Holocene and Anthropocene aeolian reactivation of the Willandra Lakes lunettes, semi-arid southeastern Australia

Kathryn E. Fitzsimmons*

Research Group for Terrestrial Palaeoclimates, Max Planck Institute for Chemistry, Hahn-Meitner-Weg 1, 55128 Mainz, Germany

Nicola Stern

Department of Archaeology and History, La Trobe University, Bundoora VIC 3086, Australia

Caroline Spry

Department of Archaeology and History, La Trobe University, Bundoora VIC 3086, Australia

*** Corresponding author: k.fitzsimmons@mpic.de***

Abstract

The Willandra Lakes in semi-arid southeastern Australia provide some of the most continuous combined palaeoenvironmental and archaeological records on the continent. These are best preserved within the transverse shoreline (lunette) dunes on their downwind margins. Following final lake retreat c. 15 ka, the Willandra lunettes periodically reactivated, experiencing erosion, aeolian redeposition, and alluvial sheetwash onto the lake floors. These reworked sedimentary archives reflect local climatic conditions, and yet the focus of study in the region to date has largely remained on the late Pleistocene. The general paucity of information about this later period has contributed to a perception that people largely abandoned the area in favour of the perennial Murray and Darling Rivers to the south and west.

Our study reconstructs palaeoenvironmental conditions and patterns of human mobility in adjacent Lakes Mungo and Durthong over the last c. 15 ky subsequent to final lake retreat, including the most recent 150 years since Europeans established pastoralism in the region. Our data conclusively show that Indigenous people did not abandon the area as previously assumed, but developed effective strategies for responding to the changed environmental conditions. Final lake retreat transitioned into a phase of aeolian accumulation c. 15-12 ka, indicating locally dry conditions. Subsequent aeolian reactivation peaked during arid phases in the early Holocene and twice in the most recent thousand years prior to European settlement in the area. Alluvial sheetwash was deposited on the lake floors during the mid-Holocene, and again in the early decades of European settlement. We observe a distinct anthropogenic signature in the most recent 150 years in the form of aeolian reactivation. Our study underscores the necessity of integrating geomorphological and archaeological investigations over landscape scales in order to optimise our understanding of interactions between people and their environment through time.

Keywords:

Holocene, Anthropocene, luminescence dating, Lake Mungo, Australia, lunette, archaeology

1. Introduction

The Willandra Lakes system in semi-arid southeastern Australia is well known for providing one of the most continuous, and longest, combined palaeoenvironmental and archaeological records on the continent (Bowler, 1998; Bowler et al., 2003). The lakes are a relict overflow system, fed by a distributary of the Lachlan River, which rises in the temperate subhumid southeastern Australian highlands. The lakes have been dry since c. 15 ka (Bowler et al., 2012; Fitzsimmons et al., 2014) following avulsion of the Willandra Creek distributary. During the time that the Willandra Creek was active, the lakes experienced sediment deposition onto their downwind margins, forming transverse shoreline, or lunette, dunes. These so-called lunettes preserve the most conspicuous and abundant archaeological traces in the region (Stern et al., 2013) – including the oldest known ritual burials in Australia (Bowler and Thorne, 1976; Bowler et al., 2003; Bowler et al., 1970; Bowler and Magee, 2000; Bowler et al., 1972) - but also the best-preserved archives for past hydrological change (Bowler et al., 2012; Fitzsimmons et al., 2014; Fitzsimmons et al., 2015). The lunette stratigraphy of the Willandra Lakes reflects the environmental conditions of the headwaters rather than local climate.

Following final lake retreat at c. 15 ka, the lunettes of the Willandra periodically reactivated, experiencing erosion, aeolian redeposition, and alluvial sheetwash onto the lake floors. These more recent sedimentary archives consequently reflect local environmental conditions, in contrast to the preceding deposits (Fitzsimmons et al., 2014). Yet despite the opportunity provided by these reactivated lunette sediments to investigate local Holocene palaeoenvironmental history, the focus of scientific study to date in the Willandra has largely remained on the late Pleistocene (Bowler et al., 2012; Bowler, 1998; Fitzsimmons, 2017; Fitzsimmons et al., 2015; Long et al., 2014; Long et al., 2018).

The nature of human occupation in the Willandra following final lake retreat has likewise received limited attention compared with the late Pleistocene (Barbetti and Allen, 1972; Barbetti and McElhinny, 1972; Bell, 1991; Bowler et al., 2003; Bowler et al., 1970; Bowler and Price, 1998; Long et al., 2014; 2018; Olley et al., 2006; Shawcross and Kaye, 1980; Shawcross, 1998; Stern et al., 2013; Stern, 2015; Webb et al., 2006; Westaway et al., 2013; Weston et al., 2017). Traces of human activity post-15 ka have been observed on the Lake Mungo lunette, and elsewhere in the Willandra system, including hearths, chipped stone artefacts, faunal remains and grinding stones (Allen, 1972; Anderson et al., 1984; Dare-

Edwards, 1979; Fitzsimmons et al., 2014; Fullagar et al., 2015a; Fullagar et al., 2015b). However, the general paucity of information about this later period has contributed to a perception that people largely abandoned the area in favour of the perennial Murray and Darling Rivers (Allen, 1972, 1974; Pardoe, 2015).

This study seeks to address the gap in knowledge about palaeoenvironmental conditions and settlement and land use in the Willandra Lakes area over the 15 ky subsequent to final lake retreat. We examine the post-lake depositional history at the south-central Lake Mungo and adjacent Lake Durthong lunettes with respect to the nature of sediment reactivation, and provide a chronological framework based on optically stimulated luminescence (OSL) dating. These are integrated with data documenting the abundance and types of past activity traces preserved in the Mungo lunette over the past 15 ky, including more detailed information about the stone technology generated from clusters of chipped stone artefacts. Together, these lay a foundation for investigating the relationships between changes in land use, occupancy and mobility and the palaeoenvironmental changes that took place after the overflow system ceased to function as such.

2. Regional setting

The Willandra Lakes system lies in the southwest of Australia's second largest catchment, the Murray-Darling Basin (MDB), located in the southeast of the continent. The lakes are a series of five larger, and several smaller, dry lakes (Figure 1), and are surrounded by linear and parabolic dune systems (Bowler and Magee, 1978). The lakes were filled at various times in the past by the Willandra Creek, a presently inactive channel of the Lachlan River which has its headwaters approximately 600 km to the east in the southeastern Australian highlands. The palaeohydrology of the Willandra lakes is recorded in their transverse lunette dunes, which lie on the downwind, eastward lake margins (Bowler, 1983). Until the creek ceased to flow c. 14-15 ka (Bowler, 1998; Fitzsimmons et al., 2014) due to drainage avulsion to a different channel (Kemp et al., 2017), lake hydrology and consequently lunette sedimentation reflected runoff from the distal uplands rather than local conditions.

(Figure 1)

In this study, we focus on the reactivation of the Lake Mungo and Durthong lunettes over the last c. 15 ky, subsequent to cessation of flow in the Willandra Creek. The larger lake, Mungo, is an overflow lake hydrologically linked to Lake Leaghur immediately to the north. Its lunette is c. 30 km in length. Lake Durthong is a through-flow lake located approximately 10 km west and downstream of Mungo. Its lunette extends c. 8 km from north to south (Fitzsimmons, 2017).

2.1 Sample sites

Reactivation of the sedimentary system in the Willandra post-lacustrine system takes three main forms:

1. As aeolian erosion and deposition on the lunettes and immediately downwind thereof;
2. As sheetwash scour and alluvial fan deposition onto the lake floor;
3. As pedogenesis within these various phases.

These three phases are recorded over four-dimensional space, since erosion and deposition, as well as preservation of any given depositional phase, has always been spatially variable across the lunettes (Fitzsimmons, 2017; Fitzsimmons et al., 2014; Stern et al., 2013). In this study, we sampled sites yielding representative information about post-lacustrine palaeoenvironmental change in the region and integrated these data with those from other studies of the central Mungo lunette (Barrows et al., 2014; Fitzsimmons et al., 2014).

At Lake Mungo, multiple phases of aeolian redeposition or alluvial fan deposition overlie one another in some places, separated by weakly developed humic paleosol horizons. Such sites give the clearest indication of palaeoenvironmental variability through time and therefore formed the focus of our sampling at this lake. Chronostratigraphic work focussed on Locality 973659, a small erosion basin in the central part of the lunette that lies just downwind of the present-day dune crest (Figure 1C, shown in green). Three small, vegetated hummocks (Residuals 1-3), and a larger residual (4) on the rim of the blowout, record the post-lunette depositional history. The new geochronological data presented here comes from these four residuals (Figure 2A). We also revisited the sampling sites discussed by Barrows et al. (2014) in order to place their respective chronostratigraphies into the post-lunette framework.

(Figure 2)

Residual 1 is approximately 1.5 m high and 3 m wide and capped by an eastward-sloping bench representing the surface of a brownish soil, which to the north is overlain by mobile, aeolian sands. The stratigraphy of Residual 1 is exposed to the south towards the blowout surface, and comprises a brownish paleosol with minor ped development, which overlies the final lacustrine phase (Fitzsimmons et al., 2014; known as Unit E or the Zanci Unit) without visible unconformity (Figure 1). Two OSL samples were collected from residual 1 (Table 1, Figure 2C). One sample (EVA1100) was collected at the base of the paleosol and residual, immediately above the laminated clay-sand sediments that are characteristic of the final lake-phase of sediment accumulation on the lunette (Unit E or Zanci; Figure 1). The other (EVA1101) was collected from the middle of the soil profile, within massive brown sands containing some roots; visible bioturbation was avoided during sampling.

Residual 2 is the largest of the three residuals within the blowout (Figure 2A). It rises c. 3 m above the floor of the erosional hollow and contains a bench of brownish sandy soil slightly lower in altitude than that occurring on top of Residual 1. Pale, unconsolidated aeolian sands overlie the brown sandy soil. Three OSL samples were collected from Residual 2 (Table 1, Figure 2D): one from the base of the residual (EVA1106), assumed to represent the age of the blowout floor and the artefacts scattered across its surface; and two from upper and lower parts of the reworked unit, respectively (EVA1103 and EVA1104).

Residual 3 lies on the edge of the hollow, above mobile aeolian sands to the north of Residual 2 (Figure 2A). The pale sands exposed in this residual are laminated, especially towards the base; such laminations are common in recently deposited dune sediments (Bagnold, 1941). The sediments of Residual 3 comprise well sorted fine to medium pale sand, and most likely correspond to the uppermost pale sands of residual 2. One sample (EVA1105; Table 1, Figure 2A) was collected from the lower laminated exposures of Residual 3.

Residual 4 lies on the present-day lunette crest, at the southern end of an extensive exposure of sediments representing the final phase of lacustrine deposition, at the top of Unit E (Figure 2A, B). The northern flank of Residual 4 provides the best exposure of the stratigraphy which comprises massive yellowish sands with carbonate concretions. Towards the base of the residual, these sands are laminated, and grade upwards into more massive sands with no noticeable unconformity. Two OSL samples were collected from Residual 4 at Locality 697626: one (EVA1107) from the lower, laminated sands, stratigraphically equivalent to the blowout surface that contains the refitted artefacts; and the other (EVA1108) from pale, massive sands in the middle part of the residual (Figure 2b).

Locality 973659 is of particular interest for reconstructing human-environmental interactions, because the artefacts lying on the surface of the erosion hollow were part of a broader investigation of the stone technology employed in this area during the post-lake era (Spry,

2014) The surface of the erosional hollow surrounding residuals 1-3 contains several groups of refitting artefacts demonstrating sequences of stone tool production, as well as clusters of artefacts that were arguably struck from the same block of raw material (Figure 3). Several sets of refitting artefacts also lie on the surface of upper part of Unit E (Zanci), which is well exposed in the area surrounding Residual 4 (Spry, 2014).

(Figure 3)

At Lake Durthong, aeolian sediment overlying lake-phase lunette stratigraphy is not as extensive or as thickly deposited as at Lake Mungo. Consequently, investigation of post-lacustrine stratigraphy was limited to single OSL samples from four exposures (Table 1): two in the southern part of the lunette (DTH26, 27), one in the central part of the lunette adjacent the inflow channel (DTH07), and one in the central-northern lunette (DTH31) (Figure 1). Two additional samples were collected from linear dunes on the north-northwestern margins of the lake (DTH14, 15), and are interpreted to correspond to activation of those dunes.

(Table 1)

In addition, we incorporate recently available data from previous studies at Lake Mungo (Figure 1; Barrows et al., 2014; Fitzsimmons et al., 2014). This includes two dates from a chronostratigraphic transect in the central part of the lunette, several hundred metres south of Locality 973659, that sampled superimposed outwash fans on the lake floor, and one that sampled reactivated aeolian sediment near the lunette crest (Fitzsimmons et al., 2014). Barrows et al. (2014) sampled residuals in three erosional basins on the lunette (Figure 1): Locality 969660 (2 samples), Locality 940691 (4 samples; Tumney, 2011) and Locality 966617 (2 samples; Tumney 2011). Most of these were collected from unconsolidated, reactivated aeolian sediment overlying the final lake-phase of the lunette sequence, but one was collected from a reactivated aeolian sample underlying a weakly developed brown paleosol at Locality 969660, and two were collected from outwash fans, one each from 966617 and 940691 (Figure 4). Two samples were also collected from a low elevation dune bounding a soak on the now-dry lake floor c. 2 km from 940691 (Figure 4), and two from a linear dune on the western shoreline of Lake Mungo (Barrows et al., 2014).

3. Methods

3.1 Field methods

Tight integration of geological and archaeological data is needed in order to build an understanding of the strategies people developed in response to the palaeoenvironmental changes that followed the drying of the Willandra Lakes. This has been achieved by systematically documenting the distribution and three-dimensional stratigraphy of post-lacustrine sedimentary units and the archaeological features they contain. The study area is a 3km x 600 m swath of the central Mungo lunette that incorporates Localities 973659 and 969660, *and* the chronostratigraphic section referred to above (Figure S6). It extends from the lake floor immediately adjacent the lunette, including low slope-angle fans of redeposited lunette material, as well as the lee slope of the lunette, much of which is overlain by reactivated aeolian sediment (Fitzsimmons et al., 2014; Stern, 2015; Stern et al., 2013). Over three field seasons, the three-dimensional locations of stratigraphic boundaries and archaeological features were plotted onto georectified aerial photographs, so that the number and type of activity traces preserved in the post-lake strata could be analysed using GIS software. The OSL sampling strategy described above was designed to provide bracketing age estimates for those strata.

Traces of past human activity, including hearths, clusters of food-remains, patches of tool-making debris and isolated finds, like grindstones and shell tools, were located and documented during systematic inspection of 50 x 50m grid-squares superimposed on the georectified aerial photographs. Information was recorded about the content, and the context, of each archaeological feature or isolated find that remained at least partially embedded in sediment. Only a small proportion of the chipped stone artefacts found on the surface of the lunette are still encased in sediment, so discrete clusters of surface artefacts were included in the data base when their stratigraphic origin could be inferred using information about their distribution in relation to topographic features and sedimentary units, as well as the presence of refitting artefacts, and artefacts struck from the same block of raw material (Foley et al. 2017).

During the initial survey work, information was recorded about the type of heat retainer or baked sediment hearth encountered, and whether any food remains or tools are scattered in or around it (Stern 2015). It also included information about the types of stone artefacts encountered, including the raw materials from which they were made, and about the prey species and body parts represented in the patches of food remains. This was followed by more detailed studies of particular activity traces, with an initial focus on the chipped stone artefacts (Spry, 2014), grindstones (Fullagar et al., 2015a) and shell tools (Weston et al., 2017). Study of the chipped stone artefacts was designed to identify the stone working activities undertaken at specific locations and what these could reveal about changes in the way people moved around the landscape after the lakes had dried out (Spry, 2014).

The Lake Durthong lunette is substantially smaller and more subdued than that of Mungo, with fewer stratigraphic exposures. Work undertaken at this site was solely palaeoenvironmental in nature (e.g. Fitzsimmons, 2017). The length of the Durthong lunette was traversed with the aim of locating suitable residuals and sedimentary exposures for palaeoenvironmental reconstruction and OSL dating. Seven sites were sampled, of which six (Figure 1) exposed sediment representing aeolian reactivation or linear dune activity post-dating the final retreat of the lake. Although hearths were observed on the lunette and lake floor, as yet no archaeological survey has been undertaken of this basin.

OSL sampling involved driving 4 cm diameter, 10 cm long stainless steel tubes horizontally into cleaned, exposed surfaces. The sample holes were then widened and deepened to fit a three-inch diameter portable sodium iodide gamma spectrometer for dosimetric analyses. These measurements were made in each hole for 30 minutes. The sediment removed was collected in a sealed plastic bag for additional laboratory measurements of moisture content, beta and gamma spectrometry.

3.2 Luminescence dating

We applied single grain quartz OSL dating to all 14 samples collected from the post-lacustrine lunette sediments at Lakes Mungo and Durthong. Single aliquot OSL measurements were additionally undertaken on small aliquots (<100 grains) of sand-sized quartz on all 8 of the Mungo samples, and 4 of the 6 Durthong samples (due to limited datable sample).

The OSL samples were opened and processed under dim red light conditions in the luminescence dating laboratory of the Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany. The sediment from the innermost part of the tubes was used for dating, with the material from the ends of the tubes used to calculate in situ moisture content based on its raw and oven-dried masses. Quartz was extracted from the raw dateable sample using published methods (Fitzsimmons et al., 2014), following a protocol of digestion in hydrochloric acid to remove calcium carbonate, hydrogen peroxide to remove organic content, sieving to isolate the sand-sized (180-212 μm) size fraction, density separation in lithium heterotungstate at 2.62 and 2.68 g cm^{-3} and etching by hydrofluoric acid at 40% concentration for 60 minutes. The etched material was rinsed again with HCl and sieved to remove small flakes produced by the last procedure.

For each sample, 24 small (1 mm) aliquots and 6 single grain discs were prepared for equivalent dose (D_e) measurement, plus an additional 24 discs for preheat plateau testing of representative sample EVA1100 (Figure S1). Small aliquots of the clean quartz grains were prepared for measurement by mounting c. 100 grains each (Duller, 2008) onto the central 1 mm of 10 mm diameter stainless steel discs using silicone oil. Single grains were swept using a fine paintbrush onto 10 mm diameter anodised aluminium discs, each containing 10x10 grids of 300 μm diameter holes. Six single grain discs (so 600 grains) were measured for each sample.

D_e measurements on both single aliquots and single grains were undertaken using an automated Risø TL-DA-20 reader equipped with a single grain laser attachment. Clusters of blue light-emitting diodes (Bøtter-Jensen et al., 2000; 1999) provided light stimulation for single aliquot measurement. Single grain light stimulation was provided by green and infrared lasers emitting at 532 nm and 830 nm respectively (Bøtter-Jensen et al., 2000). The luminescence signal was detected by EMI 9235QA photomultiplier tubes with coated Hoya U-340 filters (Bøtter-Jensen, 1997). Irradiation was undertaken using calibrated $^{90}Sr/^{90}Y$ beta sources (Bøtter-Jensen et al., 2000). D_e was determined using the single aliquot regenerative dose (SAR) protocol of Murray and Wintle (2000; 2003). Preheat plateau tests were undertaken on small aliquots of sample EVA1100 using preheat temperatures between 180°C and 280°C. Since the preheat plateau extended to 260ºC (Supplementary Figure S1), preheat and cutheat temperatures of 260°C and 220°C respectively were used in the measurement protocols. Depending on aliquot or single grain dose distribution, the central or minimum age models (CAM and MAM, respectively; Galbraith et al., 1999) were used to calculate sample D_e. For the majority of samples, both aliquots and single grains yielded broadly normal distributions (Figures S2, S3), so justifying application of the CAM. Generally the very youngest samples gave indication of incomplete bleaching of the OSL signal – a trait which may broadly characterise modern, unconsolidated sediments and which is mitigated by age – for these samples (Table 2), where appropriate, the MAM was used to calculate D_e.

Sample dose rates were determined by in situ gamma spectrometry and laboratory beta counting. Attenuation of the dose rates was accounted for using published factors (Guérin et al., 2011). In-situ moisture content, which contributes to dose rate attenuation, was calculated by weighing the raw and oven-dried weight of material from the ends of the tubes and bulk sediment collected from around the sample points. The average of these two values was taken as the final value (Table S2). The cosmic ray component of the dose rates was determined from sample depths and uniform values for sediment density and site altitude, latitude and longitude, following Prescott and Hutton (1994).

3.3 Analysis of previously published chronological data

In addition to incorporating the luminescence ages for palaeoenvironmental records from previous studies (Barrows et al., 2014; Fitzsimmons et al., 2014), we generated a dataset of published radiocarbon dates based on archaeological traces in the vicinity of the Lakes Mungo and Durthong for the most recent 15 ky (Table S3, Supplementary information). The majority of published legacy data precede radiocarbon measurements using accelerator mass spectrometry (AMS) and modern pretreatment methods (Allen, 1972; Allen, 1998; Clark, 1987; Johnston and Clark, 1998), and must therefore be treated with caution. Dates from material deemed unsuitable for dating using earlier methods based on the current state of the art (including burnt earth, soil carbonates) were removed from the dataset as unreliable; those derived from skeletal remains (bone collagen, amino acids) are not included since permission has not been granted to use these. Radiocarbon dates were calibrated based on IntCal09 (Reimer et al., 2009). Given the limitation to reliable radiocarbon dating for very young samples (Fitzsimmons et al., 2007; Walker, 2005), the youngest date in the dataset exceeds 500 y cal BP. Despite the limitations of these legacy data, this metadataset provides an additional chronological overview regarding human presence on the landscape against the backdrop of the palaeoenvironmental information generated in this study.

4. Results

4.1 Stratigraphy

The stratigraphic contexts and locations of the samples collected for this study are listed in Table 1. The residuals studied include the full range of sediment types observed for material deposited following lake retreat, including profiles that preserve the stratigraphic contact between the sediments representing the final oscillating lake, (Unit E or Zanci unit) and overlying material (Figure 1).

The crest of the dune surrounding the sampled residuals at Lake Mungo comprises an expansive surface of pale yellow, laminated sand. This closely resembles, and appears to grade upwards from, the lacustrine Unit E (Zanci) but is distinct from it in having no clay enrichment. We refer to this transitional stratigraphic layer as Unit F (Figure 1). This laminated sand is exposed in Residual 4 and the base of Residual 1, can be traced towards the lake floor, and appears to conformably overlie Unit E (Zanci). At the base of Residual 1, and also within a residual at 969660 (Barrows et al., 2014), this unit is overprinted by a weakly developed, brownish, humic paleosol. We propose that this laminated sand represents a gradational change from lake drying conditions to deflation of the completely dried lake bed. This interpretation contrasts with previous work proposing an abrupt end to the final lacustrine phase followed by superposition of a weakly developed soil (Bowler, 1998), but may be explained by variability in stratigraphic preservation along the length of the lunette (Fitzsimmons, 2017) and the geographical focus of earlier studies.

At Residual 1, and at Locality 969660, Unit F is capped by massive, unconsolidated, brownish sands that lack the laminations characteristic of the lower part of the unit. The relative intensity of the brownish sediment suggests increased humic content. This brown unit outcrops at the base of Residual 2 and Residual G of a previous study (Fitzsimmons et al., 2014), although both of these appear to have been truncated. It can also be traced near to residuals A and B (Fitzsimmons et al., 2014), where it contains traces of burnt sediment hearths. Despite its colour, it otherwise lacks pedogenic structure and may reflect coeval vegetation cover and relatively high rates of aeolian accumulation.

Much of the crest and lee of the Lake Mungo lunette surface comprises pale, unconsolidated aeolian sediment. At times this uppermost aeolian sediment preserves laminations indicative of relatively recent deposition. This unit, H, overlies the brown humic unit at Residual 2, comprises the entirety of Residual 3, as well as previously sampled residuals (Barrows et al., 2014) at 966617, 940691 and BLW4. We assume Unit H to represent the most recent period(s) of aeolian reactivation.

Towards the lake floor, just to the north of the Walls of China tourist area at Lake Mungo, several generations of alluvial fan or sheetwash activity superpose one another. The lowermost layer observed in outcrop is a brownish, poorly sorted, relatively clay-rich sand, identified as Unit G in Fitzsimmons et al. (2014) and containing in situ hearths and stone artefacts. In this earlier study Unit G was interpreted as a single unit representing more humid environmental conditions, although it may have deposited over multiple episodes. Unit G is unconformably overlain by the pale clay-rich sands of Unit I, which contains little organic material and was inferred to represent recent sheetwash accumulating during intense rainfall events (Fitzsimmons et al., 2014).

At Lake Durthong, sediments clearly post-dating lacustrine phases are comparatively sparse, thin, and variable in character compared with those at Lake Mungo. In the southern part of the lunette, reworked, pale aeolian sediments, less than one metre thick, unconformably overlie laminated pelletal clay layers interpreted to represent the Durthong equivalent to Unit E/Zanci (Fitzsimmons, 2017). In the central part of the lunette, sediments occupying the same post-lacustrine stratigraphic context are reddish in colour. At the more northerly of the two sites sampled, the red reactivated aeolian sand is unconformably overlain by a pale, unconsolidated sediment a few tens of centimetres thick. At the northern end of the lunette, reddish unconsolidated sand contains a substantial silt component, and may represent part of an incipient linear dune overlying the abandoned lunette. The stratigraphic equivalence of the Durthong reactivated sites to one another, and to the sites at Mungo, is unclear based on sedimentological characteristics alone.

4.2 OSL dating

The OSL characteristics of the quartz samples from both Lakes Mungo and Durthong, even the very youngest, are generally well suited to dating with OSL using the SAR protocol. Proportions of aliquots or grains passing criteria for age analysis are generally high (Table S1). OSL signals of datable aliquots or grains are bright relative to background, even in the case of very young samples (Figure S4); generate simple exponential dose-response curves; and with only a few exceptions, yield recycling ratios within 10-15% of unity (Table S1) and limited thermal transfer. Dose recovery of single grains of the Lake Durthong sample EVA1069 lies at unity (1.00 ± 0.02; Figure S5). Dose recovery of samples from Lake Mungo, when given an applied dose comparable with the equivalent dose, also yield ratios close to unity (Doerschner et al., 2016). The preheat plateau results of sample EVA1100 (Figure S1) are comparable with tests run on other, older sediments from Lake Mungo (Fitzsimmons et al., 2014; Fitzsimmons et al., 2015), from which the reactivated sediments in this study are presumed to have been derived. Single grain and single aliquot dose distributions from Lake Mungo, and consequently equivalent dose values, generally lie within error of one another (Figure S2). The comparability of OSL characteristics between the younger samples from this study and older samples from earlier work reinforces the argument for inheritance of luminescence characteristics over depositional generations (Fitzsimmons, 2011).

Some variability was observed in the luminescence characteristics between sites. Generally, luminescence characteristics of the Lake Mungo samples are better than for those from Lake Durthong. In part this may be due to the fact that the Durthong sample set comprises a larger number of younger samples. Single aliquot samples from Lake Mungo generally yield overdispersion values below 22%, and below 37% for single grains (Table S1). The exceptions to these are the three youngest samples, EVA1103-EVA1105, for which higher percentages of overdispersion are not unexpected, given proportionally higher scatter in very young samples at the limits of the technique. These three samples also yielded the lowest proportions of datable single grains for the Mungo dataset, which is also attributed to comparably low doses and correspondingly dim signals at the lower limits to the dating technique. The Lake Durthong dataset produced less satisfactory OSL characteristics (Table S1), including lower proportions of single aliquots and single grains passing quality control criteria for age analysis, and relatively high overdispersion values in most cases. Substantial discrepancies between the single aliquot and single grain equivalent doses were observed in the Durthong samples. Aliquot D_e values yielded higher overdispersion values and were calculated using the CAM, resulting in much older ages than for the younger single grain D_es, which yielded lower overdispersion and were generally calculated using the MAM due to incomplete bleaching of the very young signal. In this case, the single grain ages are preferred to the single aliquot values since incomplete bleaching is more reliably identified than in aliquots, and given the lower overdispersion values.

A statistically robust number of single grains from even the youngest samples yielded sufficient signal for dating (Figure S4). The very young ages provide a reliable lower limit to OSL dating for the Willandra Lakes area of c. 30 years (EVA1105: 0.03 ± 0.02 ka). In part this is assisted by the generally very low dose rates, which in the case of the youngest samples are well below 1 Gy/ka (Table 2).

Data relating to OSL age calculations for this study are listed in Table 2. Subsequent discussion of the chronology will be based on the single grain ages, given in italics.

(Table 2)

4.3 Chronology for palaeoenvironmental change

The OSL chronology generated by this study (Table 2) was integrated with published ages (Barrows et al., 2014; Fitzsimmons et al., 2014), divided into age groups, and summarised in Table 3.

(Table 3)

The chronology of post-lunette reactivation is presented visually in Figure 4. On this map, sediment type and antiquity are differentiated by colour. Alluvial fans and sheetwash are shown in blue-green, aeolian reactivation of the lunettes is indicated by yellow-brown colours, and linear dune activity surrounding the lakes is shown in red.

(Figure 4)

Figure 4 provides a spatial and chronological overview of sedimentary reactivation of the post-lake lunettes and provides a first organisation of the synthesised chronology which is discussed in more detail in Section 5.

4.4 Archaeological survey and artefact analysis

Archaeological traces are present in the post-lake sedimentary units on the Lake Mungo lunette, attesting to continued land-use and occupancy after the overflow system dried out. However, the activity traces that accumulated in the post-lake aeolian sands (Unit F) and alluvial fans (Unit G) are much less abundant than predicted on the basis of their areas of exposure (Table S1; Figure S7), which is consistent with the observation that they make up < 9% of the activity traces preserved in the central Mungo lunette study area (Table S2). This suggests that significant shifts in land use, occupancy and patterns of mobility took place during this time, related, at least in part, to changes in the distribution and abundance of critical resources, like water and staple plant foods.

Clusters of chipped stone artefacts are by far the most abundant trace of past human activity in the post-lake lunette sediments (63%), although hearths (~ 17%) and isolated finds (~ 20%), are also part of the record (Table S3). Most hearths consist of heat retainers, occasionally made from carbonate nodules but mostly from material collected from termite mounds. Two consist of a lens of disseminated charcoal, representing the final remnants of hearths eroded away in antiquity. Food remains and/or tools are rarely found in association with these hearths but a few chipped stone tools, highly fragmented terrestrial mammal bones and pieces of emu egg-shell were documented at two hearths (including one of the charcoal lenses). The isolated finds include one shell tool, two grindstones and some manuports, unworked blocks of sandstone, quartzite and nodules of silcrete that were carried to the lunette, which is naturally devoid of workable rocks. In view of the materials preserved, initial efforts to understand how people responded to the palaeoenvironmental changes associated with the avulsion of the Lachlan River have focused on the information that can be gleaned from the chipped stone artefacts, found in the post-lake aeolian sediments that accrued on the crest and lee of the Lake Mungo lunette. Analysis of these assemblages was designed to investigate whether the accumulation of fewer activity traces in the post-lake sediments was related in any way to increased mobility, given that water sources would have been smaller, more dispersed, and a greater proportion of them more ephemeral, than when the overflow system was operating.

Only 1% of the clusters of stone artefacts in these sediments preserve in situ artefacts; the rest are surface scatters made up either of artefacts struck from the same block of raw material (19%) or refitting sets of artefacts (80%). As such, they provide remarkable insights into episodes of stone-working activity that took place on the lunette, but to generate information about the technological system of which they were a part, they have been analysed and interpreted as an aggregated assemblage (Spry, 2014).

To investigate changes in the frequency and/or distance and/or duration of moves between residential campsites, and between campsites and activity loci, archaeologists try to identify the strategies people used to ensure that they had raw materials and/or tools, where and when they were needed (Kuhn 1995). Inferences about the strategy employed in any particular situation are usually based on information generated about the form in which particular raw materials of different origin and knapping quality were introduced to, and taken away from, different locations on the landscape, as well as the types of stone working techniques used and types of tools produced. This includes information about the way in which and the intensity with which cores were reduced, the types of tools produced, including the relative abundance of long use-life tools to those made, used and discarded on-site, and the strategies used to replace or rejuvenate them (eg. Bleed, 1986; Andrefesky, 1994; Kuhn, 1994; Nelson, 1991). Mobility can also been assessed using ratios that estimate the selective removal and transport of cortical material and cores between different locations on the landscape (eg. Douglass et al., 2008; Phillips et al., 2016), but the wide size range of the cobbles and boulders encountered at the silcrete outcrops in the Willandra Lakes region, as well as the presence of both cortical and non-cortical material, precludes their application to artefact assemblages in this area (Kurpiel, 2017).

To find out whether the chipped stone artefacts found in the post-lake aeolian sediments (Unit F) indicate a shift in mobility, they were compared to those found in the underlying Last Glacial Maximum age sediments (Unit E/Zanci; Table S4; Figure S7). During both time periods, most of the material for making tools was obtained from outcrops of silcrete that lie within 5–80 km of the central Mungo lunette, although small quantities of higher-quality quartzite, available within 30 - 80 km, were also used (Kurpiel, 2017). However, after the lakes dried out, a smaller proportion of the cores carried onto the lunette were made from cobbles or slabs and greater proportion were made from flakes or tools, and more cortex had been removed from these before they arrived on the lunette. This suggests that after the lakes dried out, raw material was more often carried around the landscape in the form of smaller, lighter and more prepared cores.

The cores and flakes in the stone clusters indicate more efficient reduction of the cores carried to the lunette after lake retreat, since more elongate flakes with were produced at this time than during the LGM. A greater proportion of these more elongate flakes exhibit evidence of re-sharpening before they were discarded than do other artefacts, suggesting that after the lakes dried out, tools with greater length of cutting edge/unit mass were more likely to be carried around and re-worked as needed. Although the composition of the stone clusters indicates that some tools were made, used and discarded on the lunette during the post-lake period, the presence of small, backed artefacts also suggests that these small, highly portable tools were also replaced during visits to the lunette (Spry, 2014).

Taken together, these features of the Unit F chipped stone assemblage suggest that once the lakes dried out, there was greater emphasis on provisioning individuals with tools and highly portable cores than provisioning the landscape with raw material. In contrast, the characteristics of LGM assemblages from the same part of the lunette suggest that provisioning the landscape with raw material was the predominant strategy employed at that time (Kurpiel, 2017). This suggests that people were more mobile after the lakes dried out and that a change in stone technology was one of the ways in which they responded to the altered environmental conditions.

5. Discussion

5.1 Holocene palaeoenvironments on the southeastern Australian desert margins

Subsequent to final lake retreat around 15 ka, the Mungo and Durthong lunettes experienced multiple phases of enhanced aeolian reactivation, and two phases of water-lain erosion and sheetwash (Table 3, Figure 4). The most recent phase of aeolian reactivation, spanning the last c. 130 years and corresponding to the Anthropocene, is coeval with intensified pastoralism following European settlement of the area, and is discussed in Section 5.3.

Figure 5 provides a timeline for palaeoenvironmental change in the Willandra over the post-lunette period, based on a dichotomy between aeolian conditions interpreted to reflect relative aridity, and wetter conditions represented by alluvial fan and sheetwash deposition. Alluvial fan and sheetwash may have been deposited either under sustained or catastrophic wetter conditions.

(Figure 5)

The earliest period of post-lake lunette reactivation appears to be a transitional phase of laminated aeolian sediments grading without unconformity upwards from the Unit E (Zanci) oscillating and regressing lake event. This period provides an aggregate age of 13.5 ± 1.5 ka (n=4) and is coeval with linear dune accumulation on the western shoreline dating to 14.2 ± 1.3 ka (Barrows et al., 2014). The gradation from laminated Unit E pelletal clay-quartz sand lunette couplets into a post-lake aeolian depositional regime indicates a more gradual evolution of the sediment sequence than has previously been assumed (Bowler et al., 1998). The dominance of aeolian activity suggests persistently dry climatic conditions in the region which is supported by a coeval peak in nearby desert dune activity from 14.5-12 ka in the western MDB (Lomax et al., 2011), as well as inferred aridity from linear dune reactivation in the Strzelecki Desert to the northwest (Fitzsimmons et al., 2007). It is likely that the c. 13.5 ka aeolian event postdates a slightly wetter period as demonstrated by accelerated speleothem growth from 20-15 ka in the Flinders Ranges, several hundred kilometres to the west (Cohen et al., 2011), indicating increased effective precipitation associated with temporary northward penetration of the westerlies into inland southern Australia (Barrows and Juggins, 2005). Palynological records from the nearby Darling River Anabranch lakes suggest that vegetation during the 18-9 ka period was a heterogeneous mosaic of tall and low shrublands (Cupper, 2005), not inconsistent with semi-arid conditions conducive to aeolian activity.

Aeolian reactivation peaked again around 8.2 ± 0.6 ka (n=2), following a break in the stratigraphic record which cannot clearly be associated with stability in the form of pedogenesis or erosion and unconformity. We interpret this phase to correspond to the next phase of relative aridity in the region, particularly given the evidence for a coeval increase in dune activity in the western MDB (Lomax et al., 2011), as well as sediment provenancing indicating that the MDB dominated the aeolian dust load transported eastwards into the southeast Australian highlands at this time (Marx et al., 2009).

Two mid-Holocene ages, averaging 4.3 ± 1.3 ka, correspond to alluvial fan deposition onto the Mungo lake floor. We interpret this phase to correspond to relatively wetter conditions in the Willandra region. Our interpretation is consistent with evidence for more humid climates during the mid-Holocene across southeastern Australia, in the form of lake recharge in a number of basins (Bray et al., 2012; Cohen et al., 2011, 2012; Fitzsimmons and Barrows, 2010; Gell et al., 2005; Gouramanis et al., 2010; Jones et al., 1998; Magee et al., 1995) and increased river discharge (Cohen and Nanson, 2007; Gingele et al., 2007).

Linear dune activity persists in the area throughout the period c. 4-1 ka (also Lomax et al., 2011), however, without more detailed sedimentological analyses (e.g. Fitzsimmons et al., 2009), this activity cannot be inferred to represent any more than intermittent partial reactivation, as is common in a semi-arid environment (Hesse and Simpson, 2006). The most recent 4 ky oversaw a general decline of woodland vegetation in the Willandra region (Cupper et al., 2000; Cupper, 2005), interpreted to represent the establishment of semi-arid conditions that have persisted to the present day (Bray et al., 2012) and which are associated with the development of enhanced El Niño-Southern Oscillation (ENSO) variability (Shulmeister and Lees, 1995, Moy et al., 2002, Quigley et al., 2010) and overall aridification of the southern half of the continent (Moros et al., 2009).

The most recent millennium records two apparently distinct phases of aeolian reactivation of the Mungo and Durthong lunettes, defined by weighted average as 0.75 ± 0.19 ka (n=3) and 0.23 ± 0.04 ka (n=3). The earlier phase appears to immediately postdate a brief period of pluvial conditions, recorded by lake filling in the Frome-Callabonna basin to the northwest (Cohen et al., 2011; 2012) and flooding in the Barrier Ranges north of the Willandra (Jansen and Brierley, 2005). The wet conditions have been interpreted to correspond to a brief phase of intensified high-pressure systems over the Indian Ocean and Tasman Sea propagating northward penetration of a trough into inland Australia (Cohen et al., 2012). It is unclear what mechanisms may have driven the aeolian reactivation in the Willandra shortly thereafter, nor for the arid peak c. 230 years ago.

Whilst our study provides the most substantial record yet for palaeoenvironmental change on the semi-arid southeastern Australian desert margins, distinct from the main lunette archives that represent more distal climatic influences, it is subject to several limitations. The limited sample number reduces confidence in identifying peak phases in aeolian or sheetwash accumulation, although the pattern is consistent with other archives across southeastern Australia. Luminescence dating of the aeolian sediments only provides the most recent age of activity and cannot inform us about the duration of depositional events. This study may incorporate some spatial and temporal bias, since sampling at Lake Mungo focuses on the central portion of the lunette, and therefore does not consider aeolian reactivation and spatially variable sediment supply along the length of this landform (Fitzsimmons, 2017). The limited degree of correlation between aeolian reactivation events between the Mungo and Durthong lunettes, the latter of which was sampled at multiple points along the lake margins, may underscore this limitation.

5.2 Implications for human adaptation to landscape change in desert margins

The archive of activity traces preserved by the post-lake reactivation of the Mungo lunette has significant potential for filling a longstanding gap in our knowledge of early Holocene settlement in Australia's desert margins (Hiscock, 2008; Smith 2013). It is important to recognize, however, that understanding of post-lake settlement history in this area is constrained by the existence of landforms that were accumulating sediment during the post-lake period, the landforms whose archaeological traces have been documented up to now, and the ways in which they have been studied. At present, integrated archaeological and geological data are available only for the central Mungo lunette, which represents a 2 km^2 sample from one 33 km-long landform, in a semi-arid landscape in which foraging ranges may have been extensive (perhaps up to 4,500 km^2; Marlowe, 2005). Legacy data from the 1970s provide a less systematic record of 359 sites scattered across the Willandra Lakes region, with less reliable age attribution, however, ~ 4% of these are attributed to the post-lake period and ~ 10% to the late Holocene. Together, these data highlight the need to re-evaluate long-standing interpretations about the post-lake history of settlement in the Willandra (eg. Allen, 1974; 1990) and provide a basis for comparing continent-wide models of demographic change (eg. Williams et al. 2013; 2015a; 2015b) with the documented settlement history of one, climatically sensitive locale.

Following an initial phase of research in the Willandra Lakes (1968-1972), it was argued that people largely abandoned the area after the lakes dried out, shifting the focus of their lives to the better watered corridors bounding the Murray or Darling Rivers (Allen, 1974; 1990), a suggestion supported by an apparent absence of hearths at Lake Mungo in the time range between 19 and 5 ka (Barbetti, 1973). Ethno-historic information about the subsistence activities of the Barkindji/Paakantyi, who lived along the Darling River during the late nineteenth century, provided the rationale for arguing that the Willandra Lakes had become part of the riverine hinterland, visited only following good falls of winter rain when seeds collected from a range of shrubs and grasses provided a predictable food staple (Allen 1974). At the time, the idea of seasonal transhumance as a fundamental of the hunter-gatherer adaptation was pervasive (Higgs et al., 1967), but in the intervening decades, numerous studies from around the world have shown that most social groups ranged across the interior ranges *or* the coastal plains (eg. Sealy, 2006), the riverine corridor *or* the arid plains beyond (Pardoe 2006).

The systematic data that are the focus of this study identify three aspects of this initial account of settlement history that need re-evaluating. Firstly, people did not abandon the Willandra Lakes region when the overflow system ceased to operate as such: traces of their activities are found not only in the post-lake sediments that accrued on the Mungo lunette (Figure S6), but also in other landforms within the overflow system (Clark, 1987). Secondly, seeds were not incorporated into the diet to replace the loss of aquatic resources after the lakes dried out (Allen 1974, 1990). Seed-processing was part of the subsistence repertoire during the Last Glacial Maximum, although which seeds were being ground, the contribution they made to the overall diet, and how this may have changed over time, is not yet known (Fullagar et al. 2015a, 2015b). Furthermore, evidence for the exploitation of fish and shellfish is largely restricted to the Last Glacial Maximum (Bowler et. al 2012) and when the overflow system was active, these were probably fall-back foods rather than a focus of the diet (Stern et al. 2103).

Although the activity traces found in the post-lake sediments on the Mungo lunette are much less abundant than those found in the underlying strata, at this stage in research there is no rationale for attributing this to a demographic change rather than a change in land use and occupancy. Information generated from the analysis of the stone artefacts certainly indicates an increase in relative mobility, although it is not yet known whether this was associated with shifts in diet and foraging activities, social networks or a pattern of intermittent occupancy. At present the Holocene activity traces cannot be parsed into clusters representing different episodes of relatively wetter or drier conditions because the incipient soil horizons which would otherwise provide a means of achieving this, are not laterally extensive. Only direct dating of a large sample of hearths preserved in different landforms would permit a finer-scale analysis of human responses to fluctuating local conditions over shorter time spans (e.g. Fanning et al., 2008; Holdaway et al., 2005).

Models of demographic history, based on analysis of the geographic and temporal distribution of radiocarbon age determinations from archaeological sites across the continent, suggest an overall decline in population size during the LGM, as well as abandonment of areas without reliable surface water (Williams et al., 2013; 2015a; 2015b). The Willandra Lakes overflow system, which received large volumes of spring melt-water from the south east highlands at this time, is identified as a LGM refugium (Williams et al., 2013). During the early Holocene populations rebounded and colonised or re-colonised areas that had been uninhabitable previously (Williams et al. 2013; 2015b). At present, there is insufficient detail in the Willandra's Holocene record to attempt comparisons with the subsequent changes identified though the analysis of the time-series data (Williams et al. 2015b).

The settlement history of the Willandra Lakes region is based on substantively different data: the number of discrete activity traces, like cooking hearths or patches of tool-making debris, contained within sedimentary envelopes whose bracketing ages have been established and which were laid down by a single sedimentary system. As such, it presents an internally consistent set of data for comparing the density of activity traces in sediments representing different time intervals and correspondingly different palaeoenvironmental conditions. The density of sites encapsulates a number of variables including the number and the sizes of social groups visiting the area, as well as the frequency and duration of their visits. To establish whether there were changes in all or some of these variables, and whether those changes were influenced by demographic or behavioural changes or both, requires additional information about diet and foraging activities, technologies and social networks, currently being sought.

The stone artefact assemblages studied up to now, indicate that people were relatively more mobile following final lake retreat but mobility also encapsulates a number of variables, including the frequency, distance and duration of moves between campsites and between camps and activity loci. The relative import of the variables contributing to observations of 'greater mobility' cannot be disentangled without more detailed information about diet and foraging strategies, and the use made of materials from different geographic locations, than is presently available. For this reason, it is premature to conclude that a higher density of activity traces and evidence for reduced mobility in the LGM record indicates that Lake Mungo was a refugium or that a lower density of sites together with evidence for greater mobility in the post-LGM record reflects the movement of people out of the Willandra Lakes region once surface water was more dispersed and less abundant.

(Figure 6)

5.3 Anthropocene impact of post-colonial land use on desert margin landscapes associated with the introduction of pastoral activities in the 1860s

The first Europeans to arrive in the Willandra belonged to the exploration party of Charles Sturt (Sturt, 1833; Sturt, 1984), who described a barren country of sandy plains following expeditions in 1833 and 1844-5. Based on the chronology presented in our study, these decades would most likely correspond to the tail end of the dry phase III, thus providing confidence in our age estimates and interpretation of the post-lacustrine sediment records. Despite the pessimistic accounts, European settlers brought cattle and sheep to the region from the 1860s (Withers, 1989). Two ages for alluvial fans on the Mungo lake floor averaging 0.12 ± 0.02 (at 95% confidence), indicating wetter conditions than experienced by Sturt's company c. 1870-1910 CE, might provide some basis for their optimism.

The intense drought in the years around Australia's federation (c. 1901 CE) brought about a return to arid conditions in the Willandra area. During this period, however, aeolian reactivation accompanying the dry years (0.10 ± 0.01 ka; n=8) was exacerbated by erosion through grazing of stock and the introduction of rabbits, as well as the removal of stabilising vegetation (Cupper, 2005; Cupper et al., 2000). European land use in the MDB over the last 150 years has affected enormous changes across the landscape, including increased salinity and sedimentation in lagoons associated with the MDB rivers (Gell et al., 2005, 2009).

Reorganisation of the sedimentary system in response to the intense impact of European land use on this vulnerable desert marginal environment continues to the present day in the form of accelerating erosion of the lunette sediments and their redeposition by wind on the crest and lee slopes, as well as catastrophic sheetwash onto the lake floors following even moderate rainfall events. This legacy has substantial implications for land management in the Willandra Lakes area, even subsequent to cessation of pastoral activities and the establishment of a National Park.

6. Conclusions

The reactivation of lunette sediments in the Willandra Lakes region following final lake retreat provides a valuable insight into the response of desert marginal systems to changing climatic conditions over the Holocene. Our chronology generally corresponds to broader evidence for Holocene environmental change across southeastern Australia. The archaeological traces preserved in the post-lake sediments demonstrate the continued use and occupancy of Lake Mungo area after the overflow system dried out. Although these activity traces are less abundant than those found in the sedimentary envelopes dating to the LGM, it is premature to attribute this to demographic rather than behavioural change, particularly as the artefact analyses indicates that people were relatively more mobile at this time. This study rectifies long-standing mis-perceptions about the history of human settlement in the Willandra Lakes region and lays an important foundation for future research aimed at generating more detailed, landscape-scale information about changes in economy, technology and social networks over the past 15 ky.

Acknowledgements

This research was undertaken with permission from the Elders' Council and the Technical and Scientific Advisory Committee of the Willandra Lakes Region World Heritage Area. We thank the Paakantyi/Barkindji, Ngiyampaa and Mutthi Mutthi Elders for welcoming us into their Country and for their support of this work. We are especially indebted to Daryl Pappin, the Mungo Archaeology Project's Cultural Heritage Officer, for his dedicated assistance during fieldwork. Rudy Frank, Paul Penzo-Kajewski and students from the Department of Archaeology and History at La Trobe University provided invaluable assistance in the field. We are grateful to Ian Wakefield for permission to work on Top Hut station and to the staff of

Mungo National Park for facilitating fieldwork on the Lake Mungo lunette. We thank Paul Penzo-Kajewski from the Department of Archaeology and History at La Trobe University for his work on the MapInfo files, Steffi Albert, from the Max Planck Institute for Evolutionary Anthropology in Leipzig, for preparing the samples in the OSL laboratory and Elizabeth Foley and Katherine Thomas for discussions of an earlier draft of this paper. This work was funded by grants from the Australian Research Council (DP1092966 and LP0775058) and by a Higher Degree Research Grant and Post-doctoral Write-up Grant awarded to Caroline Spry by the Faculty of Humanities and Social Sciences at La Trobe University.

Table captions

Table 1. OSL sample codes, locations and stratigraphic units.

Table 2. Equivalent dose (D_e), dose rate data (attenuated) and OSL age estimates for the Lake Mungo and Durthong lunette samples. Single aliquot D_es and age estimates are shown in plain text; single grain results are in italics.

Table 3. Synthesis of post-lacustrine OSL ages and proposed scheme for aeolian reactivation. Ages in italics (marked with asterisk) represent linear dune activity surrounding the lake basins.

Figure captions

Figure 1. (left-right) Location of the Willandra Lakes system in the semi-arid zone of southeastern Australia; the Willandra Lakes system and distribution of lunette dunes, with the Mungo and Durthong lunettes highlighted in orange; location of sampling sites along the Durthong and Mungo lunettes, colour-coded according to study.

Figure 2. Photographs of Locality 973659 in the central Lake Mungo lunette: A. Looking north across the erosion basin showing the four residuals sampled, including the location and age of the OSL sample collected from Residual 3. B-D. Photographs of Residuals 4, 1 and 2 respectively (displayed as observed from left to right in photo A), showing sampling locations and ages.

Figure 3. Refitting sets of stone artefacts found on the floor of the erosion basin at Locality 973659, in the central Mungo lunette. A. Refit set 1262: 774-777f; B. Refit set 1537: 1482-1486; C. Refit set 1488f; Refit set 1039: 1339-1353t.

Figure 4. Spatial distribution of sediment ages from the Lake Durthong and Mungo lunettes, colour-coded according to depositional phase and type. Depositional phases are summarised in the legend, together with the study from which they derive.

Figure 5. Probability distribution functions highlighting peak probability of aeolian reactivation phases as well as individual ages for coeval linear dune activity, contrasting with periods of outwash fan activity onto the Lake Mungo lake floor. Climatic phases and possible relevant events are listed in black text above the graph: HCO (Holocene Climatic Optimum), MWP (Medieval Warm Period), LIA (Little Ice Age), arrival of Europeans and establishment of pastoral activity (1860s-), 1937-1947 drought, introduction of myxoma virus to rabbit populations resulting in reduced numbers (1950s).

References

Allen H (1972) *Where the crow flies backwards: man and land in the Darling Basin*. PhD Thesis, Australian National University, Australia.

Allen H (1974) The Bagundji of the Darling Basin: cereal gatherers in an uncertain environment. *World Archaeology* 5: 309–322.

Allen H (1990) Environmental history in southwestern New South Wales during the Late Pleistocene. In Gamble C and Soffer O (eds) *The World at 18000 BP. Volume 2. Low Latitudes*. London: Unwin Hyman, pp.296–321.

Allen H (1998) Reinterpreting the 1969–1972 Willandra Lakes archaeological surveys. *Archaeology in Oceania* 33: 207–220.

Anderson M, Capel J, Galloway D, Holmes D, Houghton G, Male L, Moss S, Potter J, Pyemont B, Thorley P, Yeomans A and Russell G (1984) Aboriginal occupation of the Lake Mungo region during mid–late Holocene Times. *Quaternary Australasia* 2: 16–23.

Andrefsky W (1994) Raw material availability and the organization of technology. *American Antiquity* 59: 21–34.

Bagnold RA (1941) *The Physics of Blown Sand and Desert Dunes*. London: Methuen and Co.

Barbetti M and Allen H (1972) Prehistoric man at Lake Mungo, Australia, by 32,000 years BP. *Nature* 240: 46–48.

Barbetti M and McElhinny M (1972) Evidence of a geomagnetic excursion 30,000 yr BP. *Nature* 239: 327–330.

Barbetti M (1973) *Archaeomagnetic and radiocarbon studies of Aboriginal fireplaces*. PhD Thesis, Australian National University, Australia.

Barrows TT, Fitzsimmons KE, Stern N, Tumney J and Grün R (2014) Environmental change at Lake Mungo, Willandra Lakes World Heritage Area, semi-arid Australia. In: *Australasian Quaternary Association Biennial Meeting*, Mildura, Australia, 29 June–4 July 2014.

Barrows TT and Juggins S (2005) Sea-surface temperatures around the Australian margin and Indian Ocean during the Last Glacial Maximum. *Quaternary Science Reviews* 24: 1017–1047.

Bell WT (1991) Thermoluminescence dates for the Lake Mungo Aboriginal fireplaces and the implications for radiocarbon dating. *Archaeometry* 33: 43–50.

Bleed P (1986) The optimal design of hunting weapons: maintainability or reliability. *American Antiquity* 51: 737–747.

Bøtter-Jensen L 1997 Luminescene techniques: instrumentation and methods. *Radiation Measurements* 27 (5/6): 749–768

Bøter-Jensen L, Bulur E, Duller GAT and Murray AS 2000 Advances in luminescence instrument systems. *Radiation Measurements* 32: 523–528

Bøtter-Jensen L, Mejdahlb V and Murray AS 1999 New light on OSL. *Quaternary Science Reviews* 18: 303–309

Bowler JM (1983) Lunettes as indices of hydrologic change: a review of the Australian evidence. *Proceedings of the Royal Society of Victoria* 95: 147–168.

Bowler JM (1998) Willandra Lakes revisited: environmental framework for human occupation. *Archaeology in Oceania* 33: 120–155.

Bowler JM, Gillespie R, Johnston H and Boljkovac K (2012) Wind v water: glacial maximum records from the Willandra Lakes. In: Haberle S and David B (eds) *Peopled Landscapes: Archaeological and Biogeographic Approaches to Landscapes*. Canberra: The Australian National University, pp.271–296.

Bowler JM, Johnston H, Olley JM, Prescott JR, Roberts RG, Shawcross W and Spooner NA (2003) New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421: 837–840.

Bowler JM, Jones R, Allen H and Thorne AG (1970) Pleistocene human remains from Australia: a living site and human cremation from Lake Mungo, western New South Wales. *World Archaeology* 2: 39–60.

Bowler JM and Magee JW (1978) Geomorphology of the Mallee region in semi-arid northern Victoria and western New South Wales. *Proceedings of the Royal Society of Victoria* 90: 5–25.

Bowler JM and Magee JW (2000) Redating Australia's oldest human remains: a sceptic's view. *Journal of Human Evolution* 38: 719–726.

Bowler JM, and Price DM (1998) Luminescence dates and stratigraphic analyses at Lake Mungo: review and new perspectives. *Archaeology in Oceania* 33: 156–168.

Bowler JM and Thorne A (1976) Human remains from Lake Mungo: discovery and excavation of Lake Mungo III. In: Kirk R and Thorne A (eds) *The Origin of the Australians*. Canberra: Australian Institute of Aboriginal studies, pp.127–138.

Bowler JM, Thorne AG and Polach HA (1972) Pleistocene man in Australia: age and significance of the Mungo skeleton. *Nature* 240: 48–50.

Bray PS, Jones CM, Fallon SJ, Brocks JJ and George SC (2012) Radiocarbon analysis of halophilic microbial lipids from an Australian salt lake. *Quaternary Research* 77: 104–109.

Clark PM (1987) *Willandra Lakes World Heritage Area archaeological resource study*. Report for the New South Wales Department of Planning and the Western Lands Commission of NSW, Sydney, Australia.

Cohen TJ and Nanson GC (2007) Mind the gap: an absence of valley-fill deposits identifying the Holocene hypsithermal period of enhanced flow regime in southeastern Australia. *The Holocene* 17: 411–418.

Cohen TJ, Nanson GC, Jansen JD, Jones BG, Jacobs Z, Larsen JR, May J-H, Treble P, Price DM and Smith AM (2012) Late Quaternary mega-lakes fed by the northern and southern river systems of central Australia: varying moisture sources and increased continental aridity. *Palaeogeography, Palaeoclimatology, Palaeoecology* 356–357: 89–108.

Cohen TJ, Nanson GC, Jansen JD, Jones BG, Jacobs Z, Treble P, Price DM, May J-H, Smith AM, Ayliffe LK and Hellstrom JC (2011) Continental aridification and the vanishing of Australia's megalakes. *Geology* 39: 167–170.

Cupper ML (2005) Last glacial to Holocene evolution of semi-arid rangelands in southeastern Australia. *The Holocene* 15: 541–553.

Cupper ML, Drinnan AN and Thomas I (2000) Holocene palaeoenvironments of salt lakes in the Darling Anabranch region, south-western New South Wales, Australia. *Journal of Biogeography* 27: 1079–1094.

Dare-Edwards AJ (1979) *Late Quaternary soils on clay dunes of the Willandra Lakes, New South Wales*. PhD Thesis, Australian National University, Australia.

Doerschner N, Hernandez M and Fitzsimmons KE (2016) Sources of variability in single grain dose recovery experiments: Insights from Moroccan and Australian samples. *Ancient TL* 34: 14–25.

Douglass MJ, Holdaway SJ, Fanning P and Shiner J (2008) An assessment and archaeological application of cortex measurement in lithic assemblages. *American Antiquity* 73: 513–526.

Duller G (2008) Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas* 37: 589–612.

Fanning PC, Holdaway SJ and Rhodes EJ (2008) A new geoarchaeology of Aboriginal artefact deposits in western NSW, Australia: establishing spatial and temporal geomorphic controls on the surface of the archaeological record. *Geomorphology* 101: 524–532.

Fitzsimmons KE (2011) An assessment of the luminescence sensitivity of Australian quartz with respect to sediment history. *Geochronometria* 38: 199–208.

Fitzsimmons KE (2017) Reconstructing palaeoenvironments on desert margins: new perspectives from Eurasian loess and Australian dry lake shorelines. *Quaternary Science Reviews* 171: 1–19.

Fitzsimmons KE and Barrows TT (2010) Holocene hydrologic variability in temperate southeastern Australia: an example from Lake George, New South Wales. *The Holocene* 20: 585–597.

Fitzsimmons KE, Gell PA, Bickford S, Barrows TT, Mooney SD and Denham TP (2007) The OZPACS database: a resource for understanding recent impacts on Australian ecosystems. *Quaternary Australasia* 24: 2–6.

Fitzsimmons KE, Stern N and Murray-Wallace CV (2014) Depositional history and archaeology of the central Lake Mungo lunette, Willandra Lakes, southeast Australia. *Journal of Archaeological Science* 41: 349–364.

Fitzsimmons KE, Stern, N, Murray-Wallace CV, Truscott W, Pop C (2015) The Mungo mega-lake event, semi-arid Australia: non-linear descent into the last ice age, implications for human behavior. *PLoS ONE* 10: e0127008.

Foley E, Spry C and Stern N (2017) Establishing the integrity and stratigraphic origin of stone artefact scatters on the surface of the Lake Mungo lunette in south-eastern Australia. *Journal of Archaeological Science: Reports* 13: 547–557.

Fullagar R, Hayes E, Stephenson B, Field J, Matheson C, Stern N and Fitzsimmons KE (2015a) Evidence for Pleistocene seed grinding at Lake Mungo, south-eastern Australia. *Archaeology in Oceania* 50 (S1): 3–19.

Fullagar R, Hayes E, Stephenson B, Field J, Matheson C, Stern N and Fitzsimmons KE (2015b) The scale of seed grinding at Lake Mungo. *Archaeology in Oceania* 50: 177–179.

Galbraith RF, Roberts RG, Laslett GM, Yoshida H and Olley JM (1999) Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part 1, Experimental design and statistical models. *Archaeometry* 41: 339–364.

Gell P, Bulpin S, Wallbrink P, Bickford S and Hancock G (2005) Tareena Billabong: a palaeolimnological history of an everchanging wetland, Chowilla Floodplain, lower Murray-Darling Basin. *Marine and Freshwater Research* 56: 441–456.

Gell P, Fluin J, Tibby J, Hancock G, Harrison J, Zawadzki A, Haynes D, Khanum S, Little F and Walsh B (2009) Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray-Darling Basin, Australia. *Geomorphology* 108: 122–126.

Gingele F, De Deckker P and Norman M (2007) Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray Mouth. *Earth and Planetary Science Letters* 255: 257–272.

Gouramanis C, Wilkins D and De Deckker P (2010) 6,000 years of environmental changes recorded in Blue Lake, South Australia, based on ostracod ecology and valve chemistry. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297: 223–237.

Guérin G, Mercier N and Adamiec G (2011) Dose-rate conversion factors: update. *Ancient TL* 29: 5–8.

Hesse PP and Simpson RL (2006) Variable vegetation cover and episodic sand movement on longitudinal desert sand dunes. *Geomorphology* 81: 276–291

Higgs ES, Vita-Finzi C, Harris DR and Fagg AE (1967) The climate, environment, and industries of Stone Age Greece. Part 3. *Proceedings of the Prehistoric Society* 33: 1–29.

Hiscock P (2008) *Archaeology of Ancient Australia*. Oxford: Routledge.

Holdaway SJ, Shiner JC and Fanning PC (2005) Absence of evidence or evidence of absence? Understanding chronology of Indigenous occupation of western New South Wales. *Archaeology in Oceania* 40: 33–49.

Jansen JD and Brierley GJ (2005) Pool-fills: a window to palaeoflood history and response in bedrock-confined rivers. *Sedimentology* 51: 901–925.

Johnston H and Clark P (1998) Willandra Lakes archaeological investigations 1968–98. *Archaeology in Oceania* 33: 105–119.

Jones RN, Bowler JM and McMahon TA (1998) A high resolution Holocene record of P/E ratio from closed lakes in Western Victoria. *Palaeoclimates* 3: 51–82.

Kemp J, Pietsch T, Gontz A and Olley J (2017) Lacustrine-fluvial interactions in Australia's Riverine Plains. *Quaternary Science Reviews* 166: 352–362.

Kuhn SL (1994) A formal approach to the design and assembly of mobile toolkits. *American Antiquity* 59: 426–442.

Kuhn SL (1995) *Mousterian Lithic Technology: An Ecological Perspective*. New Jersey: Princeton University Press.

Kurpiel R (2017) *Stone sources in the Willandra Lakes region, in south-eastern Australia: A study of source characterisation and raw material procurement*. PhD Thesis, La Trobe University, Australia.

Lomax J, Hilgers A and Radtke U (2011) Palaeoenvironmental change recorded in the palaeodunefields of the western Murray Basin, South Australia: new data from single grain OSL dating. *Quaternary Science Reviews* 30: 723–736.

Long K, Stern N, Williams IS, Kinsley L, Wood R, Sporcic K, Smith T, Fallon S, Kokkonen H, Moffat I and Grün R (2014) Fish otolith geochemistry, environmental conditions and human occupation at Lake Mungo, Australia. *Quaternary Science Reviews* 88: 82–95.

Long K, Wood R, Williams IS, Kalish J, Shawcross W, Stern N and Grün R (2018) Fish otolith microchemistry: snapshots of lake conditions during early human occupation of Lake Mungo, Australia. *Quaternary International* 463: 29–43.

Magee JW, Bowler JM, Miller GH and Williams DLG (1995) Stratigraphy, sedimentology, chronology and paleohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeography Palaeoclimatology Palaeoecology* 113: 3–42.

Marlowe FW (2005) Hunter-gatherers and human evolution. *Evolutionary Anthropology* 14: 54–67.

Marx SK, McGowan HA and Kamber BS (2009) Long-range dust transport from eastern Australia: a proxy for Holocene aridity and ENSO-type climate variability. *Earth and Planetary Science Letters* 282: 167–177.

Moros M, De Deckker P, Jansen E, Perner K and Telford RJ (2009) Holocene climate variability in the Southern Ocean recorded in a deep-sea sediment core off South Australia. *Quaternary Science Reviews* 28: 1932–1940.

Moy CM, Seltzer GO, Rodbell DT and Anderson DM (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420: 162–165.

Murray AS and Wintle AG (2000) Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32: 57–73

Murray AS and Wintle AG (2003) The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* 37: 377–381.

Nelson MC (1991) The study of technological organization. *Archaeological Method and Theory* 3: 57–100.

Olley JM, Roberts RG, Yoshida H and Bowler JM (2006) Single-grain optical dating of grave-infill associated with human burials at Lake Mungo, Australia. *Quaternary Science Reviews* 25: 2469–2474.

Pardoe C (2006) Becoming Australian: evolutionary processes that structure biological variation from origin to modern times. *Before Farming* 2006 (1).

Pardoe C (2015) Riverine, biological and cultural evolution in southeastern Australia. *Antiquity* 69: 696–713.

Phillipps RS and Holdaway SJ (2016) Estimating core number in assemblages: core movement and mobility during the Holocene of the Fayum, Egypt. *Journal of Archaeological Method and Theory* 23: 520–540.

Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long term variations. *Radiation Measurements* 23: 497–500.

Quigley MC, Horton T, Hellstrom JC, Cupper ML and Sandiford M (2010) Holocene climate change in arid Australia from speleothem and alluvial records. *The Holocene* 20: 1093–1104.

Reimer P, Baillie M, Bard E, Bayliss A, Beck J, Blackwell P, Bronk Ramsey C, Buck C, Burr G, Edwards R, Friedrich M, Grootes P, Guilderson T, Hajdas I, Heaton T, Hogg A, Hughen K, Kaiser K, Kromer B, McCormac F, Manning S, Reimer R, Richards D, Southon J, Talamo S, Turney C, Van der Plicht J and Weyhenmeyer C (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0–50 000 years cal BP. *Radiocarbon* 51: 1111–1150.

Sealy J (2006) Diet, mobility and settlement pattern among Holocene Hunter□Gatherers in Southernmost Africa. *Current Anthropology* 47: 569–595

Shawcross FW and Kaye M (1980) Australian archaeology: implications of current interdisciplinary research. *Interdisciplinary Science Reviews* 5: 112–128.

Shawcross W (1998) Archaeological excavations at Mungo. *Archaeology in Oceania* 33: 183–200.

Shulmeister J and Lees B (1995) Pollen evidence from tropical Australia for the onset of an ENSO-dominated climate at c. 4,000 BP. *The Holocene* 5: 10–18.

Smith MA (2013) *The Archaeology of Australia's Deserts*. New York: Cambridge University Press.

Spry C (2014) *Refitting a past: a comparison of late Pleistocene and Terminal Pleistocene/early Holocene stone tool technology at Lake Mungo, southwestern New South Wales, Australia*. PhD Thesis, La Trobe University, Australia.

Stern N 2015 The archaeology of the Willandra: its empirical structure and narrative potential. In: McGrath A and Jebb MA (eds) *Long History, Deep Time*. Canberra: ANU Press, pp.221–240.

Stern N, Tumney J, Fitzsimmons K and Kajewski P (2013) Strategies for investigating human responses to changes in landscape and climate at Lake Mungo in the Willandra Lakes, southeast Australia. In: Frankel D, Webb J and Lawrence S (eds) *Archaeology in Environment and Technology: Intersections and Transformations*. New York: Routledge, pp.31–50.

Sturt C (1833) *Two Expeditions into the Interior of Southern Australia*. London: Smith, Elder and Co.

Sturt C (1984) [1844–6] *Journal of the Central Australian Expedition* (edited by Waterhouse J). Dover: Caliban Books.

Tumney J (2011) *Environment, landscape and stone technology at Lake Mungo, southwest New South Wales, Australia*. PhD Thesis, La Trobe University, Australia.

Walker M (2005) *Quaternary Dating Methods*. Chippenham: John Wiley and Sons.

Webb S, Cupper ML and Robins R (2006) Pleistocene human footprints from the Willandra Lakes, southeastern Australia. *Journal of Human Evolution* 50: 405–413.

Westaway MC, Cupper ML, Johnston H and Graham I (2013) The Willandra Fossil Trackway: assessment of ground penetrating radar survey results and additional OSL dating at a unique Australian site. *Australian Archaeology* 76: 84–89.

Weston E, Szabó K and Stern N (2017) Pleistocene shell tools from Lake Mungo lunette, Australia: identification and interpretation drawing on experimental archaeology. *Quaternary International* 427: 229–242.

Williams AN, Ulm S, Cook AR, Langley MC and Collard M (2013) Human refugia in Australia during the Last Glacial Maximum and terminal Pleistocene: a geo-spatial analysis of the 25–12ka Australian archaeological record. *Journal of Archaeological Science* 40: 4612–4625.

Williams AN, Veth PM, Steffen W, Ulm S, Turney CSM, Reeves J, Phipps S and Smith M (2015a) A continental narrative: human settlement patterns and Australian climate change over the last 35,000 years. *Quaternary Science Reviews* 123: 91–112.

Williams AN, Ulm S, Turney CSM, Rhode D and White G (2015b) Holocene demographic changes and the emergence of complex societies in prehistoric Australia. *PLoS ONE* 10: e0128661.

Withers M (1989) *Bushmen of the Great Anabranch*. Wentworth: Maxine Withers.

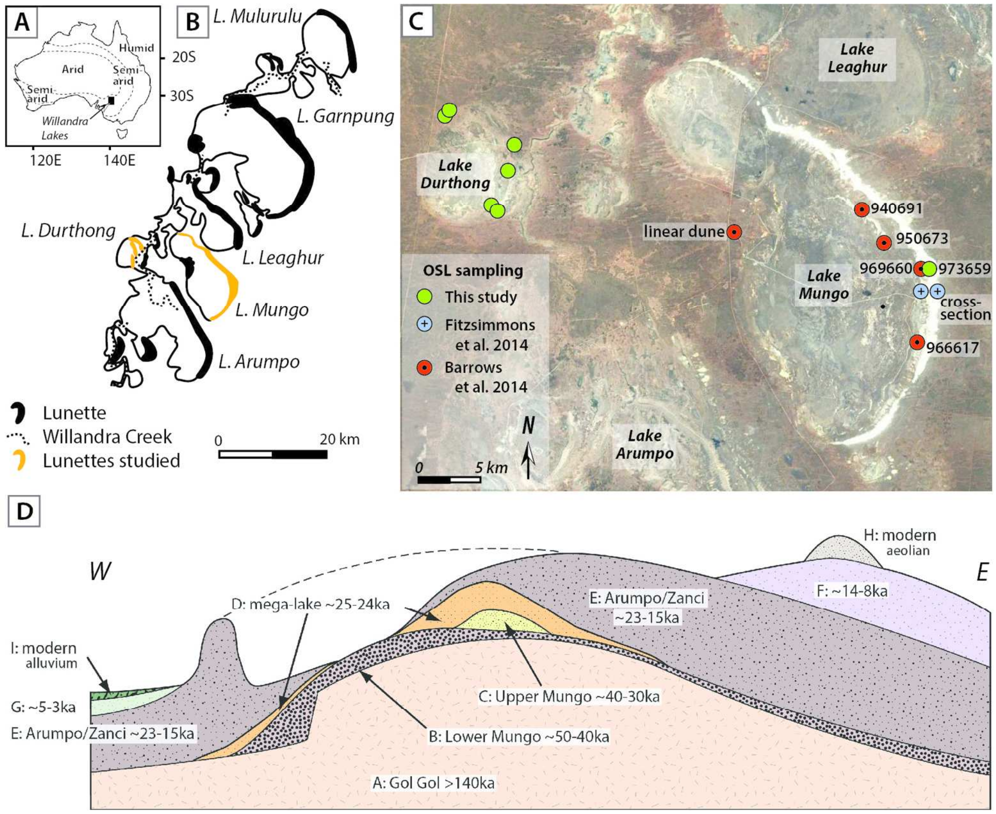


Figure 1. A. Location of the Willandra Lakes system in the semi-arid zone of southeastern Australia. B. The Willandra Lakes system and distribution of lunette dunes, with the Mungo and Durthong lunettes highlighted in orange. C. Location of sampling sites along the Durthong and Mungo lunettes, colour-coded according to studies providing data on the post-lunette period. The numbers are the labels assigned to each of the erosion basins studied. D. Schematic cross-section across the central Mungo lunette (refer to C for location), showing stratigraphic units and their bracketing age estimates.

160x129mm (300 x 300 DPI)

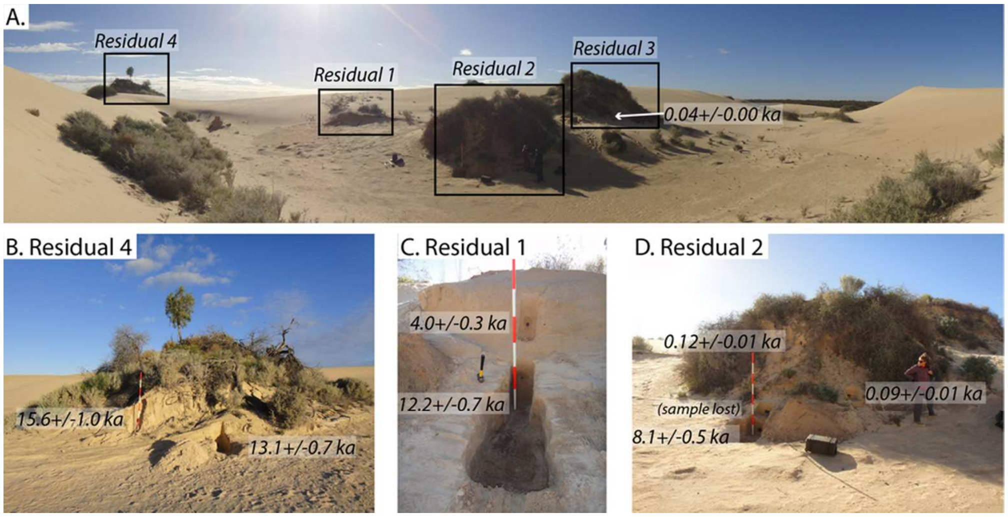


Figure 2. Photographs of Locality 973659 in the central Lake Mungo lunette: A. Looking north across the erosion basin showing the four residuals sampled, including the location and age of the OSL sample collected from Residual 3. B-D. Photographs of Residuals 4, 1 and 2 respectively (displayed as observed from left to right in photo A), showing sampling locations and ages.

88x44mm (300 x 300 DPI)

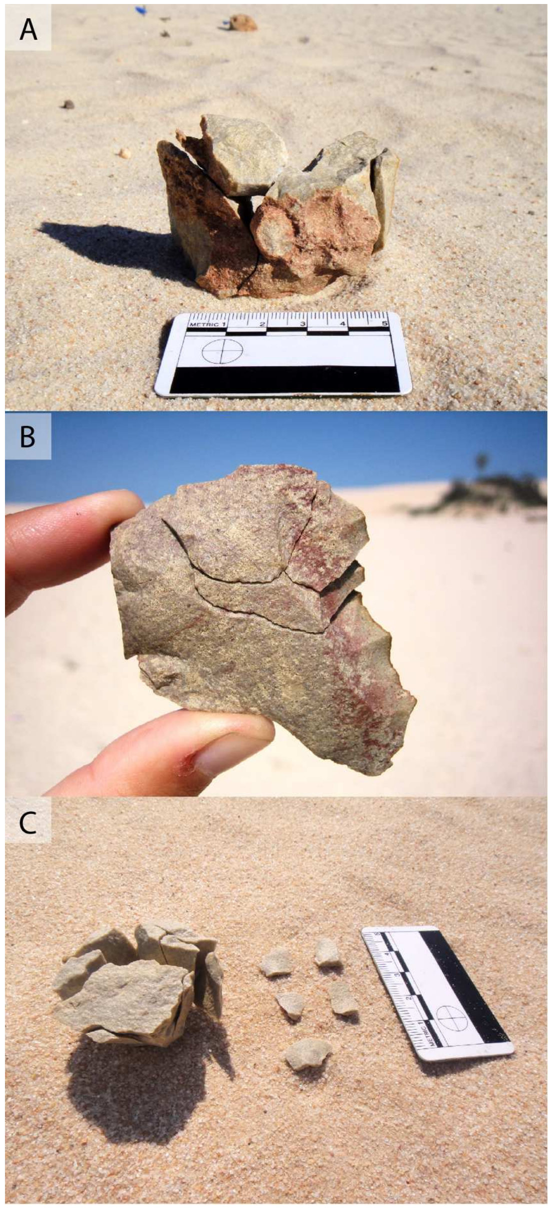


Figure 3. Refitting sets of stone artefacts found on the floor of the erosion basin at Locality 973659, in the central Mungo lunette. A. Refit set 1262: 774-777f; B. Refit set 1537: 1482-1486; C. Refit set 1488f; Refit set 1039: 1339-1353t.

96x213mm (300 x 300 DPI)

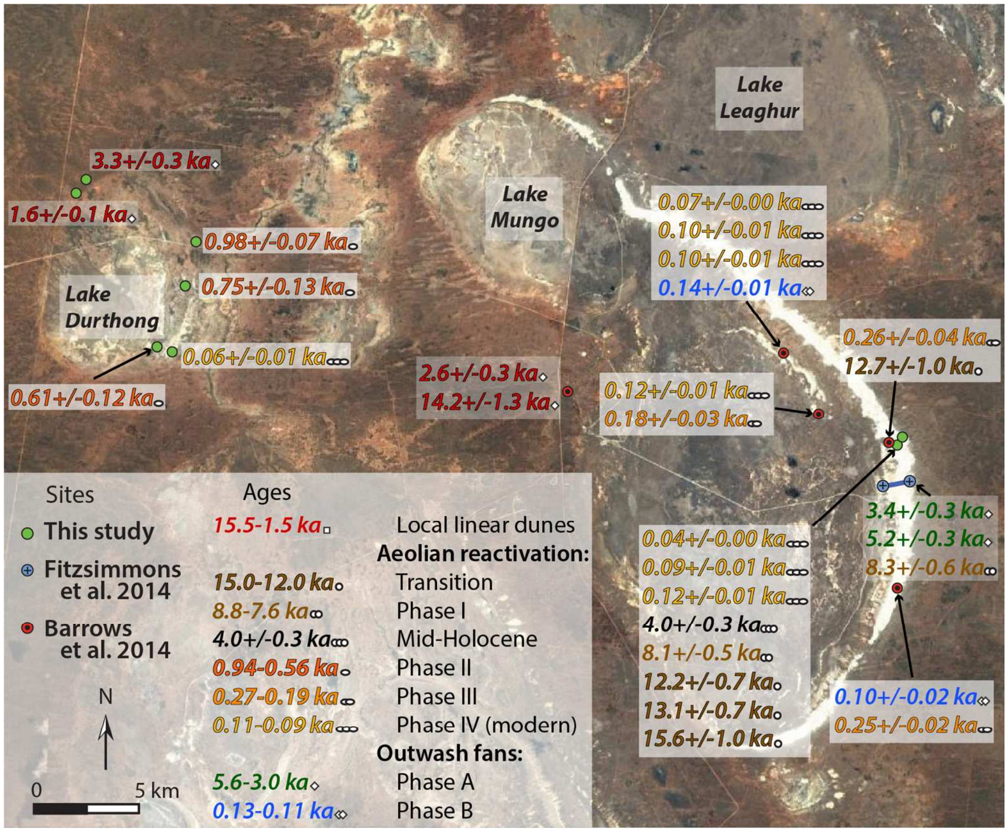


Figure 4. Spatial distribution of sediment ages from the Lake Durthong and Mungo lunettes, colour-coded according to depositional phase and type. Depositional phases are summarised in the legend, together with the study from which they derive.

148x122mm (300 x 300 DPI)

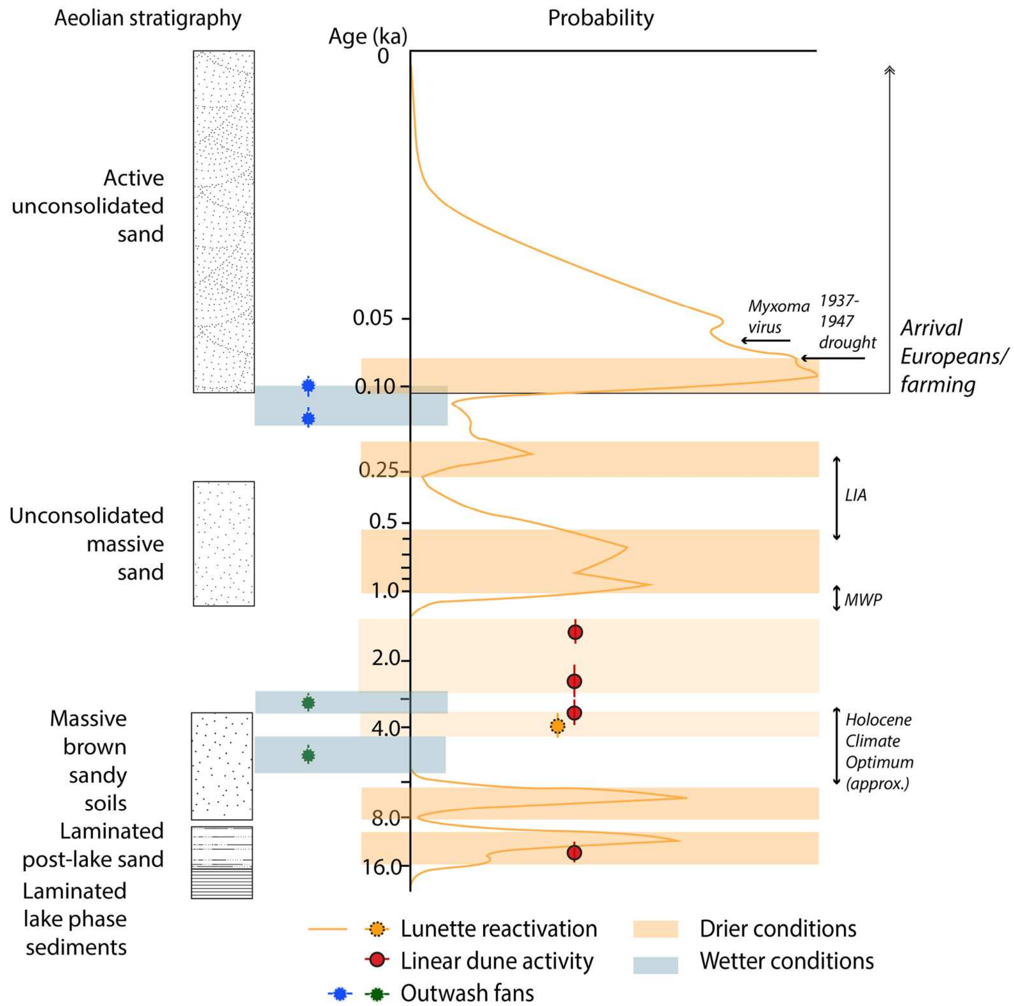


Figure 5. Probability distribution functions highlighting peak probability of aeolian reactivation phases as well as individual ages for coeval linear dune activity, contrasting with periods of outwash fan activity onto the Lake Mungo lake floor. Note the vertical log scale. Climatic phases and possible relevant events are listed in black text above the graph: HCO (Holocene Climatic Optimum), MWP (Medieval Warm Period), LIA (Little Ice Age), arrival of Europeans and establishment of pastoral activity (1860s-), 1937-1947 drought, introduction of myxoma virus to rabbit populations resulting in reduced numbers (1950s).

180x181mm (300 x 300 DPI)

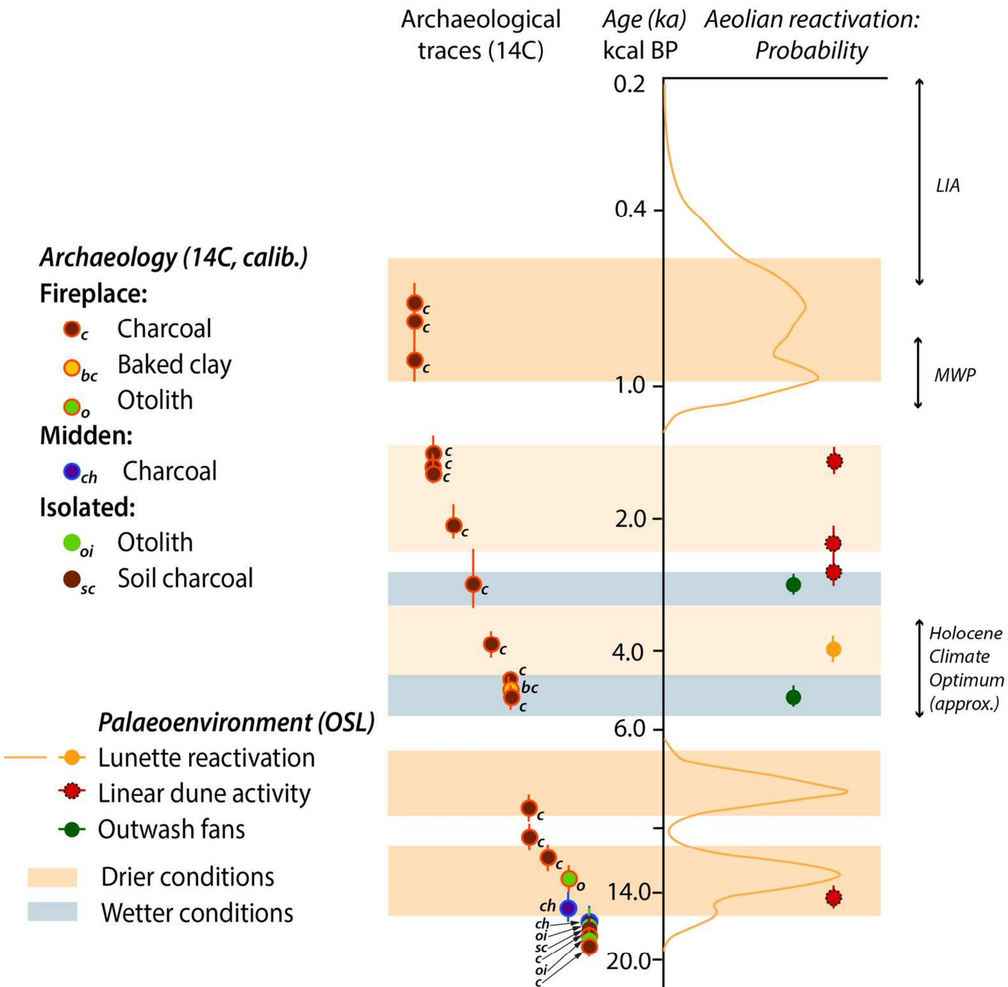


Figure 6. Holocene palaeoenvironmental history at Lake Mungo pre-Anthropocene (from Figure 4), compared with calibrated radiocarbon dates for archaeological traces (fireplaces, middens and isolated finds) derived from legacy data. The climatic phases HCO, MWP and LIA are shown in black text on the right.

171x179mm (300 x 300 DPI)

Table 1. OSL sample codes, locations and stratigraphic units.

Laboratory code	Location along lunette	Field code	Description
Lake Mungo, Locality 973659 (central lunette)			
EVA1100	Residual 1	973659-1	Immediately overlying Arumpo/Unit E sediments
EVA1101	Residual 1	973659-2	Middle of brown unit overlying Arumpo/Unit E sediments
EVA1103	Residual 2	973659-4	Upper part of uppermost reworked unit
EVA1104	Residual 2	973659-5	Lower part of uppermost reworked unit
EVA1105	Residual 3	973659-6	Lower laminated reworked sands (no soils identified)
EVA1106	Residual 2	973659-7	Base of residual, lowermost of three units exposed. Likely age of adjacent blowout surface which has refitting sets of artefacts and clusters of artefacts struck from the same core
EVA1107	Residual 4	973659-8	Lower part of residual, laminated sands, equivalent to surface with refitting sets of artefacts and clusters of artefacts struck from the same core
EVA1108	Residual 4	973659-9	Middle part of residual, pale massive sands
Lake Durthong			
EVA1069	DTH27: southeastern lunette	DTH27-1	Reworked brown aeolian sand
EVA1072	DTH26: southeastern lunette	DTH26-1	Reworked fine aeolian sand
EVA1092	DTH07: central lunette, proximal to inflow channel	DTH07-1	Unconsolidated red-brown aeolian sand with carbonate lag; possible incipient soil development
EVA1094	DTH31: central lunette, north of inflow channel	DTH31-2	Unconsolidated red-brown aeolian sand
EVA1097	DTH14: North lunette, western extremities of lunette sediments	DTH14-3	Silty red sand with weak soil development; possible alluvial or dust component
EVA1099	DTH15: North lunette, western extremities of lunette sediments	DTH15-2	Unconsolidated silty, dark red aeolian sand

Table 2. Equivalent dose (D_e), dose rate data (attenuated) and OSL age estimates for the Lake Mungo and Durthong lunette samples. Single aliquot D_es and age estimates are shown in plain text; single grain results are in italics.

Sample code	De (Gy)	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Age (ka)
Lake Mungo							
EVA1100	10.6 ± 0.5[a] *5.7 ± 0.2[a]*	0.42 ± 0.02	0.53 ± 0.03	2.65 ± 0.13	0.17 ± 0.02	0.87 ± 0.04	12.2 ± 0.7 *6.5 ± 0.4*
EVA1101	3.8 ± 0.2[a] *3.1 ± 0.1[a]*	0.45 ± 0.02	0.62 ± 0.03	2.61 ± 0.13	0.19 ± 0.03	0.93 ± 0.04	4.0 ±0.3 *3.3 ± 0.2*
EVA1103	0.05 ± 0.00[b] *0.04 ± 0.01[b]*	0.24 ± 0.01	0.44 ± 0.02	1.55 ± 0.08	0.13 ± 0.01	0.56 ± 0.02	0.09 ± 0.01 *0.06 ± 0.02*
EVA1104	0.06 ± 0.01[b] *0.04 ± 0.00[a]*	0.19 ± 0.01	0.43 ± 0.02	1.38 ± 0.07	0.13 ± 0.01	0.49 ± 0.02	0.12 ± 0.01 *0.07* ± 0.01
EVA1105	0.04 ± 0.00[b] *0.03 ± 0.02[b]*	0.52 ± 0.03	0.81 ± 0.04	2.99 ± 0.15	0.12 ± 0.01	0.99 ± 0.04	0.04 ± 0.00 *0.03 ± 0.02*
EVA1106	8.3 ± 0.3[a] *9.4 ± 0.4[a]*	0.55 ± 0.03	0.78 ± 0.04	3.33 ± 0.17	0.12 ± 0.01	1.03 ± 0.04	8.1 ± 0.5 *9.1 ± 0.5*
EVA1107	13.1 ± 0.4[a] *14.4 ± 0.4[a]*	0.47 ± 0.02	0.85 ± 0.04	3.18 ± 0.16	0.15 ± 0.01	1.00 ± 0.04	13.1 ± 0.7 *14.4 ± 0.7*
EVA1108	19.2 ± 0.9[a] *19.0 ± 0.6[a]*	0.67 ± 0.03	0.79 ± 0.04	3.78 ± 0.19	0.17 ± 0.02	1.23 ± 0.05	15.6 ± 1.0 *15.5 ± 0.8*
Lake Durthong							
EVA1069	*0.84 ± 0.16[b]*	0.69 ± 0.04	2.61 ± 0.13	0.95 ± 0.05	0.20 ± 0.03	1.37 ± 0.08	*0.61 ± 0.12*
EVA1072	*0.15 ± 0.01[a]*	1.30 ± 0.07	8.20 ± 0.41	1.94 ± 0.10	0.20 ± 0.03	2.42 ± 0.13	*0.06 ± 0.01*
EVA1092	2.10 ± 0.6[a] *0.84 ± 0.13[a]*	0.49 ± 0.03	4.20 ± 0.21	0.69 ± 0.04	0.20 ± 0.04	1.12 ± 0.06	1.87 ± 0.55 *0.75 ± 0.13*
EVA1094	1.00 ± 0.03[a] *0.97 ± 0.04[a]*	0.43 ± 0.02	3.20 ± 0.16	0.74 ± 0.04	0.20 ± 0.02	0.99 ± 0.05	1.01 ± 0.06 *0.98 ± 0.07*
EVA1097	13.1 ± 7.5[a] *1.80 ± 0.10[b]*	0.43 ± 0.02	4.31 ± 0.22	1.01 ± 0.05	0.19 ± 0.02	1.14 ± 0.06	11.5 ± 6.6 *1.58 ± 0.12*
EVA1099	16.5 ± 1.9[a] *3.80 ± 0.21[b]*	0.49 ± 0.03	3.86 ± 0.19	0.98 ± 0.05	0.19 ± 0.02	1.14 ± 0.06	14.4 ± 1.8 *3.33 ± 0.25*

[a] Calculated using the central age model of Galbraith et al. (1999).

[b] Calculated using the minimum age model of Galbraith et al. (1999).

Table 3. Synthesis of post-lacustrine OSL ages and proposed scheme for aeolian reactivation. Ages in italics (marked with asterisk) represent linear dune activity surrounding the lake basins.

Depositional phase	**Aeolian deposition**		**Alluvial fan/sheetwash deposition**	
	Ages (ka)	**Mean (ka)**	**Ages (ka)**	**Mean (ka)**
Transitional post-lake	15.6 ± 1.0[a] 13.1 ± 0.7[a] 12.7 ± 1.0[b] 12.2 ± 0.7[a] *14.2 ± 1.3*[b,*]	13.5 ± 1.5		
Phase I aeolian	8.3 ± 0.6[c] 8.1 ± 0.5[a]	8.2 ± 0.6		
Phase A fans (mid-Holocene aeolian)	4.0 ± 0.3[a]		5.2 ± 0.3[c] 3.4 ±0.3[c]	4.3 ± 1.3
Local linear dune activity	*3.33 ± 0.3*[a,*] *2.62 ± 0.3*[b,*] *1.58 ± 0.12*[a,*]			
Phase II aeolian	0.98 ± 0.07[a] 0.75 ± 0.13[a] 0.61 ± 0.12[a]	0.75 ± 0.19		
Phase III aeolian	0.26 ± 0.04[b] 0.25 ± 0.02[b] 0.18 ± 0.03[b]	0.23 ± 0.04		
Phase B sheetwash			0.14 ± 0.01[b] 0.10 ± 0.01[b]	0.12 ± 0.01
Phase IV aeolian	0.12 ± 0.01[b] 0.12 ± 0.01[a] 0.10 ± 0.02[b] 0.10 ± 0.01[b] 0.09 ± 0.02[a] 0.07 ± 0.01[a] 0.07 ± 0.00[b] 0.06 ± 0.01[a] 0.04 ± 0.00[a]	0.10 ± 0.01		

[a] This paper.
[b] Barrows et al. (2014).
[c] Fitzsimmons et al. (2014).

Supplementary Information

OSL dating

Table S1. Sample statistics from single aliquot and single grain OSL measurements at Lakes Mungo and Durthong.

Sample	Single aliquot				Single grain				
	D_e (Gy)	OD (%)	Aliquots accepted	Recycling ratio	D_e (Gy)	OD (%)	Grains accepted	Thermal transfer (%)	Recycling ratio
Lake Mungo									
EVA1100	10.6 ± 0.5	20	24/24	0.97 ± 0.02	5.7 ± 0.2	34	121/600	-	0.98 ± 0.11
EVA1101	3.8 ± 0.2	22	24/24	0.97 ± 0.03	3.1 ± 0.1	37	244/600	-	0.99 ± 0.11
EVA1103	0.05 ± 0.00	80	22/24	0.89 ± 0.14	0.04 ± 0.01	28	55/600	-	0.98 ± 0.17
EVA1104	0.06 ± 0.01	92	23/24	0.17 ± 0.11	0.04 ± 0.00	49	59/600	7.4	0.96 ± 0.10
EVA1105	0.04 ± 0.00	70	23/24	0.90 ± 0.13	0.03 ± 0.02	49	65/600	-	0.99 ± 0.12
EVA1106	8.3 ± 0.3	15	24/24	1.00 ± 0.02	9.4 ± 0.4	36	160/600	-	1.00 ± 0.10
EVA1107	13.1 ± 0.4	12	24/24	0.98 ± 0.01	14.4 ± 0.4	26	230/600	-	1.00 ± 0.10
EVA1108	19.2 ± 0.9	20	24/24	0.97 ± 0.02	19.0 ± 0.6	29	231/600	-	0.99 ± 0.10
Lake Durthong									
EVA1069	-	-	-	-	0.84 ± 0.16	91	63/600	-	0.97 ± 0.10
EVA1072	-	-	-	-	0.15 ± 0.01	15	45/600	6.5	0.97 ± 0.06
EVA1092	2.10 ± 0.60	93	12/24	0.99 ± 0.11	0.84 ± 0.13	36	8/600	0.1	1.00 ± 0.12
EVA1094	1.00 ± 0.03	0	20/24	1.01 ± 0.07	0.97 ± 0.04	0	17/600	7.7	0.94 ± 0.10
EVA1097	13.1 ± 7.5	>90	19/24	NDA	1.80 ± 0.10	63	60/600	1.1	0.99 ± 0.01
EVA1099	16.5 ± 1.9	44	16/24	NDA	3.80 ± 0.21	0	88/600	1.3	1.00 ± 0.09

Figure S1. Results of preheat plateau test undertaken on reactivated aeolian sample EVA1100.

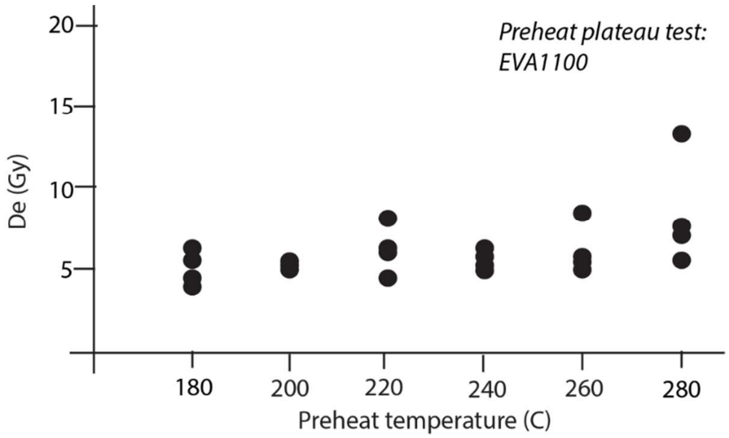


Figure S2. Radial plots for the single grain and single aliquot measurements on the samples from Lake Mungo. Single aliquot values are plotted as open triangle, and the corresponding D_e is given as a black line. Single grain results as closed circles and the corresponding D_e is shown as the horizontal shaded line.

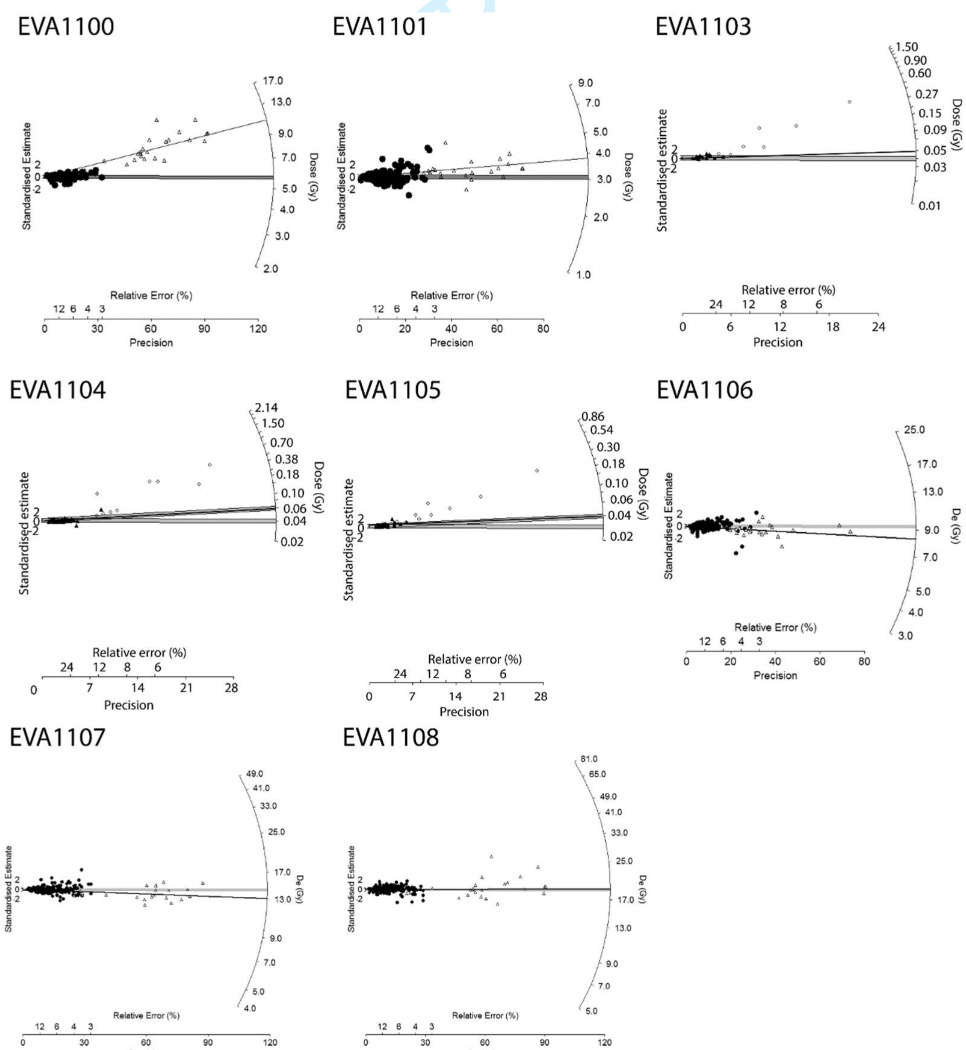


Figure S3. Radial plots for the single grain and single aliquot measurements on the samples from Lake Durthong. Single aliquot values are plotted as open triangle, and the corresponding D_e is given as a black line. Single grain results as closed circles and the corresponding D_e is shown as the horizontal shaded line.

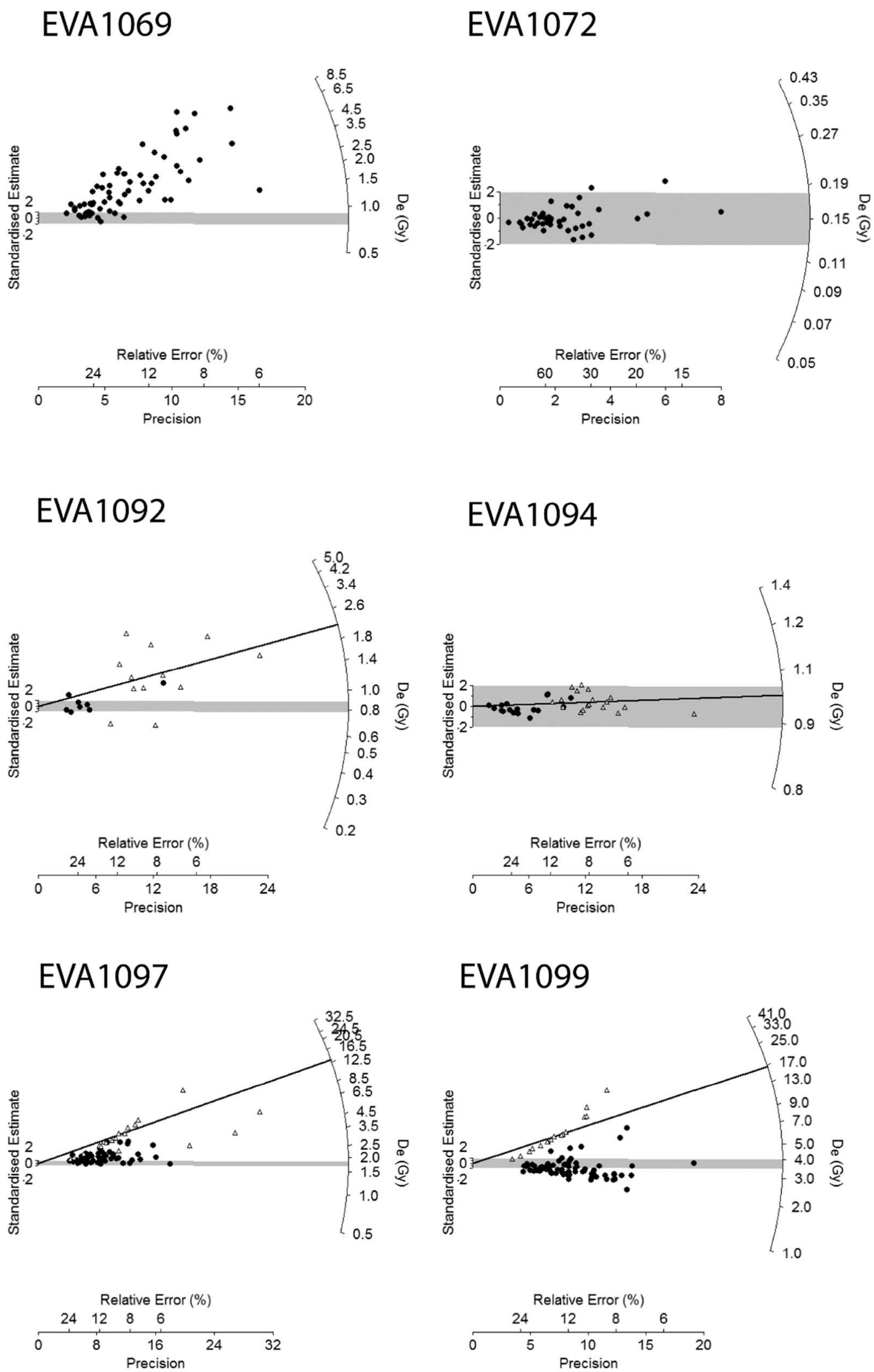


Figure S4. OSL signal decay curves from single grains of quartz from Lake Mungo. The uppermost sample, from modern sands, is dated to 0.06 ± 0.02 ka (c. 1950s); the lowermost sample is a Holocene aeolian reactivation, dated to 9.1 ± 0.5 ka. Both yield a clear signal of comparable brightness with respect to dose, with rapid signal decay.

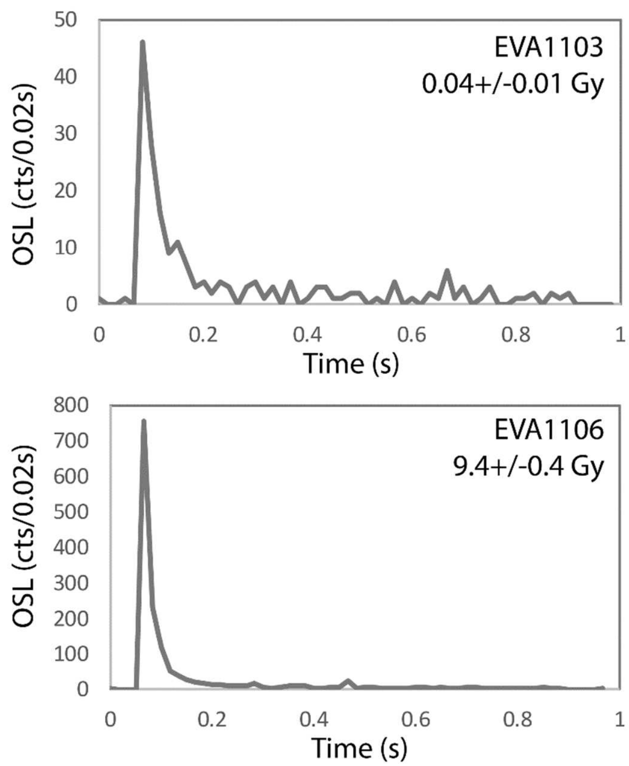
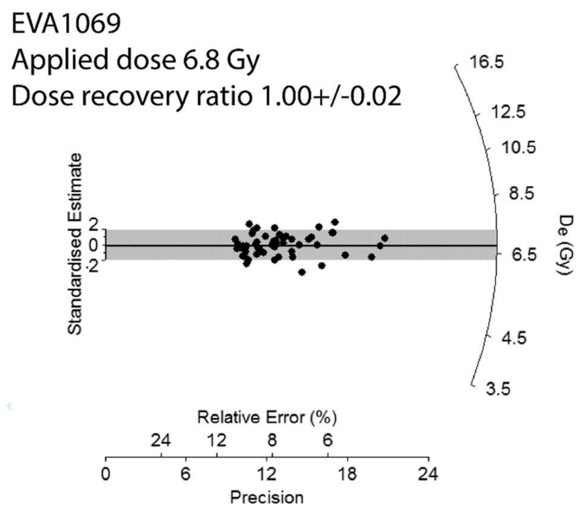


Table S2. Water content values from both Lake Mungo and Durthong samples.

Sample code	**Water content (%)**
Lake Mungo	
All samples	5 ± 3
Lake Durthong	
EVA1069	6 ± 3
EVA1072	4 ± 2
EVA1092	2 ± 2
EVA1094	3 ± 2
EVA1097	2 ± 2
EVA1099	3 ± 2

Figure S5. Dose distribution resulting from dose recovery test for sample EVA1069 (Lake Durthong). From an applied dose of 6.8 Gy (50s), a CAM dose of 6.82 ± 0.11 Gy (overdispersion 8%) was calculated, yielding a dose recovery ratio of 1.00 ± 0.02.



Previously published chronological data for archaeological traces

Table S3. Published radiocarbon dates from archaeological traces in the Willandra Lakes. Dates are calibrated using Reimer et al. (2009); data points not used in comparative analyses in the main text due to lack of reliability are identifiable by italics.

Lake basin	Site	Description	Lab code	Feature	Sample type	Reference	^{14}C uncalibrated	^{14}C calibrated
Mungo	MLE5	East of lake	SUA1737	Fireplace	Charcoal	Clark (1987)	700 ± 100	658 ± 79
Mungo	WOC	Walls of China, lunette	ANU666	Fireplace	Charcoal	Clark (1987)	740 ± 70	685 ± 55
Mungo	WOC	Walls of China, lunette	ANU663	Fireplace	Charcoal	Clark (1987)	950 ± 120	875 ± 113
Mungo-Leaghur interlakes	ML40	In between lake basins	ANU4135	Fireplace	Charcoal	Clark (1987)	1490 ± 130	1419 ± 117
Mungo	MLB	Lake bed	ANU661	Fireplace	Charcoal	Clark (1987)	1610 ± 110	1530 ± 123
Mungo-Leaghur interlakes	ML40	In between lake basins	ANU4136	Fireplace	Charcoal	Clark (1987)	1640 ± 80	1547 ± 104
Mungo	WOC	Walls of	ANU664	Fireplac	Charcoa	Clark	2060 ± 170	2053 ±

		China, lunette		e	l	(1987)		208
Mungo	WOC-F80	Walls of China, lunette	ANU2167A	Fireplace	Charcoal	Clark (1987)	2670 ± 370	2788 ± 447
Garnpung-Leaghur	GL1	In between lake basins	ANU701	Fireplace	Charcoal	Johnston and Clark (1998)	3560 ± 85	3857 ± 115
Mulurulu	*ME3*	*East of lake*	*ANU464B*	*Midden*	*Bone collagen*	*Johnston and Clark (1998)*	*4020 ± 320*	*4496 ± 434*
Mungo	WOC	Walls of China, lunette	ANU665	Fireplace	Charcoal	Clark (1987)	4020 ± 100	4534 ± 168
Mungo	WOC	Walls of China, lunette	ANU669	Fireplace	Baked clay	Clark (1987)	4260 ± 190	4850 ± 284
Mungo	WOC-F80	Walls of China, lunette	ANU2167B	Fireplace	Charcoal	Clark (1987)	4410 ± 360	4993 ± 462
Mulurulu	*ME3*	*East of lake*	*ANU464A*	*Midden*	*Bone calcite*	*Johnston and Clark (1998)*	*7210 ± 100*	*8052 ± 96*
Willandra Creek	WCW 6	West of creek	SUA870	Fireplace	Charcoal	Clark (1987)	8200 ± 95	9186 ± 129
Willandra Creek	WCW 3	West of creek	SUA871	Fireplace	Charcoal	Clark (1987)	9390 ± 120	10671 ± 213
Garnpung-Leaghur	GL13	In between lake basins	ANU2165	Fireplace	Charcoal	Johnston and Clark (1998)	10250 ± 540	11853 ± 728
Mungo			SANU27810	Fireplace	Otolith	Clark (1987)	11840 ± 45	13475 ± 130
Mulurulu	ME3, M11A midden 6	Mulurulu East	ANU948	Shell midden	Charcoal	Clark (1987)	12800 ± 990	15348 ± 1375
Mungo	WOC	Walls of China, lunette	ANU684	Fireplace	Charcoal	Clark (1987)	12920 ± 550	15528 ± 962
Garnpung	GL1	Garnpung-Leaghur	ANU373	Shell midden	Charcoal	Allen (1972)	13920 ± 480	16867 ± 765

Garnpung			OZB606		Otolith	Bowler et al. (2012)	14500 ± 600	17691 ± 682
Arumpo	OA13	Outer Arumpo lunette	ANU881	Soil	Charcoal	Clark (1987)	14630 ± 110	17947 ± 389
Garnpung		Lake Garnpung	OZB605		Otolith	Bowler et al. (2012)	14800 ± 370	18002 ± 457
Garnpung -Leaghur	GL13	In between lake basins	ANU2166	Fireplace	Charcoal	Johnston and Clark (1998)	14750 ± 230	18013 ± 397
Garnpung		Lake Garnpung	OZB602		Otolith	Bowler et al. (2012)	14900 ± 130	18198 ± 261
Garnpung		Lake Garnpung	OZB607		Otolith	Bowler et al. (2012)	15050 ± 400	18229 ± 416
Mungo	WOC 1	Walls of China, lunette	ANU293	Fireplace	Charcoal	Clark (1987)	15140 ± 850	18305 ± 938

Results of archaeological survey and artefact analysis.

Figure S6. Google Earth image showing the locations on the Lake Mungo lunette where systematic archaeological surveys and geological mapping were undertaken, and their relationship to the Locality numbers and cross-section referred to in the text.

Figure S7. Exposures of Unit E (Arumpo/Zanci), Unit F (post-lake aeolian) and Unit G (post-lake alluvium) plotted onto the project's digital air photographs, showing the distribution of hearths and clusters of stone tools in each unit. Figure prepared by Paul Penzo-Kajewski from MapInfo output.

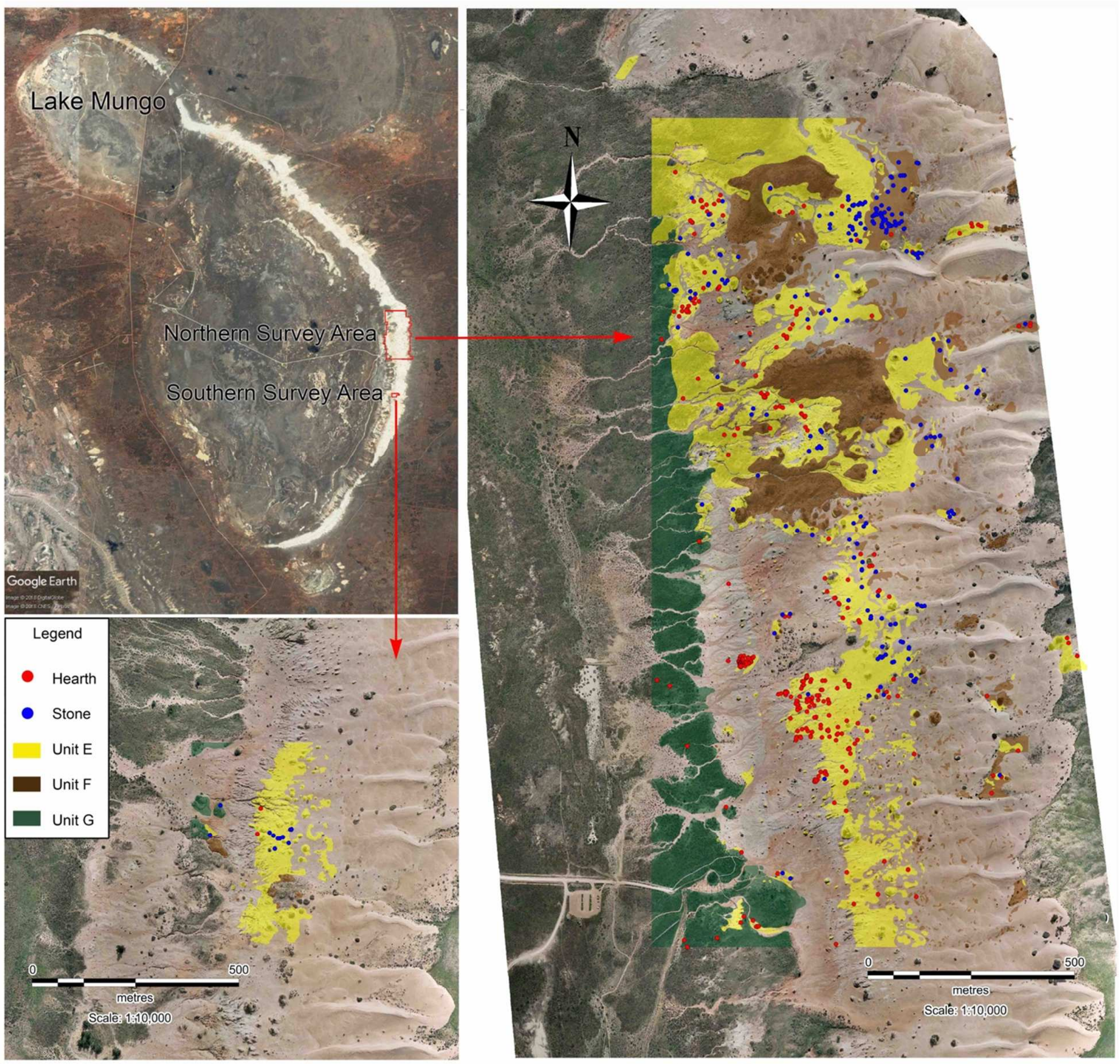


Table S1. Difference between the observed and expected number of archaeological features in the final lake-phase (Unit E/Zanci) and post-lake stratigraphic units (Units F, G) in the central Mungo lunette study area (Figures S6 and S7), based on the area of exposure of each mapped unit and assuming a homogenous distribution through the stratigraphic sequence.

stratigraphic unit	**conditions**	**approx. age ka**	**Area km ^{2}**	**observed sites**	**expected sites**	**difference**
G – alluvial fan	locally more humid	5 - 3.5	0.19	14	248	- 234
F - aeolian	locally more arid	14 - 8	0.21	106	272	- 167
E – aeolian (Arumpo/Zanci)	lake oscillating/drying	23 - 15	0.44	679	552	+ 126

Table S2. Percentage of sites, for all stratigraphic units in the central Mungo lunette study area, preserved in sediments representing different palaeoenvironmental conditions (N=1,456). For location of study area, see Figure S6).

hydrologic conditions	**% of sites**
sustained lake full	26
lake fluctuating	65
lake dry, reworking of lunette sediments under locally arid conditions	7
lake dry, reworking of lunette sediments under locally humid conditions	1.5

Table S3. Relative abundance of the different types of activity traces preserved in the post-lake stratigraphic units in the central Mungo lunette.

Stratigraphic Unit	**total number of cultural features**	**% of cultural features**		
		Hearths	**Isolated**	**Stone clusters**
Unit G	14	75%	25%	
Unit F	106	10%	20%	70%

Table S4. Ratios and indices highlighting key technological differences between flaked stone artefact assemblages from units E (n=594) and F (n=700), which formed the basis of detailed technological study (Spry, 2014).

Ratio/index	**Unit E**	**Unit F**
Quartzite to silcrete	1:25	1:7
Flake/tool core blanks to cobble/slab core blanks	1:2	1:<1
Cortical material to non-cortical material	1:2	1:3
Cores to flakes	1:14	1:14
Flake elongation (for flakes struck from cobbles/slabs)	1.22	1.38
Flake elongation (for flakes with edge modification)	1.1	1.63
Cross-sectional shape	2.74	2.63
Backed artefacts to scrapers	N/A (no backed artefacts)	1:2

References cited in the Supplementary Information

Allen H (1972) *Where the crow flies backwards: man and land in the Darling Basin*. PhD Thesis, Australian National University, Australia

Bowler JM, Gillespie R, Johnston H and Boljkovac K (2012) Wind v water: glacial maximum records from the Willandra Lakes. In: Haberle S and David B (eds) *Peopled Landscapes: Archaeological and Biogeographic Approaches to Landscapes*. Canberra: The Australian National University, pp.271–296.

Clark PM (1987) *Willandra Lakes World Heritage Area archaeological resource study*. Report for the New South Wales Department of Planning and the Western Lands Commission of NSW, Sydney, Australia.

Johnston H and Clark P (1998) Willandra Lakes archaeological investigations 1968–98. *Archaeology in Oceania* 33: 105–119.

Reimer P, Baillie M, Bard E, Bayliss A, Beck J, Blackwell P, Bronk Ramsey C, Buck C, Burr G, Edwards R, Friedrich M, Grootes P, Guilderson T, Hajdas I, Heaton T, Hogg A, Hughen K, Kaiser K, Kromer B, McCormac F, Manning S, Reimer R, Richards D, Southon J, Talamo S, Turney C, Van der Plicht J and Weyhenmeyer C (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0–50 000 years cal BP. *Radiocarbon* 51: 1111–1150.