in the Flinders region. A long history of large Pleistocene lake systems has been previously described by Nanson et al. (1998) and Cohen et al. (2011, 2012b); stratified sands and gravels (shoreline deposits) occur up to 15 m above the modern playa floor. Previously published ages from relict shorelines 4 – 5 m above the lake floor demonstrate Holocene lake filling events at 5.6 ± 0.3 ka to 5.84 ± 0.07 cal ka BP, at 4.5 ± 0.4 ka and during the medieval climatic anomaly (MCA; ~ 1 ka) (Cohen et al., 2011, 2012a,b). We have supplemented these findings with additional sampling at Salt Creek (Cohen et al., 2012a) and a new site, also on Lake Callabonna (Fig. 5). The Salt Creek transect occurs on a relatively steep lake margin with 10 m of relief over 2 km with four shorelines preserved. The Holocene age of 4.5 ± 0.4 ka (Cohen et al. 2012b) stems from a lower beach facies at 1.55 m in a shoreline 5 m above the lake floor (Fig. 5), whereas the upper beach facies within this shoreline is comprised of weakly bedded landward-dipping gravels and sands with an OSL age of 3.5 ± 0.2 ka (Fig. 5). The shoreline stratigraphy suggests at least two episodes of construction. The second transect exhibits more subdued lake-margin morphology with three shorelines up to 8 m above the lake-floor. The lowermost shoreline is at 2 m AHD and exhibits 2.25 m of interbedded sand and gravels up to 50 cm thick. The open framework and clast-supported nature of the landward and lakeward dipping deposits suggest sorting by wave action. OSL ages from 1.45 and 0.65 m (Fig. 5) are from two depositional units separated by an erosional boundary and indicate shoreline construction at 3.5 ± 0.3 ka and 3.0 ± 0.2 ka. These shoreline facies unconformably overlie fine-grained lacustrine sediments which have been dated to 5.1 ± 0.5 ka. This Holocene shoreline is inset within much older shorelines that are >25 ka (Fig. 5).

5.0 Discussion

Our findings for an integrated hydrological system in southern central Australia can be compared with pre-existing regional palaeoenvironmental results and hemispheric climate data to elucidate the drivers of Holocene environmental change (Fig. 6). In the following discussion we adopt a time-slice approach to our record and its regional and global comparison.

5.1 Regional-scale Holocene landscapes around the Flinders Ranges

The early Holocene (11.7–8.2 ka)

Our record of the early Holocene includes OSL and ^{14}C ages from floodouts on the southern and middle palaeochannels of the Mt Chambers Creek alluvial fan. The southern, currently inactive palaeochannels show evidence of bedload transport during this time. Sandy loams from distal floodouts yielded ages of 11.9 ± 0.7 ka and 10.2 ± 0.7 ka, indicating that these channels were active. A large lobe of channel gravels (>2 m deep) is associated with ^{14}C ages of 9.72 ± 0.17 and 8.44 ± 0.10 cal ka BP. These results suggest that Mt Chambers Creek was actively delivering sediment to the southern side of the fan at least since ~12 ka, followed by an interval of high energy floods between 9.7 and 8.4 cal ka BP. Sandy loams associated with a floodout deposited 11.0 ± 0.8 ka indicate mid-fan alluviation.

We interpret the regional hydrological regime as being active during the early Holocene. The inferred floodout-related alluviation at this time post-dates Lake Mega-Frome's filling to ~6–7 m at 13.2 ± 0.8 ka (Cohen et al., 2011, 2012b) and palaeo-vegetation data is indicative of summer-rainfall around Lake Frome between ~13 and 4 ka (Singh and Luly, 1991). Likewise, early Holocene alluvial and flood deposits on the southern Mt Chambers Creek palaeochannels are concurrent with the onset of Yudnamutanana speleothem growth (Quigley et al., 2010) and fluvially-derived ^{14}C dates from nearby Hamilton Creek (10.2 ± 0.3 and 9.8 ± 0.3 cal ka BP; Sheard, 2009) indicating increased precipitation and highly active regional rivers with sufficient capacity to transport sediment from the upstream catchments to the alluvial fan systems and, presumably to the terminal playa lakes. The lack of early Holocene shorelines in our record may be an artefact of sampling or due to reworking by subsequent elevated lakes. Alternatively the lakes may not have filled during the early Holocene, though this is unlikely given the contemporaneity of alluviation and lakes at other times.

The middle Holocene (8.2–4.2 ka)

Our speleothem, alluvial fan and shoreline records are consistent with previous work that suggests that southern central Australia experienced a phase of increased hydrological activity during the middle Holocene. The last evidence for activity on the southern palaeochannel of Mt Chambers Creek is a MAM OSL age of 7.6 ± 0.7 ka from below a gravel lobe (~ 1 m thick). Between ~ 7.6 and ~ 6 ka, the loci of floodout deposition shifts towards the northern half of the alluvial fan, where ages from overbank and floodout sediments are exclusively < 6.0 ka. Channel avulsion during high magnitude flooding was the probable cause of the northerly switch, and this time corresponds to an interval of enhanced precipitation in the Flinders Ranges, indicated by speleothem growth (Quigley et al., 2010) and the spatially homogenous assemblage of abundant woodland and shrub vegetation between ~ 7 and 5 ka (McCarthy and Head, 2001). The Mt Chambers Gorge speleothem also begins growing at this time. Shorelines and lacustrine archives indicate that a 4 m deep lake existed at Callabonna between ~ 5.8 and 5.2 ka and again at 4.5 ± 0.4 ka (Fig. 6). The concurrent alluvial deposition on Mt Chambers fan, enhanced precipitation in the region (Wasson and Galloway, 1986; McCarthy and Head, 2001; Quigley et al., 2010), prevalence of summer-rainfall zone vegetation taxa around Lake Frome (Singh and Luly, 1991) and fluvial activity of Strzelecki Creek (5.1 ± 0.8 ka, Larsen, 2011) suggest that Lake Callabonna was likely filled by a combination of enhanced local precipitation and subtropical moisture transported down Strzelecki Creek. Together, these results strongly indicate that central Australia was generally wetter during the middle Holocene compared with current conditions, a finding echoed for this interval around the continent (Shulmeister and Lees, 1995; Xia et al., 2001; Stanley and De Deckker, 2002; Wilkins et al., 2013).

The late Holocene (<4.2 ka)

Our results (Fig. 6) suggest that the late Holocene hydrological system of southern central Australia was active and variable. The Mt Chambers Gorge speleothem grew from ~ 4 ka to 1.9 ka and shows the most pronounced growth at ~ 3.5 ka, suggesting that precipitation was abundant. This phase of high precipitation is well represented in the fluvial record of the adjacent fan, including near-channel overbank sedimentation and mid-fan floodout deposits dated to 3.7 ± 0.2 ka, 3.3 ± 0.3 ka, and 3.3 ± 0.2 ka. Around this time the depth of Lake Callabonna changed abruptly, where shorelines indicate that the lake was ~ 0.5 m deep at 3.5 ± 0.3 ka and ~ 4.55 m deep at 3.5 ± 0.2 ka. Interestingly, this lacustral phase persisted to varying extents for ~ 800 years, as Lake Callabonna was ~ 1.35 m deep at 3.0 ± 0.2 ka and ~ 3.2 m deep at 2.7 ± 0.2 ka. Additionally, a previously reported lake filling event resulted in a ~ 4 m deep lake

~1 ka (Cohen et al., 2012a). The broad consistency between shoreline and alluvial records and records of aggradational terrace construction on the Wilkatana fan (Fig. 6) implies that large floods due to rainfall events in the ranges transported water and sediment to the adjacent lakes. These data suggest that enhanced precipitation and fluvial activity in the Flinders Ranges and the Barrier Ranges (Jansen and Brierley, 2004) beginning ~3.5 ka contributed substantial amounts of water to the adjacent lake, which quickly filled and persisted until ~2.7 ka and again at ~1 ka.

While our results do not contradict the prevailing view of regional late Holocene environmental variability, we question the associated notion of concurrent aridity (e.g., Singh and Luly, 1991; McCarthy and Head, 2001; Marx et al., 2009; Quigley et al., 2010). The inferred interval of enhanced precipitation, fluvial activity and lake-shoreline construction between ~3.5 and 2.7 ka is not consistent with the idea of an arid late Holocene. In addition to lacustral conditions, the bulk of the Mt Chambers speleothem growth occurred after the termination of growth of the Yudanamutana speleothem (Quigley et al., 2010). The currently available data cannot resolve whether the marked chronological disparity between the Mt Chambers and Yudanamutana speleothems reflects differences in speleothem type (stalactite vs. flowstone), local cave-scale drainage, and/or spatial heterogeneities in regional precipitation. A more complete and representative picture of regional Holocene variation in precipitation may be extracted from a composite record of multiple dated speleothems. Nonetheless, the observation that modern speleothems are not growing in the caves suggests that precipitation must have been higher during speleothem growth than at present.

5.2 Hemispheric Holocene climate variability and its impact on southern central Australia

Our findings present important new regional evidence for changes in southern central Australian landscapes since the late Pleistocene and throughout the Holocene. These changes reflect significant regional-scale climatic variability that may be related to shifts in large-scale atmospheric circulation patterns. South American and New Zealand glacial records suggest that the SWW experienced a peak in wind strength during the terminal Pleistocene (~14–12 ka) and records from across the southern Hemisphere indicate that SWW intensity subsequently decreased (~11–8 ka) and then increased (~8–5 ka) (Fletcher and Moreno, 2012). Enhanced middle Holocene SWW intensity is corroborated by higher-than-modern lake levels for lakes Keilambete and Gnotuk, which are primarily filled by winter rainfall derived from the westerlies (Wilkins et al., 2013). Between ~14 and 5 ka ENSO variability was minimal

with more La Niña-like conditions prevailing (Koutavas et al., 2002; Donders et al., 2008) whilst an intensification of the ASM occurred between 11 and 7ka (Shulmeister and Lees, 1995; Griffiths et al., 2009) which was potentially supplying moisture to southern central Australia (Johnson et al., 1999). Flooding on Mt Chambers Creek fan and other Flinders Ranges creeks (Sheard, 2009) as well as the dominance of summer-rainfall zone vegetation around Lake Frome (Singh and Luly 1991) at a time of depressed SWW intensity suggest that the strengthened ASM was likely delivering consistent summer rains to southern central Australia during the early Holocene.

Through the middle Holocene, landscape responses to enhanced precipitation in southern central Australia include increased fluvial activity and changing fluvial regimes on Mt Chambers Creek fan, the initiation of growth of the Mt Chambers Gorge speleothem, and highstands for Lake Callabonna at ~5.8 and 5.2 ka and again at 4.5 ± 0.4 ka. In the Flinders Ranges, the Yudanamutana speleothem experienced peak growth during this interval (Quigley et al., 2010) and woodland and shrub vegetation was abundant (McCarthy and Head, 2001). Dust from the Lake Eyre catchment was not being transported to New Zealand (Marx et al., 2009) and Strzelecki Creek delivered runoff to Lake Callabonna (Larsen, 2012). These results suggest that on a centennial to millennial scale, summer rain derived from a still-active ASM (Singh and Luly, 1991; Shulmeister and Lees, 1995) may have been supplemented by winter rains derived from enhanced SWW (Fletcher and Moreno, 2012), resulting in an interval of increased precipitation in southern central Australia.

After ~5 ka, low lake-levels in western Victoria (Fig. 6) suggest that winter rainfall and the associated SWW intensity decreased in the region (Wilkins et al., 2013). Concurrent increases in Walker Cell circulation and related ENSO variability (Fig. 6) (Shulmeister, 1999; Tudhope et al., 2001; Moy et al., 2002; Koutavas et al., 2006) and the associated increased oscillation between El Niño and La Niña phases resulted in drier and wetter events, respectively, and a less consistent ASM (Shulmeister and Lees, 1995; Donders et al., 2008). An increase in the frequency of high magnitude flood events in the Barrier Ranges (Jansen and Brierley, 2004) and on the Wilkatana fan (Quigley et al., 2010) and spatially heterogeneous vegetation patterns in the Flinders Ranges (McCarthy and Head, 2001) were some landscape responses to more variable climatic conditions. The associated decrease in reliable precipitation in the region resulted in abrupt fluctuations in the level of Lake Callabonna and pulses of enhanced fluvial activity in Mt Chambers Creek. Despite this evidence for climatic variability, the consistent growth of the Mt Chambers Gorge speleothem suggests that rainfall was still more abundant than today until ~1.9 ka. The pluvial

phase at 1 ka coincides with increased depths for lakes Keilambete and Gnotuk and a trough in El Niño event frequency (Fig. 6), suggesting that a combination of enhanced winter (SWW-derived) and summer (ASM-derived) precipitation contributed to this brief pluvial phase. Finally, the enhanced precipitation and fluvial activity around Mt Chambers and pluvial conditions between ~2.0 and 3.5 ka may have resulted in more reliable hydrological resources for human populations around the Flinders Ranges. This is significant because a relative abundance of water may have attracted mobile aboriginal populations following resources (Holdaway et al., 2010) to the region during this time of reduced regional winter rainfall.

6.0 Conclusions

Our record of the Holocene hydrologic system and palaeoenvironments of southern central Australia was derived using three complementary terrestrial proxies (speleothem, alluvial, lake shoreline). The Mt Chambers speleothem grew at ~6–5 ka and ~4–1.9 ka, with the most rapid growth at ~3.5 ka. Alluvial deposits on Mt Chambers Creek fan indicate phases of fluvial activity throughout the Holocene. Lake Callabonna experienced pluvial episodes at ~5.8–5.2, ~4.5, ~3.5–2.7, and 1 ka, many of which were coincident with precipitation and fluvial activity in the Mt Chambers Creek catchment. The coincidence between high speleothem growth, widespread alluviation on Mt Chambers Creek fan, and the rapid onset of pluvial conditions at ~3.5 ka suggest that a peaks in precipitation and fluvial activity in the eastern Flinders Ranges can contribute significant amounts of water to the adjacent lakes, and would have served as a reliable resource base for human populations during a time of more widespread climatic variability and reduced winter rainfall. A comparison of multiple speleothem chronologies from across the Flinders Ranges with a more complete record of Holocene fluvial activity on Strzelecki Creek can resolve the relative contribution of locally and subtropically derived runoff to pluvial events in southern central Australia.

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Figure captions:

Figure 1 – Geographic setting of the study area. (a) The Flinders Ranges within Australia (box) and Lakes Keilambete and Gnotuk (black dot), and (b) SRTM-derived hillshaded DEM of southern central Australia showing the location of study sites. Lake Callabonna shorelines (black dots), Mt Chambers Creek alluvial fan (black triangles) and speleothem (black square). White symbols mark locations of dated Holocene records referred to in the text: Wilkatana and Depot Creek alluvial terraces (triangles, Quigley et al., 2007, 2010; Williams 1973), stick rat nest midden sites (crosses, McCarthy and Head, 2001), Yudnamutana speleothem (square, Quigley et al., 2010) and pollen record from Lake Frome sediment core (circle, Singh and Luly, 1991).

Figure 2 – Overview of landscape archives investigated. (a) Unnamed cave along Mt Chambers Gorge from which a speleothem (b) was collected. (c) Planview of a palaeofloodout (grey surface in middle of image) on Mt Chambers Creek alluvial fan into which a pit (CF344) was excavated to show stratigraphy (d). Oblique view of Salt Creek shoreline (e) and typical shoreline stratigraphy exposed in trench at White Dog with OSL ages (f). (image source in (c) Google Earth).

Figure 3 – Mt Chambers Gorge speleothem. (a) Section of speleothem showing laminae. Dashed lines demarcate four intervals of fine laminae separated by more continuous and darker laminae. (b) Positions of 30 LA-ICP-MS U/Th measurements along a transect of speleothem, the position of which is shown as the black line in (a). (c) U/Th ages (black circles) plotted against depth with the growth model (StalAge1.0) shown as black line and shading. Note that the orientation of (b) and (c) are the same.

Figure 4 – Planview map of surface deposits at Mt Chambers Creek alluvial fan, their relative chronology (Qpap, Qha2, Qha 1, and modern Mt Chambers Creek), and the spatial arrangement of the major floodout channels and lobes across the fan. Profiles show the eight stratigraphic pits and outcrops with depositional ages based on OSL (ka; numbers in bold) as well as complementary radiocarbon ages (cal ka BP; numbers in italics) (see text for more detail). Contour intervals represent 10 m.

Figure 5 – Cross-sectional schematic view of three transects across palaeoshorlines adjacent to Lake Callabonna: Callabonna Spit (a), White Dog (b) and Salt Creek (c). Trenches excavated into beach ridges are shown with associated OSL ages.

Figure 6 – Correlative plot showing middle and late Holocene results from landscape archives around the Flinders Ranges and palaeoclimate archives discussed in text. (a) Mt Chambers Gorge speleothem growth (grey, where dark grey represents rapid growth), Mt Chambers Creek alluvial ages, and shoreline ages with inferred lake-filling curve for Lake Callabonna. Black filled circles represent OSL ages, grey filled circle represents OSL age from lacustrine setting, and open squares represent calibrated ^{14}C dates. (b) Yudnamutana speleothem growth curve (Quigley et al., 2010). (c) OSL and calibrated ^{14}C ages from aggradational terraces on the Wilkatana alluvial fan, representing large-scale floods (Quigley et al., 2010). (d) Spatial variability in vegetation across Flinders Ranges (McCarthy and Head, 2001). (e) Rainfall patterns inferred from core-derived pollen record for Lake Frome (Singh and Luly, 1991). (f) Lake level reconstruction for Lakes Keilambete and Gnotuk relative to 1970 level (dashed line) modified from Wilkins et al. (2013). (g) Plot of ENSO event frequency per 100 years derived from Laguna Pallcacocha, Ecuador (Moy et al., 2002).

Table captions:

Table 1 – Results from dose recovery experiments using the optimal regenerative and test dose preheat combination.

Table 2 – OSL dating results (dose rate, equivalent dose, and age data) for shoreline and alluvial samples from Lake Callabonna and Mt Chambers Creek alluvial fan, respectively.

Table 3 – Results for AMS ^{14}C measurements. The SHcal04 curve (McCormac et al., 2004) was used to calibrate ^{14}C ages, which we report as 2σ age ranges.

Table 4 – Uranium-series data collected by laser ablation multi-collector ICP-MS.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Table 1 -

Sample	n=**	Regenerative dose preheat (°C for 10s)	Test dose preheat (°C for 5 s)	Measured / Given dose ratio		
Lake Callabonna						
CSP5_125*	3	280	220	0.95	±	0.05
Salt Creek						
LCP5_155*	4	220	160	0.95	±	0.02
LCP6_040*	3	220	160	1.02	±	0.06
SC6A1.0*	3	180	160	1.00	±	0.02
White Dog						
WDP3_065	29/800	260	220	1.01	±	0.03
WDP3_245	4	260	220	0.98	±	0.02
WDP2_190	20/300	260	220	1.00	±	0.03
WDP1_300	21/800	260	220	1.00		0.03
Mt Chambers Creek						
CF383-55	47/300	180	160	1.03	±	0.02
CF78-6A	49/300	180	160	0.99	±	0.02

*Presented in Cohen et al., (2012a,b)

**n=number of aliquots measured or number of single grains used / number of single grains measured.

Table 2 -

Sample	Shoreline elevation (m AHD)	n= ²	Water content (%)	Gamma (Gy/ka)			Beta (Gy/ka)			Total Dose Rate (Gy/ka) ³			Over-dispersion (%) ⁴			D _e (Gy)			Age model	Age (ka)		
Lake Callabonna																						
CSP5_125 ¹	5.3	26/700	0.1	0.65	±	0.002	1.44	±	0.06	2.06	±	0.08	34	±	5	11.5	±	0.5	CAM	5.6	±	0.3
Salt Creek																						
SC5A0.75	5.3	54/800	5.0	1.19	±	0.03	1.40	±	0.08	2.81	±	0.11	42	±	5	9.8	±	0.5	FMM	3.5	±	0.2
LCP5_155 ¹	5.3	16/500	2.3	0.83	±	0.03	1.72	±	0.07	2.45	±	0.11	22	±	5	11.0	±	0.7	CAM	4.5	±	0.4
SC6B0.4 ¹	4.2	68/1000	0.9	0.93	±	0.03	1.62	±	0.09	2.78	±	0.13	46	±	5	2.5	±	0.1	FMM	0.9	±	0.1
LCP6_040 ¹	4.2	11/600	0.1	0.84	±	0.03	1.70	±	0.07	2.48	±	0.11	13	±	6	2.4	±	0.1	CAM	1.0	±	0.1
SC6A0.5 ¹	4.2	55/1000	1.4	0.90	±	0.03	1.56	±	0.08	2.69	±	0.11	28	±	4	2.5	±	0.1	FMM	0.9	±	0.1
SC6A1.0 ¹	4.2	79/1000	2.1	0.91	±	0.03	1.35	±	0.08	2.46	±	0.12	30	±	3	6.6	±	0.2	FMM	2.7	±	0.2
White Dog																						
WDP3_065	2	63/900	1.1	0.88	±	0.03	1.45	±	0.08	2.57	±	0.11	28	±	3	7.7	±	0.5	FMM	3.0	±	0.2
WDP3_145	2	23/400	3.3	0.77	±	0.02	1.36	±	0.07	2.33	±	0.10	18	±	5	8.2	±	0.4	CAM	3.5	±	0.3
WDP3_245	2	22	19/12.5 ⁵	0.83	±	0.03	1.20	±	0.08	2.22	±	0.18	20	±	4	11.1	±	0.5	CAM	5.1	±	0.5
WDP2_190	2.5	71/1000	24/12.5 ⁵	0.76	±	0.03	1.06	±	0.07	2.00	±	0.16	28	±	3	54.4	±	1.8	FMM	27.2	±	2.5
WDP1_300	5	13/1000	19/12.5 ⁵										13	±	13	191.5	±	16.9	CAM			
Mt Chambers Creek																						
CF344-30		89/1000	3.0	1.30	±	0.06	2.01	±	0.10	3.54	±	0.17	57	±	5	11.7	±	0.8	FMM	3.3	±	0.3
																3.1	±	0.3	MAM	0.9	±	0.1
																14.8	±	1.0	MAXM	4.2	±	0.4
CF344-80		121/1100	4.0	0.86	±	0.03	1.84	±	0.10	2.91	±	0.15	26	±	2.3	19.6	±	0.5	CAM	6.7	±	0.4
																15.0	±	0.8	MAM	5.1	±	0.4
CF344-145		71/800	4.6	1.23	±	0.04	1.80	±	0.10	3.22	±	0.16	33	±	4	35.6	±	1.7	CAM	11.0	±	0.8
CF383-55		107/1000	7.7	1.28	±	0.03	1.95	±	0.10	3.44	±	0.20	60	±	4	20.6	±	0.9	FMM	6.0	±	0.5
CF97		91/1000	3.9	1.21	±	0.04	1.77	±	0.10	3.20	±	0.16	34	±	3	38.1	±	0.9	FMM	11.9	±	0.7
CF95		80/1000	4.4	1.20	±	0.04	1.78	±	0.10	3.19	±	0.16	30	±	3	32.6	±	1.2	FMM	10.2	±	0.7
																24.2	±	2.0	MAM	7.6	±	0.7
CF373-6B		98/900	2.4	1.33	±	0.04	1.87	±	0.10	3.43	±	0.15	45	±	4	11.2	±	0.3	FMM	3.3	±	0.2
CF373-6A		116/1100	4.5	1.15	±	0.04	1.61	±	0.09	2.99	±	0.15	23	±	2	12.5	±	0.3	FMM	4.2	±	0.2
CF78-6B		94/1000	1.6	1.23	±	0.04	2.15	±	0.10	3.61	±	0.15	47	±	4	13.5	±	0.5	FMM	3.7	±	0.2
CF78-6A		134/1100	2.9	1.38	±	0.04	2.12	±	0.10	3.71	±	0.16	41	±	3	22.2	±	0.6	FMM	6.0	±	0.3

¹Presented in Cohen et al. (2012a,b)²n=number of aliquots measured or number of single grains used / number of single grains measured.³A small internal alpha dose rate of 0.03±0.01 Gy/ka was assumed based on previous measurements made on Australian quartz (Bowler et al., 2003).⁴Overdispersion value calculated using the CAM (Galbraith et al., 1999).

⁵The measured water content of samples WDP3-245, WDP2-190, and WDP1-300 are 19%, 24%, and 19%, which are unlikely to be representative of the average historical water contents; thus, an assumed water content of $12.5 \pm 6.3\%$ was used for these samples.

Table 3 –

Sample name	Lab code	Material	Depth (cm)	Conventional age (^{14}C a BP)	$\delta^{13}\text{C}$ (‰)	Calibrated 2σ age range (cal a BP)
CF-78-6BO	OZM548	Snail Fragment	30	1515 ± 35	-7.0	1298 – 1407
CF-78-6BU	OZM549	Snail Fragment	65	4230 ± 40	-2.0	4572 – 4839
CF-373-6A-S	Beta 306539	Snail Fragment	60	4440 ± 30	-2.0	4855 – 5211
CF-383-S-40	Beta 306540	Snail Fragment	40	3970 ± 30	-1.8	4236 – 4498
CF-206-VII-C	Beta 329453	Charcoal	205	3030 ± 40	-23.6	2999 – 3324
CF-96-85-S	Beta 329452	Snail Fragment	85	8780 ± 40	-7.2	9551 – 9888
CF-96-65-C	Beta 329451	Charcoal	65	7660 ± 40	-23.1	8342 – 8535
SC-P5A-SHC	Beta 329455	TOC	8	890 ± 30	-21.6	683 – 895
SC_P6A	Beta-283857	Freshwater mollusc	44	4540 ± 40	-3.9	4973 – 5302
SC_P6B	Beta-283858	Emu eggshell	40	690 ± 40	-0.4	556 – 664
SC_P6B	Beta-283859	Charcoal	50	150 ± 40	-24.7	0 – 278
LC_P5	OZL057	Charcoal	140	$5,080 \pm 60$	-25.1	5617 – 5909

Table 4 –

Spot #	U (ppm)	$\pm 2\sigma$	Th (ppb)	$\pm 2\sigma$	$(^{230}\text{Th}/^{232}\text{Th})$	$\pm 2\sigma$	Age (ka)	$+2\sigma$	-2σ
1	2.17	0.06	4.18	0.36	172	23	5.82	0.42	0.42
2	2.31	0.08	1.99	0.31	264	64	3.84	0.34	0.33
3	2.35	0.03	19.7	1.58	27	3	3.96	0.32	0.32
4	2.22	0.04	8.37	0.46	53	5	3.45	0.22	0.22
5	2.08	0.05	4.28	0.55	119	24	4.2	0.26	0.26
6	4.91	0.13	11.21	0.91	93	12	3.61	0.26	0.25
7	3.22	0.06	3.83	0.21	202	18	4.09	0.34	0.33
8	1.19	0.05	3.21	0.19	87	8	4.1	0.34	0.34
10	2.21	0.05	9.42	0.79	49	6	3.53	0.3	0.29
11	0.83	0.03	5.57	0.49	30	4	3.26	0.39	0.39
12	0.6	0.01	8.99	1.16	15	3	3.83	0.58	0.58
13	2.55	0.05	7.03	0.28	79	5	3.56	0.34	0.33
14	1.48	0.06	3.58	0.44	103	20	4.23	0.35	0.35
15	2.01	0.05	1.92	0.19	229	36	3.66	0.33	0.33
16	1.04	0.03	4.15	0.61	57	13	3.85	0.36	0.36
17	0.51	0.02	3.06	0.21	39	4	3.88	0.54	0.54
18	2.25	0.03	7.06	0.63	58	8	3.09	0.25	0.25
19	1.06	0.02	2.31	0.16	83	9	3.06	0.35	0.35
20	1.93	0.07	2.38	0.15	137	14	2.82	0.24	0.24
21	1.82	0.02	1.96	0.2	158	25	2.9	0.32	0.31
22	1.64	0.03	2.04	0.19	141	21	2.92	0.31	0.31
23	2.76	0.04	14.25	1.4	32	5	2.78	0.22	0.21
24	2.21	0.04	7.87	0.9	45	8	2.78	0.19	0.19
25	3.06	0.07	3.05	0.33	152	26	2.59	0.21	0.21
26	2.01	0.04	8.25	0.79	38	6	2.62	0.24	0.24
28	2.1	0.05	4.34	0.35	66	8	2.27	0.24	0.24
29	2.31	0.03	3.85	0.4	81	13	2.27	0.22	0.21
30	3.91	0.07	14.19	0.85	30	3	1.85	0.16	0.15