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Continental aridification and the vanishing of Australia's megalakes

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Continental aridification and the vanishing of Australia's megalakes

Abstract

The nature of the Australian climate at about the time of rapid megafaunal extinctions and humans arriving in Australia is poorly understood and is an important element in the contentious debate as to whether humans or climate caused the extinctions. Here we present a new paleoshoreline chronology that extends over the past 100 k.y. for Lake Mega-Frome, the coalescence of Lakes Frome, Blanche, Callabonna and Gregory, in the southern latitudes of central Australia. We show that Lake Mega-Frome was connected for the last time to adjacent Lake Eyre at 50-47 ka, forming the largest remaining interconnected system of paleolakes on the Australian continent. The final disconnection and a progressive drop in the level of Lake Mega-Frome represents a major climate shift to aridification that coincided with the arrival of humans and the demise of the megafauna. The supply of moisture to the Australian continent at various times in the Quaternary has commonly been ascribed to an enhanced monsoon. This study, in combination with other paleoclimate data, provides reliable evidence for periods of enhanced tropical and enhanced Southern Ocean sources of water filling these lakes at different times during the last full glacial cycle. © 2011 Geological Society of America.

Keywords

megalakes, vanishing, continental, aridification, australia, GeoQUEST, CAS

Disciplines

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Geology

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Notes

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ABSTRACT

The nature of the Australian climate at about the time of rapid megafaunal extinctions and humans arriving in Australia is poorly understood and is an important element in the contentious debate as to whether humans or climate caused the extinctions. Here we present a new paleoshoreline chronology that extends over the past 100 k.y. for Lake Mega-Frome, the coalescence of Lakes Frome, Blanche, Callabonna and Gregory, in the southern latitudes of central Australia. We show that Lake Mega-Frome was connected for the last time to adjacent Lake Eyre at 50–47 ka, forming the largest remaining interconnected system of paleolakes on the Australian continent. The final disconnection and a progressive drop in the level of Lake Mega-Frome represents a major climate shift to aridification that coincided with the arrival of humans and the demise of the megafauna. The supply of moisture to the Australian continent at various times in the Quaternary has commonly been ascribed to an enhanced monsoon. This study, in combination with other paleoclimate data, provides reliable evidence for periods of enhanced tropical and enhanced Southern Ocean sources of water filling these lakes at different times during the last full glacial cycle.

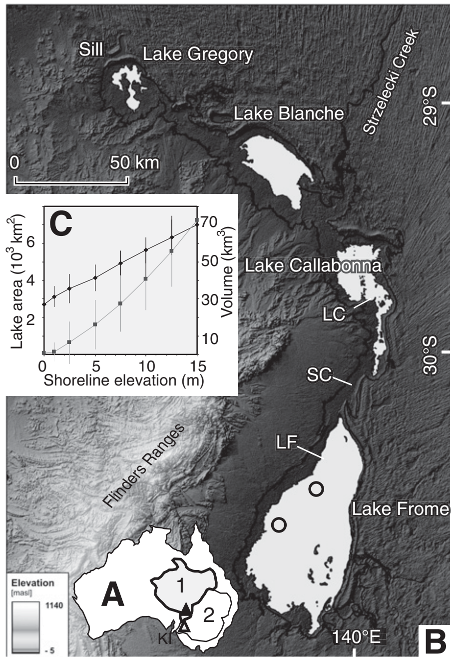

Figure 1. A: Locations of sites in Australia. 1—Lake Eyre Basin; 2—Murray Darling Basin; solid triangle—Mairs Cave (32°S); open triangle—Victoria Fossil Cave, Naracoorte (37°S); KI—Kelly Hill Caves on Kangaroo Island, 36°S. B: Shuttle Radar Topography Mission–derived digital elevation model (DEM) of Lake Mega-Frome; current playa is shaded at 1 m contour. Black outline denotes 15 m contour and/or shoreline. LF—Lake Frome transect, SC—Salt Creek transect, LC—Lake Callabonna transect. Open circles—core locations; Sill—location of Warrawoocara sill. C: Lake Mega-Frome area-volume curve (DEM analysis in Item DR4; see footnote 1).

INTRODUCTION

Two dominant synoptic conditions drive precipitation on the Australian continent today: the Indo-Australian summer monsoon, and the fronts and depressions associated with the mid-latitude westerlies. The monsoon, modulated by the El Niño–Southern Oscillation (ENSO), directly contributes runoff to northern Australia by feeding the major northern tributaries of Australia's largest endoreic drainage system, the Lake Eyre basin (1.2×10^6 km^2; Fig. 1). While tropically derived moisture episodically fills Lake Eyre via Cooper Creek and the Diamantina River, floodwaters can also travel south via Strzelecki Creek (a distributary of Cooper Creek) to the playa lakes surrounding the eastern and northern margins of the Flinders Ranges in South Australia (Fig. 1). These playas (Frome, Callabonna, Blanche, and Gregory), which have combined in the past at 5 ± 2 m depth to form Lake Mega-Frome, have received water from tropically derived floodwaters, from temperate westerlies, or from some combination of these. Consequently, Lake Mega-Frome represents a long-term record of continental precipitation derived from the Southern Ocean and/or a northern tropical moisture source. We assess the nature and timing of major climatic shifts in Australia over the last glacial cycle and evaluate the first-order control of orbital forcing on enhanced precipitation over the Australian continent. This record has important implications for understanding global climate drivers at 60–51 ka, when humans first arrived in Australia (Roberts et al., 1994; Bowler et al., 2003).

Paleolake records provide a direct measure of the moisture balance in the landscape and thus provide valuable data about environmental change and climatic forcing over the late Quaternary (Magee et al., 2004). We adopt a robust approach to unravelling the paleohydrology of the Lake Mega-Frome-Eyre system by linking lake-floor sedimentary sequences to paleoshoreline chronology bolstered by independent environmental proxies from beyond the lakes. Paleoshorelines provide the best, and only, direct measure of paleolake levels, and here we use optically stimulated luminescence (OSL) and thermoluminescence (TL) ages (ka) from paleoshoreline deposits (30°S), along with ^{14}C ages (calibrated, cal., kyr B.P.) from in situ freshwater molluscs. We supplement these data with existing and new independent terrestrial proxies, i.e., age measurements of speleothem growth from three cave sites in a north-south transect, from winter rainfall–dominated in the south to weakly winter rainfall–dominated in the north (Fig. 1). Speleothem growth in these regions today is limited and we compare increased growth rates in the past with paleolake levels.

METHODS

This study uses georeferenced geological maps and digital elevation model (DEM) data (Shuttle Radar Topography Mission version 2, SRTM V2) along with previously published research (Nanson et al., 1998) to guide excavations on paleoshorelines on the western margins of Lakes Frome and Callabonna (30°S, 140°E) to 15 m above the current playa lake floors (Fig. 1). Lake volumes were determined using the SRTM-derived DEM assuming no change in lake-floor elevations. This assumption is validated by the elevation of lacustrine units on Lake Frome islands, which suggest no appreciable lake-floor deflation (see the GSA

Data Repository[1] for error analysis of DEM and details on lake-floor deflation). Three lake margin transects, each with 1–4 paleoshorelines, were surveyed using high-resolution differential global positioning system, and logged and sampled for a range of chronological analyses. OSL and TL signals from quartz using both single and multigrain techniques were used and paired OSL-TL samples were compared with duplicate ^{14}C accelerator mass spectrometry (AMS) analyses on freshwater molluscs analyzed in two AMS laboratories. All optical and thermal ages were undertaken on stratified high-energy beach deposits or nearshore lacustrine facies. (For a full description of the chronological methodology and analysis, see the Data Repository) Two stalagmites from Mairs Cave (32°10′S, 138°50′E) were sampled for multicollector–inductively coupled plasma–mass spectrometry (MC-ICP-MS) analysis, and two discrete layers of the flowstone complex (KH SC S2; Fig. DR5; see the Data Repository) from Kelly Hill Caves at Kangaroo Island (36°S, 136°52′E) were analyzed using the thermal ionization mass spectrometry uranium/thorium analytical procedure (Ayliffe et al., 1998).

PALEOSHORELINE EVIDENCE FOR LAKE-LEVEL FLUCTUATIONS BEFORE THE LAST GLACIAL MAXIMUM

The oldest optical ages were obtained from the 15 m shoreline on Lake Mega-Frome; three of the six ages range from 87.3 ± 5.8 ka to 109.9 ± 7.5 ka with a pooled mean of 96 ± 7 ka (Fig. 2; for ^{14}C/OSL comparison, see the Data Repository). In mid-late Marine Isotope Stage (MIS) 5, Lake Mega-Frome was as much as 15 m deep, ~6500 km^2 in area, and ~70 km^3 in volume (Fig. 1), and connected with Lake Eyre via the 25-km-long Warrawoocara channel (Nanson et al., 1998) to form Australia's largest megalake, >30,000 km^2 in area and >400 km^3 in volume (DeVogel et al., 2004). Given that the modern playas have filled to ~1 m depth only once in historical times (1974), the MIS 5 Lake Mega-Frome was ~70 times the maximum volume of the modern lake and double its surface area (Fig. 1). The mid-late MIS 5 high lake phases in Lake Mega-Frome are coincident with increased speleothem deposition at 90–95 ka reported from the southern margin of the arid interior at Naracoorte (Ayliffe et al., 1998) (Fig. 2). Speleothem deposition at that time was interpreted in Ayliffe et al. (1998) to represent high effective precipitation (EP, that which contributes to runoff) from a strengthened Walker circulation.

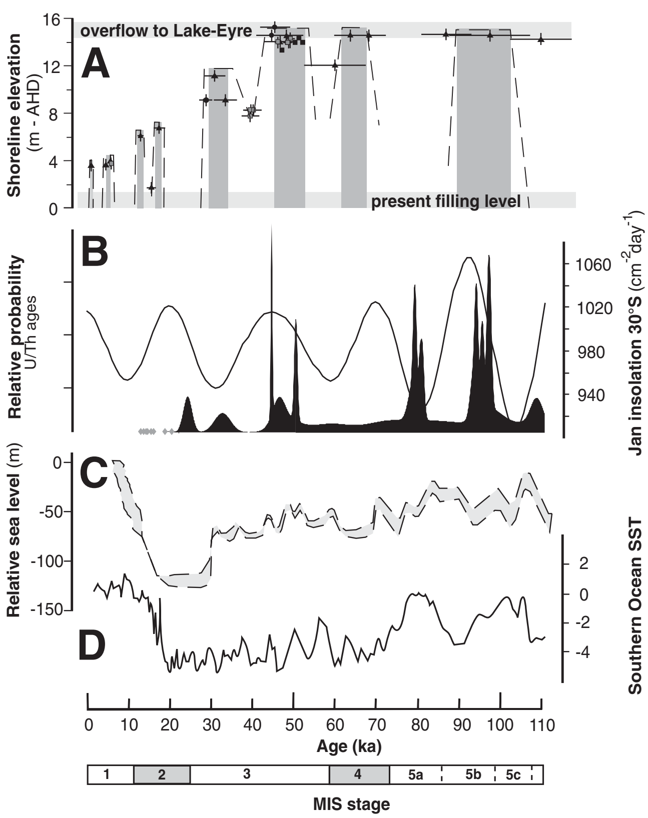

Figure 2. A: Lake-level phases of Lake Mega-Frome derived from single-grain optically stimulated luminescence (OSL) ages on stratified paleoshoreline deposits (solid black triangles), multigrain thermoluminescence (solid black circles), and calibrated accelerator mass spectrometry (AMS) ^{14}C ages on freshwater molluscs (solid gray squares; black solid squares are beyond calibration) plotted against elevation. Errors for OSL are ±1σ and for calibrated AMS ^{14}C are 2 standard deviation (for AMS ^{14}C calibration, see Item DR2; see footnote 1). Lake-phase shading: gray bars denote pooled mean estimates ±1 σ. Horizontal gray band represents elevation of Warrawoocarra sill at 15.4 m AHD (Australian Height Datum) whereby Lake Mega-Frome overtopped to join Lake Eyre. B: Histogram of summed individual $^{230}Th/^{234}U$ age distributions of speleothem ages at Naracoorte Caves and Kelly Hill Caves, Kangaroo Island (Fig. 1), normalized to unit area (Ayliffe et al., 1998) (low analytical errors give sharply defined age distributions). Multicollector–inductively coupled plasma–mass spectrometry Mairs Cave ages are not included in summed distribution due to differing techniques and are plotted on *x*-axis; January insolation at 30°S (Berger, 1992). C: Sea-level curve (Lambeck and Chappell, 2001). D: Stacked sea surface temperature (SST) record for Southern Ocean (Barrows et al., 2007). MIS—marine isotope stage.

Lake Mega-Frome refilled to this 15 m level in MIS 4 and MIS 3, leaving chronostratigraphic evidence at Lakes Callabonna and Frome (Fig. 2); three OSL ages range from 68.2 ± 4.2 ka to 60.1 ± 7.6 ka at Lake Frome and two OSL and two TL ages range from 48.4 ± 4.2 ka to 45.4 ± 3.6 ka. Between 50 and 42 ka other Australian inland lakes, such as Lake Mungo, were full (Bowler et al., 2003), rivers in the Murray-Darling Basin were much larger than present (Page et al., 1996), EP from Southern Ocean sources was high, as evident at Naracoorte and Kangaroo Island (Fig. 2; Table DR7), and humans arrived on the continent (Roberts et al., 1994; Bowler et al., 2003). Toward the end of this period the remaining Australia-wide megafauna died out (Roberts et al., 2001) and Lake Mega-Frome ceased to overflow to Lake Eyre, representing a major biophysical change for southern-central Australia.

We have not recorded a subsequent filling of Lake Mega-Frome until late MIS 3 (Fig. 2). Two optical ages range from 33.4 ± 2.9 ka to 31.4 ± 2.6, and the TL estimate is 28.7 ± 1.9 ka, yet 3 ^{14}C AMS ages (two laboratories) range from 39.5 ± 1.0 to 40.2 ± 1.0 cal. kyr B.P. We interpret the anomaly between dating techniques at this site (Salt Creek; Fig. 1) as a result of older shells reworked into the 10 m shoreline. This interpretation is supported by freshwater ostracods in a core from Lake Frome dated to 42.6 ± 0.3 cal. kyr B.P. (De Deckker et al., 2010), suggesting intermittent lake filling prior to the deep-water phase recorded in the 10 m shoreline. Temperatures in this time period in central Australia have been estimated to be 8–9 °C lower than present (Miller et al., 1997), and other playas and rivers of the Murray-Darling Basin indicate increased fluvial discharge (Bowler et al., 2003; Kemp and Rhodes, 2010). Increased speleothem deposition at Naracoorte coupled with these supporting terrestrial proxies, which are climatically influenced by the interaction of the Southern Ocean with the subtropical jet stream, may suggest that the mid-latitudes of the Southern Hemisphere experienced lower temperatures and increased EP, sourced from northward-displaced winter westerlies in late MIS 3.

[1]GSA Data Repository item 2011071, Items DR1–DR4 (details on optical, thermal, radiocarbon, and uranium series dating procedures along with digital elevation model analyses and sedimentology, including Figures DR1–DR5 and Tables DR1–DR8), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

MOISTURE SOURCES SINCE THE LAST GLACIAL TERMINATION

The paleoshorelines reveal no evidence as yet that Lake Mega-Frome filled to high levels during the Last Glacial Maximum (LGM), though ostracods indicate an ephemeral lake of unknown depth (De Deckker et al., 2010). Lake Mega-Frome refilled to a depth of 6.8 m (15–20 times the modern lake volume) from 17.6 ± 1.5 ka to 15.8 ± 1.2 ka; the latter optical age is derived from a recessional shoreline deposit 1.75 m above the current playa floor. This period of postglacial lake filling was accompanied by accelerated lake-floor sedimentation in Lake Frome (Fig. 3) between 20.0 ± 0.75 and 16.5 ± 0.4 cal. kyr B.P. (Draper and Jensen, 1976; Bowler et al., 1986), recorded in two cores. We report age measurements between 20 and 15 ka from 2 stalagmites in the Flinders Ranges (Fig. 1) supporting higher EP; the fastest growth is recorded from 17.1 ± 0.1 ka to 15.8 ± 0.1 ka, followed by growth termination (see Table DR8). The lack of speleothem growth recorded at Naracoorte or Kangaroo Island in this time period, however, may well be the result of undersampling. Palynological data from the floor of Lake Frome (Singh and Luly, 1991; Luly, 2001) and sedimentological data from valley fills in the Flinders Ranges (Haberlah et al., 2010) confirm the increased levels of precipitation, increased biomass production in the adjacent ranges, and incision of valley fills after 17.1 ± 1.4 ka. The valley-fill incision in the adjacent ranges provides supporting evidence that Lake Mega-Frome was fed directly from the Flinders Ranges (rather than via the Cooper-Strzelecki Creek), suggesting a southern and not tropically derived lake water.

Lake-full conditions in Lake Mega-Frome at 17.6 ± 1.5 ka coincide with a 3°–5° northward shift of polar waters (Barrows and Juggins, 2005) associated with winter sea ice in the Pacific sector (Gersonde et al., 2005), suggesting displaced winter westerlies, enabling greater penetration of rain-bearing fronts into southern-central Australia. Recession of Lake Mega-Frome is marked by a reduction in lake-floor sedimentation and an abrupt decline in charcoal content at 16.5 ± 0.4 cal. kyr B.P. (Luly, 2001) (Fig. 3). These independent proxies adjacent to Lake Mega-Frome, i.e., valley fills, speleothems, and pollen, present consistent evidence of a major climatic change between 16.5 ± 0.4 and 15.8 ka corresponding to the last glacial advance and final deglaciation in Australia (Barrows et al., 2001). Paleoshorelines and ostracods (De Deckker et al., 2010) indicate that Lake Mega-Frome also refilled (presumably briefly) at 13.2 ± 0.8 ka to a depth of 6 m; however, there is no broader evidence to suggest that the lake waters were tropically sourced via Cooper-Strzelecki Creek or locally derived from the Flinders Ranges.

Another filling episode (4–3.7 m depth) is obtained from 2 optical ages and 1 ^{14}C age with good consistency and a mean pooled estimate of 5.1 ± 0.23 ka (Fig. 2). This mid-Holocene period of relative moisture abundance is in good agreement with earlier interpretations from Lake Frome (Bowler et al., 1986), and other terrestrial proxies in southern Australia (Cohen and Nanson, 2007; Quigley et al., 2010) and elsewhere in the mid-latitudes of the Southern Hemisphere (Burrough et al., 2007). The onset of modern ENSO from 5 ka onward corresponds to a return to playa-dominated conditions at Lake Mega-Frome, with a brief lake-filling episode (3.5 m depth) during the Medieval Climatic Anomaly at 0.96 ± 0.07 ka. This last filling episode possibly reflects a series of high-magnitude, low-frequency events associated with an intensification of monsoonal flow related to a reduced El Niño amplitude or frequency (Langton et al., 2008) and/or an enhanced La Niña–like state (Williams et al., 2010), equivalent to the last major historical filling in 1974 caused by enhanced southward displacement of the monsoon trough. Whatever the cause, a lake volume 10–12 times that of 1974 existed within recent human history, and the nature of this remarkable lake-filling episode on a currently arid continent is a matter for further detailed investigation.

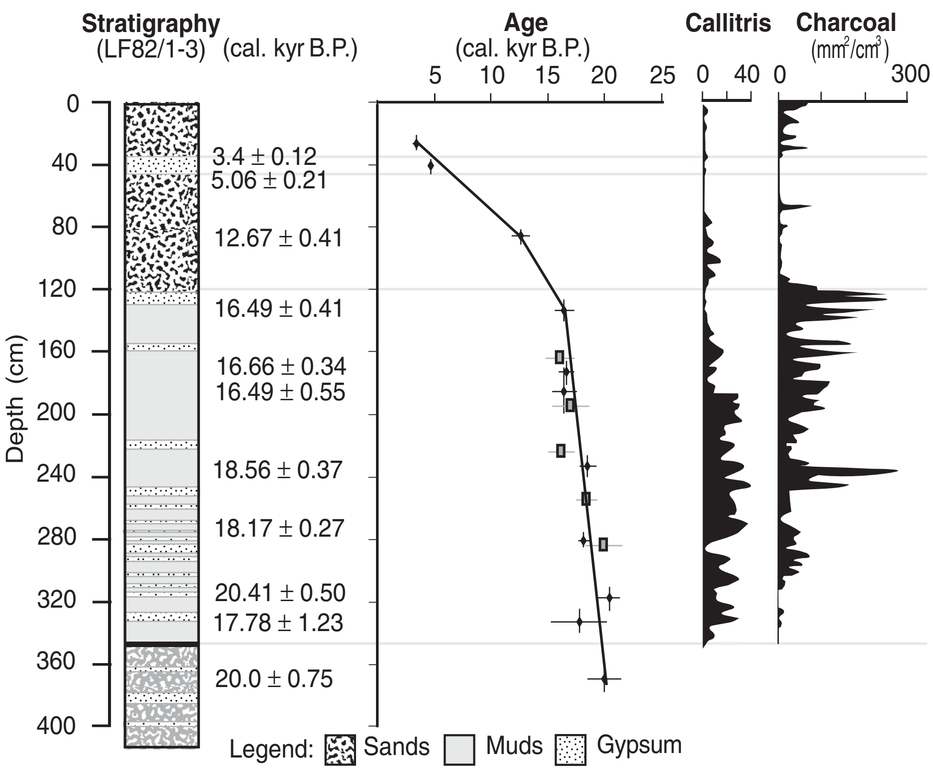

Figure 3. Age-depth profile and stratigraphy for core LF82/1-3 (Lake Frome) with calibrated radiocarbon ages on organic fraction (black circles—Bowler et al., 1986; gray squares—Draper and Jensen, 1976; 30°30′S, 39°52′). Pollen and charcoal data are from Singh and Luly (1991) and Luly (2001).

GLOBAL PALEOCLIMATIC IMPLICATIONS AND OUTLOOK

The paleohydrological record presented here is the first long-term terrestrial proxy for the mid-latitudes of Australia in which the Southern Ocean and tropical moisture sources are differentiated. Based on our lacustral record at Lake Mega-Frome plus evidence of effective precipitation from the southern arid zone (Ayliffe et al., 1998), and other published terrestrial and lacustrine records (Nanson et al., 1998, 2008; Magee et al., 2004), we argue that the continental interior was receiving abundant moisture from multiple sources in late MIS 5. Synchronous lake-full records in early MIS 3 and post-LGM in Australia and other Southern Hemisphere locations at times of insolation maxima (Baker et al., 2001; Fritz et al., 2004) might suggest orbital forcing, but it is clear from Figure 2 that not all Lake Mega-Frome filling episodes were driven by the precessional cycle. The good correspondence between lake levels and speleothem growth at Naracoorte and Kangaroo Island suggest a dominant Southern Ocean moisture source for the Australian continent at 50–45 ka (MIS 3) and ca. 32 ka (late MIS 3), periods of Southern Hemisphere summer insolation maxima and minima, respectively (Fig. 2). These intervals and the 17.6–15.8 ka (post-LGM) lake-filling episode occurred in periods when sea levels were >50 m lower and Southern Ocean sea-surface temperatures were 2–4 °C below those of the present (Fig. 2). Subsequent lake-filling episodes just prior to the Younger Dryas and the mid-Holocene require alternative climatic drivers. We suggest that rising sea levels from 13–12 ka onward and the reconnection of the Arafura Sea with the Pacific Warm Pool allowed the southward displacement of the Intertropical Convergence Zone, resulting in high lake levels derived from northern moisture sources ca. 13 ka, ca. 5 ka, and ca. 1 ka. There is no clear consistent insolation control on lake-filling episodes in this Southern Hemisphere mega-lake system throughout the last glacial cycle, and the paleohydrological record indicates a progressive shift to more arid conditions on the Australian continent, with marked drying after 45 ka.

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