

for climate events to be developed for the past 400 kyr. This constrains not only ice-core chronologies, but also all other records that are dependent upon ice-core timescales. For example, a simple intercomparison between VIL9 and GRIP records permits the precise dating of the late glacial ¹⁰Be peak, which largely covers DO 10 (ref. 22), an event extending between 40.4 and 41.5 kyr ago in the VIL9 record. Finally, it is likely that such large climatic oscillations have affected past human cultures, causing migrations and changes in living and eating habits. Archaeological remains, which can be time constrained thanks to calcite deposits found in prehistoric shelters, can then be put in a climatic framework that will lead to a better understanding of these past cultures²³. □

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Correspondence and requests for materials should be addressed to D.G. (e-mail: genty@lsce.saclay.cea.fr).

New ages for human occupation and climatic change at Lake Mungo, Australia

James M. Bowler*†, Harvey Johnston‡, Jon M. Olley§, John R. Prescott||, Richard G. Roberts†¶, Wilfred Shawcross# & Nigel A. Spooner†☆☆

* School of Earth Sciences, University of Melbourne, Melbourne, Victoria 3010, Australia
 † NSW National Parks & Wildlife Service, Buronga, New South Wales 2739, Australia
 § CSIRO Land & Water, Canberra, Australian Capital Territory 2601, Australia
 || Department of Physics & Mathematical Physics, University of Adelaide, Adelaide, South Australia 5005, Australia
 ¶ School of Geosciences, University of Wollongong, Wollongong, New South Wales 2522, Australia
 # 25 Fairfax Street, O’Connor, Canberra, Australian Capital Territory 2602, Australia
 ☆ Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory 0200, Australia
 ‡ These authors contributed equally to this work

Australia’s oldest human remains, found at Lake Mungo, include the world’s oldest ritual ochre burial (Mungo III)¹ and the first recorded cremation (Mungo I)². Until now, the importance of these finds has been constrained by limited chronologies and palaeoenvironmental information³. Mungo III, the source of the world’s oldest human mitochondrial DNA⁴, has been variously estimated at 30 thousand years (kyr) old¹, 42–45 kyr old^{5,6} and 62 ± 6 kyr old^{7,8}, while radiocarbon estimates placed the Mungo I cremation near 20–26 kyr ago^{2,9,10}. Here we report a new series of 25 optical ages showing that both burials occurred at 40 ± 2 kyr ago and that humans were present at Lake Mungo by 50–46 kyr ago, synchronously with, or soon after, initial occupation of northern^{11,12} and western Australia¹³. Stratigraphic evidence indicates fluctuations between lake-full and drier conditions from 50 to 40 kyr ago, simultaneously with increased dust deposition, human arrival and continent-wide extinction of the megafauna^{14,15}. This was followed by sustained aridity between 40 and 30 kyr ago. This new chronology corrects previous estimates for human burials at this important site and provides a new picture of *Homo sapiens* adapting to deteriorating climate in the world’s driest inhabited continent.

Lake Mungo, the centrepiece of the Willandra Lakes World Heritage Area in western New South Wales, boasts several features of significance to world archaeology, such as Quaternary climate change and the interaction of early humans with the Australian landscape and biota. It is also the type site for the Lake Mungo Geomagnetic Excursion¹⁶.

Fed by an ancestral course of the Lachlan River rising in the highland catchments near Canberra (Fig. 1), the hydrologic record from the now dry lake basin reflects Pleistocene changes in

** Present address: DSTO, Edinburgh, South Australia 5111, Australia.

temperature, precipitation and runoff from the then cold, periglaciated catchments³. Located in the zone of prevailing westerly winds, the basin has been influenced both by local dunefield activity and by dust from the central Australian dunefields further west. Severe erosion of the large crescent-shaped dune (lunette) on the eastern and southern shores of Lake Mungo has revealed its internal stratigraphy and uncovered substantial quantities of archaeological material (including burials) at the surface.

A basal lake-shore sand (Lower Mungo unit) deposited under lake-full conditions contains a rich assemblage of archaeological sites. The discovery in that unit of burnt human remains (Mungo I)² in 1969 was followed soon after (1974) by the discovery and excavation of a fully articulated skeleton (Mungo III) within the

same stratigraphic unit¹, only 450 m from the cremation site. Artefacts from deep in a trench (Mungo B) near the cremation site remained undated¹⁷. Initial cremation age estimates, based on radiocarbon dating, provided minimum values of 26 kyr (ref. 2), while thermoluminescence ages of 43 ± 4 and 41 ± 7 kyr were obtained later from sands collected at the Mungo III burial site^{5,6}.

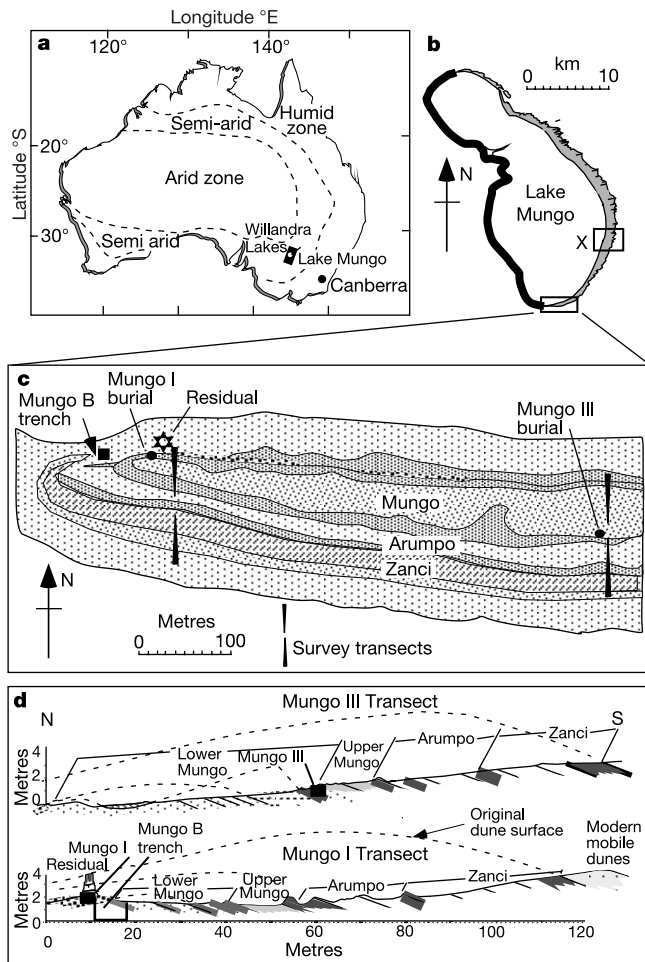


Figure 1 Location of study area. **a**, Location diagram showing Lake Mungo, the centrepiece of the Willandra Lakes World Heritage Area, in semi-arid southeastern Australia. **b**, Lake Mungo, a dry basin last filled about 22,000 years ago, has a large transverse dune (lunette) on its eastern (downwind) margin. The site of the Lake Mungo Geomagnetic Excursion¹⁶ is shown at X, some 8 km north of the burial sites. **c**, The southern sector of the Lake Mungo lunette has been truncated to a nearly horizontal surface, exposing in plan the internal dune stratigraphy, from which a geological map of the eroded surface has been constructed. **d**, Two surveyed transects across the Lake Mungo lunette at the burial sites of Mungo I and III illustrate the depth of erosion, exposing related soil-sedimentary units which can be correlated between sites. Sampling along both transects for optical dating and sedimentary analyses was supplemented by vertical sampling of the Mungo I Residual (bottom left) and the adjacent archaeological excavation (Mungo B trench). The two main units (Lower and Upper Mungo) described here form the inner core of the dune, which contains evidence of human occupation. The Mungo I and III burial sites are located on the northern (lake-shore) and southern (lee) sides of the dune axis, respectively.

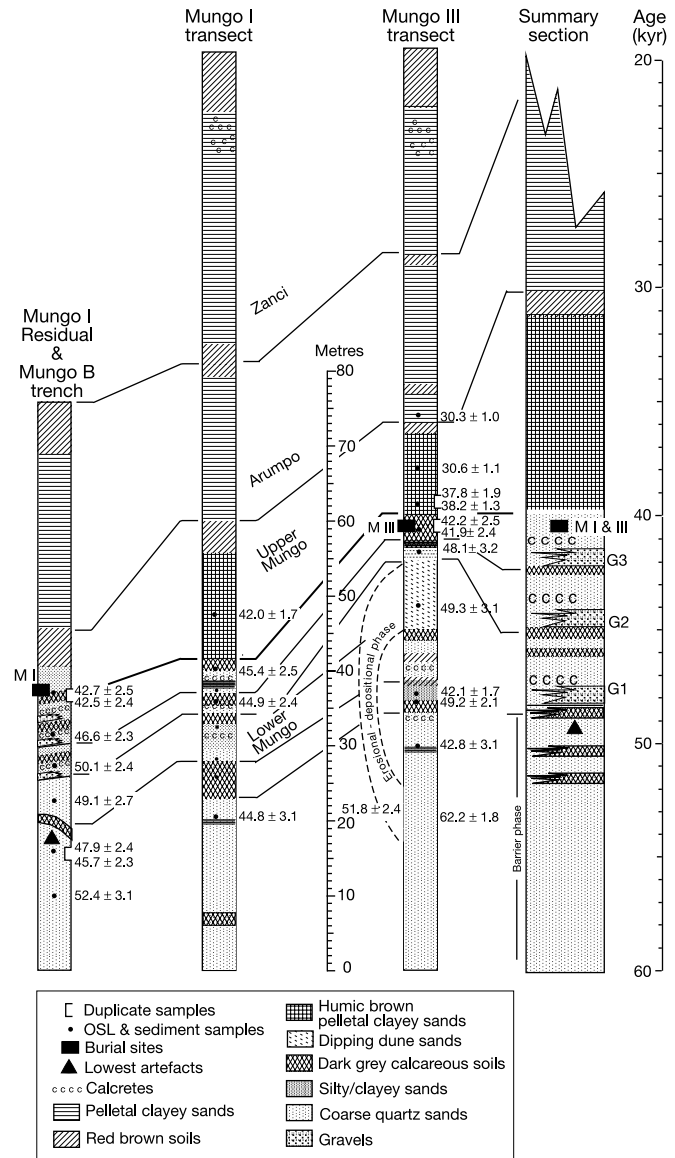


Figure 2 Stratigraphic units and age ranges of sites. The three stratigraphic columns on the left represent the measured and dated sequences. Optical ages are shown in thousands of years (kyr). Data from the Mungo I Residual and Mungo B trench are superimposed vertically for clarity of presentation. Three gravel units (G1, G2, G3) overlie barrier sands, with a band of dark humic, weak soil above the lowest recorded artefacts. The Mungo I and III transects are presented in vertical orientation to illustrate the relative unit thicknesses and to facilitate correlations between surveyed sections. The metric scale shows the actual distances from zero datum (see Fig. 1). The Mungo I and III burials (MI and MIII) have bracketing optical ages that are concordant and also consistent with stratigraphic correlations between the two transects. In the erosional cut-and-fill segment on the Mungo III transect, a unit of disconformable silty sands at 21.0 m (dated to 51.8 ± 2.4 kyr) is stratigraphically equivalent to steeply dipping dune sands near 48 m (49.3 ± 3.1 kyr); see stratigraphic reconstruction in Fig. 1. The synthetic section on the right summarizes the major units and sub-units for all sequences on the left, plotted alongside a timescale determined from the optically stimulated luminescence (OSL) chronology.

Recently, direct dating of the Mungo III skeletal remains produced Th/U and Pa/U ages of between 50.7 ± 0.9 and 82 ± 7 kyr, and electron-spin resonance (ESR) ages from a fragment of tooth enamel of 63 ± 6 (early U-uptake) and 78 ± 7 kyr (linear U-uptake)^{7,8}. Optical ages of 59 ± 3 and 63 ± 3 kyr were obtained for sands collected approximately 300 m away from the burial site and were then thought to relate to the sediments into which Mungo III was inserted⁸. The reliability of these age estimates has been contested^{18–20}.

In this study, improved resolution for the time interval beyond the range of radiocarbon dating has been achieved by optical dating of the lunette sediments, using the optically stimulated luminescence (OSL) signal from quartz^{21,22}. Our multidisciplinary

approach, involving four separate dating laboratories in both field analysis and laboratory studies, provides the first well-constrained ages for the key archaeological and palaeoenvironmental events at Lake Mungo.

Stratigraphic surveys were made of units that range in age from the last interglacial (culturally sterile Golgol unit), through the critical interval from 60 to 40 kyr ago (Lower Mungo unit), to the Last Glacial Maximum (Upper Mungo, Arumpo and Zanci units)³. Attention was focused on two north–south transects across the near-horizontal surface of the eroding lunette: one at the Mungo I burial site and the Mungo B trench, and the other at the Mungo III burial site, 450 m further east (Fig. 1). Survey profiles tied to local benchmarks provide control of horizontal and vertical co-ordinates for all samples and stratigraphic unit boundaries. Stratigraphic units identified in the horizontal transects are presented as vertical sections (Fig. 2), together with dated sample locations and ages. Correlation between transects permits establishment of a synthetic stratigraphic column showing the major hydrologic changes with the main archaeological and megafaunal features (Fig. 3). Mega-faunal remains have been discovered near Lake Mungo²³ and in the adjacent regions^{14,15}, but none were dated in this study.

Sediment samples for optical dating were collected mainly from the Lower Mungo unit, together with corresponding *in situ* gamma-ray spectrometry measurements. Duplicate samples were collected for sediment analyses, with particular attention to microscopic fabric and dust index estimates (Fig. 3d). These record the number of red, clay-coated, silt-sized quartz grains (Wüstenquarz²⁴), which were measured in thin-sections of undisturbed sediment samples on a petrographic microscope (see Supplementary Information). OSL analyses were carried out on sand-sized quartz grains extracted from the Mungo III transect samples (N. A. Spooner), and from the Mungo I transect, the adjacent sediment ‘Residual’ and the Mungo B trench (R. G. Roberts); four samples were duplicated by both laboratories. Optical ages are shown in their stratigraphic context in Fig. 2.

The optical ages for the Mungo III transect are in correct stratigraphic order, and range from about 62 to 30 kyr ago. Ages for the Mungo I transect, the Residual and the trench (Fig. 2) illustrate sequential development of the Lower Mungo unit from beyond 50 kyr to near 40 kyr ago. Confidence in the reliability of this new chronology for Lake Mungo is given by the stratigraphic correlations and consistency of ages between the two transects; by the agreement between the ages of the four duplicate samples (Fig. 2); and by the internally consistent results obtained for samples for which equivalent doses and dose rates were determined using multiple methods (see Supplementary Information). A minor anomaly occurs where ages obtained for clean quartz sands from near the top of the barrier phase³ are consistently younger than the ages for the stratigraphically higher levels (Mungo B trench at 2.40 m: 45.7 and 47.9 kyr; Mungo I transect at 20.2 m: 44.8 kyr; and Mungo III transect at 29.4 m: 42.8 kyr). We attribute this anomaly to uncertainties in the dose rate, which has a relatively greater effect on the accuracy of the optical ages of these samples because of their very low dose rates.

The first evidence for human occupation is provided by 11 silcrete flakes with plain and relatively thick striking platforms recovered from below the lowest gravels in the barrier sands of the Mungo B trench¹⁷ (Fig. 3b) and bracketed by ages of 50.1 ± 2.4 and 45.7 ± 2.3 kyr. The underlying deposits, dated to 52.4 ± 3.1 kyr ago, appear to be culturally sterile. These ages are similar to, or slightly younger than, those for initial human arrival in northern and western Australia^{11–13}, confirming completion of continental colonization soon after 50 kyr ago. In addition to charcoal and burnt bone, the Mungo B excavation¹⁷ yielded 775 artefacts, which indicate a pattern of discontinuous occupation (Fig. 3b). Maximum occupational density occurred between 45 and 43 kyr ago, preceding the Lower to Upper Mungo transition. The

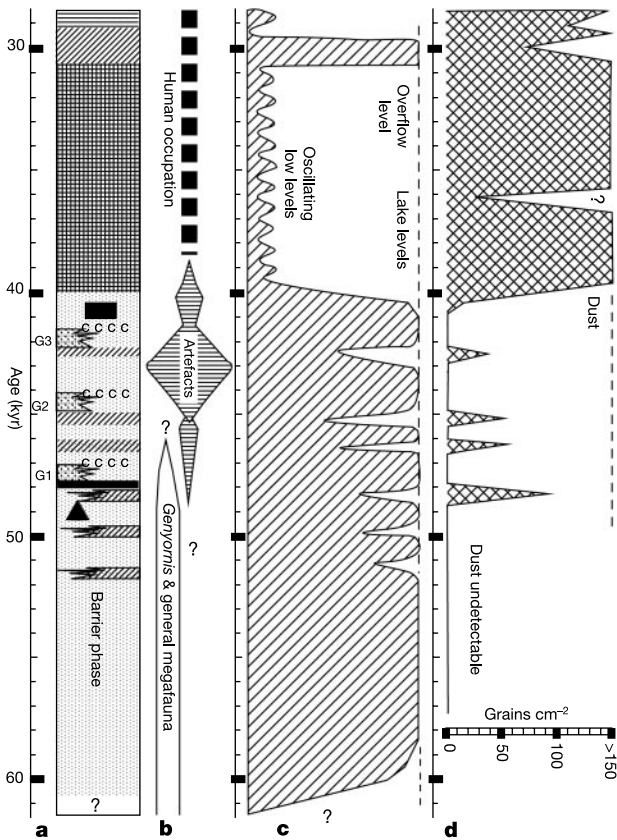


Figure 3 Major hydrological changes and main archaeological and megafaunal features of sites. **a**, Synthetic stratigraphic section (from Fig. 2, right-hand column). See the key in Fig. 2 for meanings of symbols. **b**, The artefact frequency distribution is that determined from the Mungo B trench excavations¹⁷, and indicates maximum occupational density between 45 and 43 kyr. Megafaunal extinction is shown to occur at about 46 kyr (refs 14, 15), which is shortly after initial human arrival at Lake Mungo and coincident with fluctuations between lake-full and regionally dry conditions. **c**, Low lake levels are identified by weak soils that contain clay and silty sand blown from the partly exposed lake floor. The three Lower Mungo gravel bands were formed during three high water stands, when the lake overflowed, after the sand barrier had emerged above lake level³. During Upper Mungo time, when the system was dry for long intervals (thereby permitting clay deflation from the lake floor), detailed lake oscillations are difficult to specify. A brief return to high lake levels is suggested by cessation of deflation at about 30 kyr. **d**, The record of desert dust accession constructed from microscopic analysis of Wüstenquarz grains²⁴ (grains cm^{-2} counted in thin-section) shows several weak soil-forming episodes between 48 and 42 kyr with major accession after 40 kyr. Grain counts are not significant beyond 150 grains cm^{-2} . While lake level changes reflect hydrologic controls in the southeastern highlands, the dust index is a response to erosion of the westerly dunefields. These two independent lines of evidence indicate a major climatic change of regional extent at 40 kyr.

decline in occupational density thereafter reflects the human response to increasing fluctuations in lake levels and aridity.

The initial lake filling occurred at about 60 kyr ago (Fig. 3c), broadly coincident with an ice advance in the highland catchments²⁵. High lake levels persisted, with minor and short-lived episodes of aridity, to about 40 kyr ago. Between 50 and 40 kyr ago, three phases of beach gravels alternate with weakly developed soils, in which aeolian silt and lake-floor clay components provide evidence of lake level changes of brief or intermittent duration. These changes coincide with the arrival of people at Lake Mungo and with the Australia-wide disappearance of megafauna by about 46 kyr ago^{14,15}.

A major hydrologic change occurs after the third gravel (deposited about 42 kyr ago), with a phase of prolonged silt-clay deposition. This event signals substantial changes in catchment conditions, with the end of dominantly high lake levels at about 40 kyr marking the boundary between the Lower and Upper Mungo units. The dust component, weakly preserved in soil breaks as early as 48 kyr ago, increases dramatically across this boundary, reflecting intensified aridity in upwind dunes of the continental interior.

The new chronology has important implications for the age of the Lake Mungo Geomagnetic Excursion¹⁶. Dated to between 30 and 39 kyr ago by radiocarbon (calibrated ages) and thermoluminescence^{16,26,27}, the stratigraphic level of the original site lies near, or at, the Lower to Upper Mungo boundary³, dated here to about 40 kyr ago. If, in the light of future work, this correlation holds true, then the Lake Mungo excursion and the Laschamp event, a feature dated recently to near 41 kyr ago and thought to have lasted approximately 1,500 years (ref. 28), may fall in the same time interval.

The importance of Lake Mungo to world archaeology and human evolution has recently been accentuated by claims for direct dating of the Mungo III skeleton to 62 ± 6 kyr ago⁸ and for the extraction of mitochondrial DNA from these remains⁴. The Mungo I and III burials were both inserted near the Lower to Upper Mungo stratigraphic boundary. Mungo III was placed in a grave 80–100 cm deep, and traces of pelletal clay and dark, reworked soil were found in the grave fill. The grave was dug into sands, dated here to 42 ± 3 kyr ago, underlain by a thin band of pelletal clay derived from the lake floor (Fig. 2). The overlying unit sealing the grave is dated to 38 ± 2 kyr ago. Therefore, Mungo III was buried 40 ± 2 kyr ago, close to the age estimates from two previous studies^{5,6}, but 20 kyr later than the most recent claims^{7,8}.

Reasons for the 20-kyr age discrepancy invite speculation. One factor may involve uncertainties in U-migration²⁹, which is enhanced in carbonate-rich sedimentary deposits such as those studied here. U-migration can considerably affect the accuracy of 'open system' ESR and U-series ages, such as those used to date the Mungo III skeletal remains^{7,8}. The previous two optical ages for the Mungo III burial relate to sediments collected in uncertain stratigraphic contexts more than 300 m away from the burial site⁸.

The Mungo I cremation is indistinguishable in age from the Mungo III burial. Our new age constraints for Mungo I are 15–20 kyr older than the previous radiocarbon-based estimates^{2,9,10}, a difference we attribute to contamination of the radiocarbon samples by younger carbon.

Our study shows that humans were present at Lake Mungo as early as 50–46 kyr ago. We find no evidence to support claims for human occupation or burials near 60 kyr ago. A most significant climatic change of the last 60 kyr occurred near 40 kyr ago, when early lake-shore *Homo sapiens*, with culturally advanced mortuary practices, were forced to adapt to increasing aridity. The Lake Mungo evidence presented here provides a new chronological and environmental context for examining the interaction between the first human arrivals, the last of the megafauna, and the Australian landscape under conditions of major climatic change. □

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Correspondence and requests for materials should be addressed to J.M.B. (e-mail: j.bowler@earthsci.unimelb.edu.au).