Reference: Long, K., Stern, N., Williams, I.S., 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.

Title: Thermal behaviour of organic radicals and paramagnetic centres in chert: A case study of Bergeracois brown chert, Dordogne, France

Authors: Kelsie Long, Nicola Stern, Ian S. Williams, Rachel Wood, Katarina Sporcic, Tegan Smith, Stewart Fallon, Harri Kokkonen, Ian Moffat, Rainer Grün

Fish otoliths from the Willandra Lakes Region World Heritage Area (south-western New South Wales, Australia) have been analysed for oxygen isotopes and trace elements using *in situ* techniques, and dated by radiocarbon. The study focused on the lunettes of Lake Mungo, an overflow lake that only filled during flooding events and emptied by evaporation, and Lake Mulurulu, which was part of the running Willandra Creek system. Samples were collected from two different contexts: from hearths directly associated with human activity, and isolated surface finds. AMS radiocarbon dating constrains the human activity documented by five different hearths to a time span of less than 240 years around 19,350 cal. BP. These hearths were constructed in aeolian sediments with alternating clay and sand layers, indicative of fluctuating lake levels and occasional drying out. The geochemistry of the otoliths confirms this scenario, with shifts in Sr/Ca and Ba/Ca marking the entry of the fish into Lake Mungo several years before their death, and a subsequent increase in the $\delta^{18}\text{O}$ by $\sim 4\text{‰}$ indicating increasing evaporation of the lake. During sustained lake-full conditions there are considerably fewer traces of human presence. It seems that the evaporating Lake Mungo attracted people to harvest fish that might have become sluggish through oxygen starvation in an increasingly saline water body (*easy prey* hypothesis). In contrast, surface finds have a much wider range in radiocarbon age as a result of reworking, and do not necessarily indicate evaporative conditions, as shown by comparison with otoliths from upstream Lake Mulurulu.

Introduction

The Willandra Lakes in far south-western NSW contain a remarkable archive of Australia's inland aquatic resources from the time that people first settled the continent until the final drying of the lakes some 15,000 years ago (Bowler, 1998, Bowler et al., 2012). The lakes contain an untapped source of information about the role that freshwater aquatic resources played in the successful colonisation of an unpeopled and unfamiliar continent. There is ongoing debate, however, about how indigenous Australians captured the fish that inhabited the large, shallow lakes of the arid interior, and to what extent fish contributed to their diet (Johnston, 1993, Balme, 1995, Bowler et al., 2012). The geochemistry of fossil fish otoliths collected from hearth sites at Lake Mungo is here used to date human presence, gain insights into food gathering strategies and to reconstruct past hydrologic conditions in a major overflow system.

Background

The Willandra Lakes overflow system

Lake Mungo is part of the Willandra Lakes Region World Heritage Area (WLRWHA), a relict overflow system that covers an area of 2400 km² on the edge of Australia's arid core (Fig. 1). The Willandra overflow system received its water from the Lachlan River via the Willandra Creek. This creek, now dry, only carried freshwater at certain intervals during the past 300,000 years, when reduced temperatures and evaporation resulted in more effective precipitation and large volumes of water flowed into the Lachlan River (Kemp and Rhodes, 2010). During periods of less effective precipitation and reduced creek discharge, the Willandra Lakes fluctuated or dried out completely. Each lake has a unique history that reflects its position within the system and which is recorded in the sediments that built up on its floor, on the lunette bounding its eastern margin and on the desert dunes downwind (Bowler, 1971, Bowler, 1998, Bowler et al., 2003, Bowler et al., 2012). The hydrologic determinants of the overflow system, together with its location at the edge of the continent's arid core, means that the Willandra Lakes were highly sensitive to changes in climate. This particularly applies to Lake Mungo, which filled via an overflow channel from Lake Leaghur and had no outflow.

Figure 1. Maps showing the location of the Willandra Lakes in southeastern Australia. Seven main lakes make up the Willandra Lakes World Heritage Area. The samples analysed in this study were obtained from the larger foot survey area, the northern Mungo lunette and the northern end of the Mulurulu lunette. Kindly provided by Rudy Frank mainly after Bowler (1998).

The link between sediment characteristics and hydrologic conditions was established through Bowler, 1971, Bowler, 1998 pioneering investigations of the lunette bounding the eastern shore of Lake Mungo. It consists of alternating layers of sand, clay and soil that reflect the conditions in the adjacent lake. When the lake was full, waves driven by the prevailing southwesterly winds washed sediments to the eastern shoreline, creating a high-energy beach. Sands blown from this beach were deposited on top of the remnants of an earlier dune, creating a vegetated fore-dune. When the lake fell below overflow level, water levels fluctuated and an efflorescence of salts on the partially exposed lake bed resulted in the formation of clay pellets that were blown onto the adjacent lunette. Soil formation occurred during longer periods of landscape stability associated with regional drying or with a temporary cut-off in sediment supply (Bowler, 1998).

When archaeological traces were discovered at Lake Mungo in the early 1970s, studies of the food remains recovered from hearths at the southern end of the Mungo lunette (Bowler et al., 1970), together with those from a dozen other hearths and middens of widely scattered ages and locations across the Willandra, suggested long term continuity in diet and foraging

strategies. This implied that settlement of the Willandra revolved around the exploitation of the lakes' rich aquatic resources, and that following the final drying of the lakes people moved to the river systems and compensated for the loss of lake resources by incorporating grass seeds into their diet (Bowler et al., 1970, Allen, 1974, Allen, 1998). An expanded database, however, later led to the suggestion that the bulk of the Pleistocene food diet came from small terrestrial mammals rather than lacustrine resources (Johnston, 1993). Fish and shellfish appeared to be fall-back foods.

The fish bone hearths discussed in this paper lie in the central part of the Mungo lunette (Unit E), which has been the focus of systematic archaeological surveying and geological mapping since 2009 (Stern et al., 2013). This area's stratigraphic sequence is broadly similar, but not identical, to that described by an earlier generation of researchers for the southern tip of the lunette, where the oldest known traces of human activity in the Willandra were found during the early 1970s (Bowler et al., 1970, Bowler, 1971, Bowler, 1998, Shawcross, 1998, Bowler et al., 2003, Bowler et al., 2012).

Unit E makes up the largest volume of sediment in the central part of the Mungo lunette, and as a result contains more than half of all the archaeological traces recorded in this part of the lunette. The unit consists predominantly of laminar sands, but also contains patches of alternating beds of pelletal clays and pale quartz sands. Weakly developed and discontinuous soil horizons occur at more than one level within unit E, reflecting mostly perennial lake conditions, interspersed with drying phases. It is the last stratigraphic unit deposited before the final drying of Lake Mungo. Unit E is the lateral equivalent of Bowler's Arumpo and Zanci units (Bowler, 1998, Bowler et al., 2012) but in this part of the lunette there is no well-developed brown soil to suggest an hiatus in deposition. Eighteen OSL dates from residual and gully sections and hearths in the central Mungo lunette show that these predominantly sandy sediments accumulated between about 25 and 14 ka (Fitzsimmons et al., 2014). This corresponds to a period of increased discharge in the Lachlan River system, a response to increased runoff due to reduced vegetation cover and increased snowmelt (Barrows et al., 2004, Kemp and Rhodes, 2010). Although Lake Mungo held a significant volume of water at this time, the surrounding sand plains would have been arid (Lomax et al., 2011).

The archaeological remains in the central part of the Mungo Lunette

Archaeological traces occur in all stratigraphic units, although they are most abundant in sediments representing oscillating or fluctuating lake conditions and much less abundant in the sediments that accumulated after the lake dried out (Stern et al., 2013). They include a variety of heat-retainer and non-heat retainer hearths, many of which are associated with burned food remains and tools. Also included are clusters of burned animal bone or eggshell and discrete scatters of chipped stone artefacts that commonly contain refitting flakes and cores, and sometimes, tools. Isolated finds are a conspicuous component of the record and include unworked nodules of silcrete, large cores, grindstones, shell tools and ochre pellets.

Human presence at Lake Mungo and the ‘easy prey’ vs active fishing hypotheses

The differential distribution of archaeological traces throughout the central Mungo lunette suggests that the margins of Lake Mungo provided a more attractive foraging base when flood pulses regularly entered the overflow system (Stern et al., 2013). When the lakes were full, fish would have been hard to locate and would have offered limited return for the energy spent harvesting them. By analogy with floodplain wetlands, however, regular flood pulses would have enhanced the biological productivity of the overflow system, resulting in more abundant, more predictable and more varied food sources (Robertson et al., 1999, Scholz et al., 2002, King et al., 2008). The hearths are evenly distributed in strata made up of alternating sands and clays, suggesting that oscillating lake conditions and not high or low lake levels per se, brought people to the margins of Lake Mungo (Stern et al., 2013). A dearth of surface water on the surrounding plains would also have encouraged people to fall back to the lake margins (Bowler, 1998).

After a flood pulse, large quantities of fish, mainly golden perch (*Macquaria ambigua*), were trapped in the lake by evaporative conditions (Bowler, 1998, Bowler et al., 2012). It is thought that humans then came to the lakeshore and took advantage of the supine, oxygen-starved state of the fish to easily ‘scoop [them] up in shallow waters’ (Bowler, 1998: 146). This is referred to as the *easy prey* hypothesis. It stands in contrast to the suggestion of Kefous (1977) who thought that the large amounts of immature fish otoliths in the Mungo lunette were due to humans using gill nets. Balme (1995) also suggested that populations living at the same time on the Darling River anabranch lakes, approximately 200 km to the northwest, actively engaged in fishing using nets.

Fish otoliths

Fish otoliths consist of 99% aragonitic calcium carbonate which is deposited incrementally on an organic matrix within the inner ear epithelium of teleost fish (Degens et al., 1969, Casteel, 1976, Campana, 1999, Payan et al., 2002). Otolith growth is continuous and occurs even when somatic growth has ceased (Maillet and Checkley, 1990, Campana, 1999, Campana and Thorrold, 2001). Once deposited, the crystal structure of the otolith becomes metabolically inert. Teleost fish have three types of paired otoliths, the lapillus, astericus and sagittae (Panfili et al., 2002). The last are usually analysed in geochemical studies, due to their larger size and thus greater likelihood of unmodified preservation. The calcium carbonate deposition onto the otolith surface forms annual rings similar to those of trees. There is a well-established link between the number of pairs of light and dark rings and the number of years it took the otolith to form (Campana, 1999, Morales-Nin, 2000, Woydack and Morales-Nin, 2001). Annual banding has been validated in golden perch otoliths up to 22 years of age (Anderson et al., 1992, Stuart, 2006). Most studies have successfully employed banding identification for the determination of seasonal fluctuations in chemical composition across the otoliths from a range of fish (Wurster and Patterson, 2001) and for identifying the season of death (Higham and Horn, 2000, Disspain, 2009, Disspain et al., 2011).

Golden perch, *Macquaria ambigua*

The golden perch is a carnivorous, migratory fish today commonly found in the Murray-Darling River system of NSW and in the Lake Eyre and Bulloo drainage systems of Queensland, NSW and South Australia (Allen et al., 2002). Golden perch usually grow to between 40 and 50 cm in length, weighing less than 5 kg, but in extreme cases individuals may reach 75 cm in length and 23 kg in weight. They have an average life expectancy of about 10–12 years. The oldest on record was 26 years old (Mallen-Cooper and Stuart, 2003). Golden perch inhabit a wide range of environments including lakes, rivers and impoundments, but are commonly associated with turbid, slow flowing, lowland rivers. They can live in waters with temperatures between 4 °C and 35 °C and salinity levels up to the equivalent of seawater (Langdon, 1987). They have home ranges of about 100 m for weeks and months before they relocate to another river section, establishing a new home range (Lintermans, 2007). Males tend to mature at 2–3 years and females at 4 years. Golden perch have flexible breeding strategies with spawning and recruitment occurring both during full flood conditions and when waters rise only to the river banks. While some adult fish may migrate up to 1000 km upstream for spawning, such migrations are not essential. Juvenile fish feed on zooplankton while adults are predators living on invertebrates, frogs and smaller fish (Allen et al., 2002).

Geochemical archives in fish otoliths

The chemical composition of the endolymph fluid, from which otoliths are formed, controls the rate of calcium carbonate deposition on the otolith surface and is affected by environmental and biological variables such as temperature, spawning and food availability (Wurster and Patterson, 2001, Payan et al., 2002, Elsdon and Gillanders, 2004, Payan et al., 2004, Tohse et al., 2006). Because of their annual banding, otoliths can provide valuable annual time series of seasonal environmental changes.

Radiocarbon dating

Otoliths provide an ideal substrate for radiocarbon dating. Aragonite is the metastable carbonate polymorph, so the incorporation of autochthonous carbon through recrystallisation can be readily identified by the presence of calcite. The only potential problem is a freshwater reservoir effect, resulting from the incorporation of ancient carbon, e.g. from dissolved limestone. However, no evidence for a reservoir effect was found in modern shells (Gillespie et al., 2009) or archaeological samples (Gillespie and Roberts, 2000) in the region. Relatively few archaeological studies report otolith radiocarbon dates from the Willandra lakes (Gillespie, 1998, Bowler et al., 2012). This is perhaps due to the fact that otoliths are much rarer and smaller than mollusc shells, so the latter have been collected in preference for radiocarbon analysis.

Oxygen isotopes

Laboratory studies under controlled conditions have shown that O isotopes are incorporated in otolith calcium carbonate layers close to equilibrium with the ambient water, with a small fractionation effect caused by changing water temperatures (Kalish, 1991, Radtke et al., 1996, Pak et al., 1997, Patterson, 1999). The O isotope composition of surface waters depends on precipitation, floods, and the linking of different water source areas and is thus highly variable both spatially and over time. Due to the temperature dependence of $\delta^{18}\text{O}$ values in otoliths, past temperatures can be calculated if the contemporaneous water composition can be determined independently (Faure and Mensing, 2005).

Laboratory experiments on marine fish have shown that the O isotope composition of otoliths depends on neither kinetic nor metabolic effects (Høie et al., 2003). Temperature causes a change of about -1.0‰ change in $\delta^{18}\text{O}$ per 4.8 °C (Kalish, 1991). $\delta^{18}\text{O}$ has a positive relationship with salinity (Elsdon and Gillanders, 2002). Measurements between June 2002 and October 2005 along the Darling River between Bourke and Wilcannia, to the NE of the Willandra lakes, show that long term average $\delta^{18}\text{O}$ in the river water varied between 0.6 and 2.7‰ , each value having a standard deviation of $\sim 4\text{‰}$ (Meredith et al., 2009). There was a smooth sinusoidal seasonal relationship of higher $\delta^{18}\text{O}$ in summer and lower in winter (simply a function of rainwater $\delta^{18}\text{O}$ values being highly temperature dependent) with an amplitude of $\sim 7\text{‰}$. Note that the temperature relationship between the $\delta^{18}\text{O}$ in the otoliths and ambient water is opposite to the seasonal trends in the water.

Flooding events are marked by very rapid shifts towards lighter isotopic compositions with amplitudes of up to 12‰ between one monthly measurement and the next. The river water can take several months to return to the steady-state range of $\delta^{18}\text{O}$ values (Meredith et al., 2009). This work shows that any relationship between $\delta^{18}\text{O}$ and temperature in flowing river water will be masked by short term changes in the isotopic composition of the water caused by seasonal precipitation and flooding events.

With respect to the *easy prey* hypothesis, one would expect that once the water body in Lake Mungo is separated from the Willandra Creek system, the O isotopic composition of the remaining water will generally become heavier through evaporation. The increase in the $\delta^{18}\text{O}$ values will vary with the rate of evaporation and may be modulated by rain events. Seasonal temperature variations may be deduced from the variations in the general evaporative trend.

Elemental analyses

In the marine environment, Ba/Ca, Mg/Ca, U/Ca, B/Ca and Sr/Ca in various biological calcitic tissues have shown strong correlations with ocean water temperatures (Sadekov et al., 2005, Montagna et al., 2007, Sadekov et al., 2009). There are well documented differences observed in the elemental ratios of otoliths of fish moving through freshwater, estuarine and marine waters, with higher Sr/Ca found in marine and higher Ba/Ca found in freshwater (Gillanders, 2005). A positive relationship between the Sr content of otoliths and ambient salinity has also been observed, but the magnitude of this effect varies with ambient water Sr concentrations (Secor Secor and Rooker, 2000, Kraus and Secor, 2004, Tabouret et al., 2011).

Freshwater fish have only recently been studied for environmental effects on elemental uptake so the results are still being collated. Wells et al. (2003) were among the first to apply marine elemental techniques to freshwater fish. They found a linear relationship between the Sr/Ca

and Ba/Ca ratios in the water and associated otoliths. Walther and Thorrold (2006) found that most of the Sr and Ba in the otoliths of the estuarine *Fundulus heteroclitus* came from the water (83% of Sr and 98% Ba) and not food. Woodcock et al. (2012) found that Sr/Ca increased with increasing elemental concentrations in water as well as temperature, as did Ba/Ca, except below 10 °C. In contrast, Limburg and Kennedy et al. (2000) found that both Sr/Ca ratios and Sr isotope compositions in freshwater fish otoliths were significantly affected by changes in diet. These results suggest that species specific effects may influence the elemental uptake in otoliths. In addition, Andrus and Crowe, 2002 found that elemental data in otoliths may be affected by different cooking and trash disposal treatments via experiments with modern fish, but that of all the elements Sr was the most stable. Therefore, some caution is advised when interpreting geochemical fluctuations within otoliths from hearth or midden sites.

Samples

In this study we present the analysis of four sets of samples. All otoliths are from golden perch, and therefore differences resulting from poorly understood species-specific effects can be discounted. The first set consists of otoliths collected from the surface of the Mungo lunette, which originated from non-cultural contexts. The BMLM samples were collected in 2007 by Ian Moffat at the northern tip of the Mungo lunette from exposures of Unit E sediments. Seven samples were radiocarbon dated (Table 1), three were selected for isotopic analyses (BMLM 007, 211 and 158). The LAC samples were collected from massive, unconsolidated sands at the base of Unit E that represent a low, fore-dune setting. They were recovered from the surface of a small, shallow erosional basin towards the front of the Mungo lunette, at the northern edge of the foot survey area. No hearths or middens have been recorded in these sediments in this erosional basin and the surfaces of the otoliths exhibit pre-burial weathering and abrasion, suggesting that they were blown from the beach into the foredune. Five samples were analysed by radiocarbon dating (Table 1), two were selected for isotopic analyses (LAC 9001 and 9008). These samples formed the Honours thesis of Katarina Sporcic (nee Boljkovac) (Boljkovac, 2009).

Table 1 Radiocarbon results.

Sample number	S-ANU	$\delta^{13}\text{C}$	Uncalibrated age (BP)	Unmodelled (cal BP) 95.4%		Modelled (cal BP 95.4%)	
				From	To	From	To
Start MUIRU						19,878	18,676
Interval						0	1907
MULRU 04	8823	-6.0 ± 1.2	$15,500 \pm 90$	18,876	18,560	18,897	18,602
MULRU 11	8820	-3.4 ± 1.1	$15,750 \pm 90$	19,291	18,675	19,189	18,636
MULRU 12	8819	-4.7 ± 0.6	$15,720 \pm 90$	19,275	18,652	19,199	18,649
End MULRU						18,900	17,774
Start BMLM						21,149	20,157
Interval						0	2334
BMLM 007	8805	1.2 ± 0.4	$17,060 \pm 90$	20,515	19,879	20,453	19,967
BMLM 211	8806	-4.7 ± 0.4	$17,120 \pm 90$	20,921	19,964	20,514	20,042
BMLM 121	8807	4.8 ± 1.0	$17,240 \pm 90$	21,051	20,170	20,807	20,113
BMLM 158	8817	0.7 ± 0.5	$16,070 \pm 90$	19,430	18,920	20,468	18,928
BMLM 156	8818	-1.3 ± 0.8	$21,030 \pm 130$	25,569	24,589		
BMLM 008	8821	-6.8 ± 0.8	$16,980 \pm 90$	20,421	19,843	20,391	19,890
BMLM 010	8824	-2.9 ± 0.9	$17,020 \pm 90$	20,455	19,870	20,417	19,920
BMLM 011	8825	2.7 ± 1.1	$16,710 \pm 90$	20,194	19,554	20,320	19,577
End BMLM						20,332	18,487
Start LAC						24,703	20,367
Interval						1076	5825
LAC 9001	8811	-3.7 ± 0.6	$17,190 \pm 90$	21,011	20,121	20,973	20,114
LAC 9002	8812	-2.1 ± 0.6	$41,740 \pm 650$	46,224	44,315		
LAC 9004	8813	-3.5 ± 1.1	$16,820 \pm 90$	20,295	19,580	20,302	19,578
LAC 9008	8814	-1.7 ± 1.2	$17,510 \pm 100$	21,301	20,436	21,235	20,358
LAC 9009	8816	-4.6 ± 0.8	$16,090 \pm 90$	19,435	18,924	19,450	18,928
End LAC						19,463	15,573
Start Mungo hearths						19,490	19,333
Interval						0	239
926-1	27,812	-3.3 ± 2.2	$16,240 \pm 65$	19,575	18,938	19,448	19,303
926-2	27,811	-8.9 ± 1.3	$16,096 \pm 55$	19,430	18,943	19,431	19,293
926-3	27,814	-7.3 ± 0.5	$16,015 \pm 50$	19,408	18,920	19,425	19,280
926-3 (duplicate)	27,818	-5.0 ± 1.2	$16,000 \pm 50$	19,405	18,913		
926-4	27,813	-3.4 ± 0.6	$16,250 \pm 50$	19,576	18,949	19,450	19,305
953-5	27,810	-1.1 ± 0.9	$11,840 \pm 45$	13,826	13,486		
953-6	27,809	-3.0 ± 1.7	$16,190 \pm 55$	19,543	18,928	19,441	19,302
952-7	27,807	-5.2 ± 1.5	$16,060 \pm 55$	19,420	18,934	19,429	19,287
952-8	27,816	-7.1 ± 0.5	$16,075 \pm 50$	19,424	18,938	19,430	19,289
1168-9	27,806	-8.3 ± 1.2	$16,070 \pm 50$	19,423	18,938	19,429	19,288
982-11	27,805	-7.5 ± 1.3	$16,225 \pm 55$	19,566	18,941	19,446	19,305
End Mungo hearths						19,415	19,215

The third set was collected *in situ* from hearths in the foot survey area (Fig. 1). There is a cluster of 8 hearths in the upper part of Unit E (Fig. 2), each of which contains only the remains of fish, or an overwhelming predominance of fish. The otoliths from this sample set were collected from 5 of the hearths in this cluster and formed the Honours thesis of Kelsie Long (2012). Although one sample, 953-5, was found in proximity to hearth #953, it was not securely associated with this feature. All ten samples were radiocarbon dated, eight were analysed for O isotopes. Samples 953-5 and 1168-9 were not analysed further.

Figure 2. Fish hearth complex in central Mungo lunettes. Red dots represent individual otoliths. Numbers refer to hearth sites. Each square on the grid is equal to 10 m².

For comparison, three otoliths from the northern part of the Mulurulu lunette were radiocarbon dated (MULRU in Table 1), two (11 and 12) were selected for further isotopic analyses. These were found in the vicinity of a shell midden but were not clearly associated with it. They are part of Tegan Smith's forthcoming PhD thesis. OSL dating indicated an age in the range of 17.7 ± 1.1 ka to 24.6 ± 1.4 ka. The Mulurulu samples are used for comparison with the Mungo

samples, the former representing fish from the active river system while the latter were trapped in Lake Mungo following a flood event. Only the otoliths collected from hearths can be associated unequivocally with human activity but those fish may or may not have died as a result of active fishing.

Methods

The otoliths from the hearths were analysed in more detail than the other samples, so we describe the experimental techniques that were used for those samples. While there might be small differences in the pre-treatment and experimental setups for the other sets, we do not believe that these had any influence on the final results.

Sample preparation and aging

Otoliths were cut transversely through the nucleus using a diamond edged saw and again 5 mm towards the ventral axis. This centre section was then embedded in epoxy resin and the side closest to the nucleus was polished. The left-over parts were packaged separately for radiocarbon dating.

High resolution photographs of the transverse faces were taken and an initial age assessment made. After all other analyses were completed thin sections of these faces were developed and placed on microscope slides. These thin sections were then aged under the supervision of Mark Jekabson, an ecologist with the ACT Parks, Conservation and Land, following the method described by Anderson et al. (1992) and Stuart (2006). Younger fish bands were easily counted along the dorsal–ventral axis, but for older fish the bands across the proximal face on either side of the medial groove were most visible. A band was counted as an annual mark if it could be seen on both sides of the medial groove.

Radiocarbon analysis

A fragment of 50–80 mg was cut from the otolith. Assuming that diagenetic calcite is most likely found on the outside of the otolith the surface was removed in two stages. First, the surface was physically cleaned with a Dremel drill. Second, the sample was immersed in 0.1 M HCl at 80 °C until at least 10% weight was removed. About 10 mg of otolith was treated with 0.5 ml of 85% H₃PO₄ at 85 °C in a blood vacutainer™ evacuated to 3×10^{-3} Torr for 2 h or until the reaction was complete. The CO₂ generated was cryogenically purified and graphitised over an iron catalyst with H₂ before measurement in a NEC Accelerator Mass Spectrometer (Fallon et al., 2010).

Two samples of clean otolith, including the anomalously young sample 953-5, were screened for calcite by powder X-ray diffraction (XRD). About 10 mg of sample were crushed to a fine powder and suspended in an X-Ray transparent glue on a plastic film. XRD was performed in a STOE Stadi-P diffractometer operating at 30 mA and 40 kV. CoK α radiation was used with a step size and time of 0.5° and 60s between 24 and 60° 2 θ on the Bragg scale. Siroquant™ was used to quantify the calcite content. Neither sample contained measurable calcite (953-6,

$0.2 \pm 0.2\%$ calcite and 953-5, $0.0 \pm 0.2\%$ calcite). Given the consistency of the radiocarbon dates, it was not deemed necessary to screen the remaining samples.

Radiocarbon dates were calibrated against IntCal09 (Reimer et al., 2009) in OxCal v4.1 (Bronk Ramsey, 2009a). This program was also used to build Bayesian models from the dates from the Northern Mungo lunette, LAC and MULRU. In each area, it was assumed that all otoliths were deposited within a single *Phase* of unknown length, and that each sample had a 5% prior probability of being an outlier within the *General t-type Outlier Model* of OxCal v.4.1.7 (Bronk Ramsey, 2009a, Bronk Ramsey, 2009b). Obvious outliers (ANU-27819 (Mungo hearths), SANU-8818 (BMLM) and SANU-8812 (LAC)), more than 5000 years younger/older than the nearest sample, were excluded from the models. The *Interval* function was used to calculate the duration represented by each group of otoliths. All calibrated dates and modelled probability distribution functions are given at 95.4% probability unless otherwise stated.

***In situ* elemental analyses**

Elemental measurements were made using laser ablation *in situ* microsampling coupled to a Varian 820 quadrupole ICPMS. Laser ablation was performed in a He atmosphere, using an ArF excimer laser (wavelength of 193 nm) with aperture imaging optics producing an energy density at the sample surface of approximately 5 J cm^{-2} . Samples were mounted in an ANU “Helex” 2-volume sample stage, with rapid flushing of the ablation volume and thus minimal smearing out of any signal details originating from compositional variations at the sampling site.

Elemental ratios and concentrations were calibrated against analyses of both the NIST612 glass standard and an in-house carbonate standard, a Davies Reef coral (Alibert et al. 2003). Standards were measured at the beginning and end of each session in order to detect instrument drift. Anomalous peaks in the data sets were eliminated using a custom designed MATLAB program which also corrected for machine drift.

***In situ* oxygen isotope analysis**

In situ O isotope analysis of the samples from Mulurulu and the Lake Mungo surface samples were carried out using the ANU SHRIMP II in negative ion mode (Ickert et al., 2008). The instrumental setup and measurement conditions for those samples are described in detail by Aubert et al. (2012). The hearth samples were analysed with the newly-constructed SHRIMP-SI, a high resolution ion probe being developed at the ANU specifically for the analysis of low mass stable isotopes (Ireland et al., 2008). The SHRIMP SI is optimised for negative ion analysis, having secondary ion extraction optics designed to minimise light isotope fractionation, and operating under ultra-high vacuum to minimise interferences from hydrides and electron induced secondary ion emission.

After laser ablation analysis for trace elements, the otoliths were wet-polished to remove the laser tracks and then dried in a 60 °C oven overnight. They were then cut out of their large mounts and recast in epoxy resin, along with two standards (NBS18 carbonate: $\delta^{18}\text{O}_{\text{VPDB}} = -23.1\text{‰}$ and NBS19 limestone: $\delta^{18}\text{O}_{\text{VPDB}} = -2.2\text{‰}$) into three 25 mm diameter mounts suitable for the SHRIMP SI. Prior to analysis the mounts were washed with petroleum

spirit, RBS 35 solution and Millipore water respectively, dried for 24 h in a 60 °C vacuum oven, evaporatively coated with 12 nm of high purity Al, then stored overnight in the SHRIMP SI primary sample lock before being transferred via the high vacuum secondary sample lock into the analysis chamber.

The analytical procedure on SHRIMP SI was similar to that on SHRIMP II (Aubert et al., 2012), except that no correction for electron induced secondary ion emission was required. Between 32 and 61 spots separated by about 40 µm were analysed on 8 otoliths (a total of 353 spots over 3 days) in a profile towards either the dorsal or ventral axis, starting from the outer edge and moving in towards the nucleus to ensure that all later years of growth were sampled. The spots were positioned using reflected light photomicrographs and the SHRIMP visual optics, then analysed in automated mode. Each analysis started with a preburn of 90 s to allow the isotopic composition of the secondary ion beam to stabilise, during which the multi-collector electrometer baselines were measured. This was followed by automated optimisation of the secondary ion and electron beam steering. The O isotopes were measured for 100 s (5×20 s integrations) which, with ^{16}O count rates ≥ 2 GHz, gave internal precisions of $\sim 0.15\%$. Each analysis took 7 min. Multiple analyses of the primary standard (NBS19) had a standard deviation of 0.3‰. Analyses of the secondary standard (NBS18) yielded an average of -23.4% with a standard deviation of 0.4‰. The internal precision of each analysis was 0.5‰ or better.

Results and discussion

Radiocarbon

The radiocarbon results are shown in Table 1, and models in Fig. 3. Three of the four sets of dates have one sample that is clearly an outlier (Table 1), being more than 5000 years different from other samples from the same sample set, most likely due to reworking. The younger sample in the hearths data set was flagged as potentially reworked during the original sample collection (see above). The others were mostly surface finds and so temporal connections were not assured. Fig. 3 focuses on the radiocarbon results excluding these three outliers. The most precise chronological model has been produced using dates on the otoliths from the Mungo hearths. This is due to a combination of the large number of dates (e.g., MULRU set) and the absence of close outliers (e.g., BMLM) in addition to the true variability in ages (e.g., LAC).

Figure 3. Radiocarbon dates on otoliths calibrated against IntCal09 (Reimer et al. 2009) and modelled and plotted in OxCal v.4.1.7 (Bronk Ramsey, 2009a, Bronk Ramsey, 2009b). Pale probability distributions represent calibrated dates, and darker distributions modelled dates. Outlier probabilities are given after the same names in the format; posterior probability: assigned prior probability. Three clear outliers (more than 5000 years different, see Table 1) are not included in the models.

When modelled, all otoliths from the fish bone hearths (excluding 953-5) fall between 19,490–19,330 (upper limit) and 19,420–19,220 (lower limit) cal BP at 95.4% probability (Fig. 3). At 95.4% probability, all hearths were made within a time span of between zero and 240 years, with a shorter duration more likely than a longer duration. Sample 953-5 is significantly younger, probably eroded from younger sediments and blown onto the surface of Unit E. Although earlier research suggested that the Willandra Lakes system dried out between about 17 and 15 ka (Bowler et al. 2012), OSL ages from the central Mungo lunette indicated that the final drying of the lake did not occur until 14.5–14 ka (Fitzsimmons et al., 2014). This is consistent with the implications of the radiocarbon determination for otolith 953-5, which suggests that there was water in the lake around 13,800 years ago. It seems that systematic collection and radiocarbon dating of otoliths may shed further light on the intricacies of lake level reconstructions as well as human occupation events throughout the WLWHA.

The surface otoliths collected from LAC 9001–9009, excluding 9002, have a wider age range than those from the Mungo hearths, representing a period of 1080–5830 years, and most are slightly older, falling between ~21,200 and 19,600 cal. BP. The otoliths from the northern Mungo lunette (BMLM 007 to 211, excluding 156) are dated to a similar period, most likely prior to 20,000 cal BP, representing a time span of 0–2330 years. The otoliths from Mulurulu are slightly younger than those from the Mungo hearths, spanning a period of between 0 and 1910 years between 19,880 to 18,680 and 18,900 to 17,770 cal BP.

Only the otoliths collected *in situ* from hearths are likely to be free of reworked material. The radiocarbon results from the surface collections clearly indicate reworking. The incorporation of younger samples is most likely a recent process, while the incorporation of older material could have occurred recently or in the past. Despite this, most of the fish lived within a short time span around the Last Glacial Maximum and their isotopic compositions should be comparable.

The time resolution of the radiocarbon dating is fine enough to distinguish between the time periods represented by the hearth samples and those found on the surface of the survey area. Systematic analyses of local areas of hearth and midden samples will allow the reconstruction of pulses of human habitation in the WLWHA. Any such endeavours would be impossible using any other dating methods, such as luminescence, amino acid racemisation or electron spin resonance.

The results demonstrate that direct dating with radiocarbon is much more powerful than indirect dating with OSL, particularly in the age range of the Last Glacial Maximum. At Mulurulu, the sedimentary layer overlying the otoliths yielded an OSL result of 17.7 ± 1.1 ka and the underlying layer 41.9 ± 2.8 ka, indicating that the otoliths were deposited during an erosional phase onto a much older layer. Correlations with nearby sediments might tie the older age limit of the otoliths to an OSL result of 26.6 ± 1.4 ka, leaving an uncertainty of nearly 10 ka. At the fish hearth site, no OSL analyses were carried out in the immediate vicinity of the hearths. Correlations with equivalent sedimentary units yield ages in the vicinity of 20–25 ka. The relatively small random errors of the OSL results (5–8%) allow in principle the calculation of age estimates with high precision using a Bayesian approach. This, however, would entail unreasonable amounts of laboratory work and expense. Furthermore, in contrast to radiocarbon dating, systematic errors (in source calibration and gamma spectrometry) are difficult to address.

Elements and isotopes

For the comparison of the data sets obtained from a single otolith it is important to align the data to the same scale. The time/distance series obtained from the mass spectrometers were converted to the life span of the individual fish. As shown in Fig. 4, the inner annual rings of the otoliths are much wider (up to around 1 mm) than the outer rings (around 100 μm between 7 and 10 years). In much older fish, the annual rings may be reduced to a few tens of micrometres.

Figure 4. SHRIMP analytical spots and age lines for otolith #926-1.

When looking at the life history of a fish, it is easy to align the data series at the date of birth, which is represented by the centre of the otoliths. However, for the reconstruction of the lake level histories and fishing practices, it is more important that the data sets are aligned at the date of death, which is represented by the outer rim. In this study, analytical tracks were run on different depth sections (due to polishing in between runs) and different areas of the otoliths. This can incur misalignment which is perhaps best illustrated in Fig. 5. It can be seen that some of the O isotope analyses were carried out on domains that were not present in the section used for ageing. Whilst the trace elements (Sr/Ca and Ba/Ca) were measured simultaneously in the same tracks, $\delta^{18}\text{O}$ was measured after re-polishing along a different pathway. These misalignments may involve up to a one year offset when comparing $\delta^{18}\text{O}$ with the other data sets and perhaps up to two years when comparing the results of the different otoliths from a single hearth. While the misalignments do not affect observations of general trends, they make it impossible to ascertain and compare details.

Figure 5. Otolith #926-3 thin section used for aging compared to the location of the SHRIMP SI spots illustrating the loss of material between sampling and aging due to polishing.

In the data diagrams, the life history of the fish is from right (birth) to left (death). If the data were aligned on the centre (birth), the time scale runs from right to left (e.g. Fig. 6), if they were aligned on the rim of the otolith (time of death), the age scale runs from left to right (e.g. Fig. 7).

Figure 6. Oxygen isotopes (left) and Sr/Ca ratios (Right) of the two otoliths collected from the surface of the Lake Mulurulu lunette.

Figure 7. The oxygen isotope, Sr/Ca and Ba/Ca ratios plotted against otolith age lines for each of the otoliths collected *in situ* from the hearth sites.

Mulurulu otoliths: fish living in open river systems

The otoliths from Mulurulu represent fish that lived in an open river system. These two fish are by far the oldest in the otolith sample sets. Between the ages of 3 and 26 years, MULRU 11 (Fig. 6A) shows a long-term trend towards a lower $\delta^{18}\text{O}$ (from $\sim 4\text{‰}$ to -2‰) while MULRU 12 (Fig. 6C) shows a trend towards higher $\delta^{18}\text{O}$ between age 3 and 18, from -2‰ to 2‰ . From age 5, $\delta^{18}\text{O}$ shows regular variations in the range 2‰ – 6‰ that might be due to seasonal variations, but the data density is not high enough to demonstrate regular annual variations.

There is little variation in their low Sr/Ca ratios and $\delta^{18}\text{O}$ varies greatly and apparently randomly. Sharp fluctuations are most likely due to short term flooding events. From age 5, $\delta^{18}\text{O}$ shows regular variations in the range 2‰ – 6‰ that might be due to seasonal variations, but the data density is not high enough to demonstrate regular annual variations. Although these variations could be caused by changes in temperature, they are much more likely to be due to variations in the water composition. Similar changes have been measured in the Darling River water composition (Meredith et al., 2009), while a 4‰ shift would correspond to a temperature change of about $20\text{ }^{\circ}\text{C}$ (Kalish, 1991).

As there is no clear association of the fish with human activity it is not possible to ascertain whether they were actively fished (e.g. by spear hunting because they were large, or nets) or died of natural causes.

Otoliths from Mungo hearths

It is reasonable to assume that a hearth represents a single event and that the materials contained in the hearth were the spoils of a single meal.

Three otoliths from Hearth 926 (Fig. 7A to C) were analysed for Sr/Ca, Ba/Ca and O isotope ratios. When the results from these are plotted against fish years before death (ybd) based on otolith annuli several interesting features become clear. All otoliths show an increase in Sr/Ca ratios at a similar time to an increase of $\sim 4\text{‰}$ in the $\delta^{18}\text{O}$ ratios. Ba/Ca ratios seem to show a decline at around 8 ybd and a subsequent increase just before the Sr/Ca ratios also increase. The fluctuations in Ba/Ca are relatively low and although otoliths 1 and 4 show very similar ratios/trends in the later years, otolith 3 has ratios that are slightly higher. The values for all three at time of death are the same.

The Sr/Ca ratio of 926-1 indicates that the fish entered the lake about five years before it died, while 926-3 and 926-4 have very similar Sr/Ca records, implying that they entered the lake about three ybd. Interestingly, the Ba/Ca ratios of samples 926-1 and 926-4 are very similar for the last seven years the fish were alive, while that of 926-3 increases around the same time as its Sr/Ca does. The O isotope records for all three otoliths are closely related from five ybd, $\delta^{18}\text{O}$ increasing from ~ 4 to $\sim 8\text{‰}$ in that time. The spatial resolution of the O isotope sampling, just one analysis per ring in the later years, is too low to ascertain whether modulations on the increasing trend could be used for temperature assessment. It is unlikely that this increase is solely due to temperature change as a 4‰ change in $\delta^{18}\text{O}$ would be associated with a $20\text{ }^{\circ}\text{C}$ change in temperature and thus a change in the ambient water must be occurring with increasing values showing an evaporative trend.

Two samples were analysed from hearth 952 (Fig. 7D to F). There is a distinct increase in the $\delta^{18}\text{O}$ isotopes of both from around 3 ybd. Sr/Ca ratios hover around the same level for much of both fish's life and then increase from around 1 ybd for otolith 7 and 2 ybd for otolith 8. The Ba/Ca ratios fluctuate substantially throughout the lives of the fish but also show an increase at a similar time to the increase in the Sr/Ca ratios.

Fish 952-7 appears to have entered the lake only a year before its demise, as indicated by increasing Sr/Ca and Ba/Ca, while 952-8 entered two years earlier. For both fish the isotopic and elemental records are very similar between 4 and 7 ybd, indicating time shared in Lake Mungo. Both fish show an increase in $\delta^{18}\text{O}$ of $\sim 4\text{‰}$ from ~ 4 to 8‰ from the time the elemental records indicate their entry into Lake Mungo to their demise.

The otolith from hearth 953 (Fig. 7G–I) shows only a very small increase of Sr/Ca compared to the much stronger Ba/Ca signal increase a year before death. The $\delta^{18}\text{O}$ also increases markedly at this point by $\sim 5\text{‰}$, from 2 to 7‰ . This fish seems to have entered the lake a year before it was eaten.

The fish from hearth 982 (Fig. 7J to L) shows an increase in Sr/Ca ratios 5 ybd followed by a dip down at 3ybd and then a continuing increase up until death (Fig. 7K). The Ba/Ca ratios in this otolith changed very little during this time (Fig. 7L), but the $\delta^{18}\text{O}$ values increased from ~ 5 to 10‰ (Fig. 7J). This fish entered the lake about 5 years before it was harvested.

The $\delta^{18}\text{O}$ values of the otoliths from the hearth sites all increase towards the end of the life of the fish, but there seem to be two different trends in the O isotope compositions of the earlier fish years that become clear when the ratios are plotted against age from birth. These can be seen in Fig. 8, with the first group of O isotope compositions (926-1, 952-7 and 952-8) showing a very low $\delta^{18}\text{O}$ starting point between -4 and -7‰ . The second group (926-3, 926-4, 953-6, 982-11) all start at between 0 and 2‰ and stay between 0 and 5‰ until much later in the fishes' lives. It seems likely that the fish had two different spawning grounds, one perhaps in the Lachlan River, from which they migrated westward into Lake Mungo, the other perhaps in the Murrumbidgee or Murray rivers, the fish migrating from the south-west. Detailed O isotope records from the modern rivers are required to gain further insights into this hypothesis. Considering the similarities of the O isotope records of the otoliths, particularly those shown in Fig. 8B, one is tempted to argue that these could indicate a very short time range and that therefore all hearths were established during one lake evaporation event, perhaps over days or weeks.

Figure 8. Oxygen isotopes aligned on the birth of the fish. Two distinctive trends can be distinguished, as shown in A and B.

Sample 953-5 returned a significantly younger radiocarbon date (Table 1) and it is therefore, as expected, not directly associated with hearth 953. The Sr/Ca ratios increase around 4.5 ybd (Fig. 9), but this is followed by a dip at 3.5 ybd before a final rise during its last two years of life. At roughly the same time as the Sr/Ca dip, the $\delta^{18}\text{O}$ record shows a rapid decrease of ~6%. Given the strong association of $\delta^{18}\text{O}$ with ambient water composition this is most likely due to a flooding event. The evaporative increase in the $\delta^{18}\text{O}$ values at 4.5 ybd is 4%. This fish entered Lake Mungo but was either not trapped by evaporative conditions or a second flood pulse filled the lake. It is not possible to ascertain whether its death was natural or caused by human intervention.

Figure 9. The oxygen isotope (A) and elemental ratios (B) for otolith #953-5 (assumed to be out of context of hearth 953).

To summarise: the otoliths from the fish hearths are undoubtedly associated with human activity. All samples show some increase in Sr/Ca and Ba/Ca before death. All samples have a similar increase in $\delta^{18}\text{O}$ at about the same time as changes in the associated trace element ratios. Radiocarbon dating places these hearth sites in close temporal relationship suggesting that all fish may have been consumed within a very short time span, perhaps only days or weeks.

Otoliths from Mungo surface finds

Several otoliths were analysed from surface collections and it can therefore not be ascertained whether these were *in situ* and/or associated with human activity. Nevertheless, these still offer insights into the lake level history of Lake Mungo. Three samples (953-5, LAC 9001 and 9008) originated from the survey area. Sample 953-5 was found in the vicinity of hearth 953, but was already identified in the field as potentially reworked. A further three samples (BMLM 007, 158 and 211) were collected from the northern Mungo lunette.

The LAC and BMLM Sr/Ca and O isotope compositions are shown in Fig. 10. These are presented in relation to fish age rather than ybd, these are surface finds so we cannot associate their time of death.

Figure 10. Oxygen isotopes (left) and Sr/Ca ratios (right) of otoliths collected from sediment surfaces. LAC: base of Unit E in the foot survey area; BMLM: Unit E at the northern tip of the Lake Mungo lunette.

The LAC samples both show an increase in $\delta^{18}\text{O}$ at around age 7 for LAC 9001 (Fig. 10A) and age 5 for 9008 (Fig. 10C). Only LAC 9008 (Fig. 10B) shows an increasing trend in the Sr/Ca ratios from around 6 years. LAC 9001 (Fig. 10D) shows a peak in the Sr/Ca ratios at age 8 but this drops back fairly quickly. For LAC 9001 it is neither possible to identify a lake entry event nor an evaporative trend. LAC 9008 shows an entry into the lake around three ybd (Fig. 10D). The O isotope compositions vary greatly and one could speculate about two separate evaporation trends, one between 1.5 and 3.5 years, the second starting at about 5 years and ending with the death of the fish (Fig. 10C). The range in $\delta^{18}\text{O}$ in both is $\sim 10\text{‰}$.

BMLM 007 (Fig. 10E, F) shows an increase in Sr/Ca ratios at 2 years and this value never drops back to those in its early life. BMLM 158 (Fig. 10G, H) shows fluctuating $\delta^{18}\text{O}$ but no huge increase and low Sr/Ca ratios throughout its life. BMLM 211 (Fig. 10I, J) is similar to BMLM 007 with an increase in $\delta^{18}\text{O}$ from around 2 years of age and an increase in Sr/Ca ratios at just before 3 years. BMLM 007 and 211 entered the lake quite early in their lives at age 1.5 and 2, respectively. In both fish, $\delta^{18}\text{O}$ increases by 4‰ , from 2 to 6‰ . In contrast, BMLM 158 has an open river water signature with neither a pronounced increase in Sr/Ca at any time, nor an evaporative trend in $\delta^{18}\text{O}$.

All surface samples, except BMLM 158, show indications of fish entering the lake (increases in Sr/Ca) with subsequent evaporation (increases in $\delta^{18}\text{O}$). BMLM 158 shows the same patterns as those from Mulurulu, which indicate that this fish lived in the Willandra Creek system for nearly all of its life. Considering its age of nearly 13 years, it may well have died of natural causes.

Summary

In summary, we obtained the following results:

- Radiocarbon dating of otoliths from the hearth sites provided highly precise results. At 95.4% probability, all otoliths from these hearths were deposited within a time span of less than 240 years, somewhere between 19,490–19,330 cal BP and 19,420–19,220 cal BP. The radiocarbon results from the otoliths that were collected from the surface at Lake Mungo are generally a bit older and are significantly less precise. Otoliths from the surface of the Mulurulu lunette were younger, between 19,880–18,680 and 18,900–17,770 cal BP. The results demonstrate that direct dating with radiocarbon is much more powerful than indirect dating with OSL, particularly in the age range of the Last Glacial Maximum.
- The age of one otolith, identified as out of context, confirms the OSL chronology from the central Mungo lunette indicating that the lakes received periodic flood waters at least until 13.8 ka ago.
- The Mulurulu otoliths show little variation in their low Sr/Ca and represent fish that lived in an open river system. Short term flooding events are indicated by sharp fluctuations in $\delta^{18}\text{O}$.
- Most of the samples from Lake Mungo show increases in Sr/Ca and Ba/Ca some time before death. These increases, particularly in Sr/Ca, are taken to indicate the entry of the fish into a lake with no outflow and high salinity, most likely due to the accumulation of salts from past flooding and drying events. After the fish entered the lake, all otoliths from the hearth sites show an increase in $\delta^{18}\text{O}$ of $\sim 4\text{‰}$. The geochemistry of the otoliths reconfirms the

sedimentological implications that the hearths were constructed during times of widely fluctuating lake levels and rapid accumulation of sediments on the lunette. During times of sustained lake-full conditions traces of human activity are less abundant than during periods of oscillating lake conditions. It seems that the evaporating Lake Mungo attracted people to harvest fish using the *easy prey* technique.

- All but one of the surface otoliths from Lake Mungo show indications of the fish entering the lake (increases in Sr/Ca) with subsequent evaporation (increases in $\delta^{18}\text{O}$). BMLM 158 shows a similar pattern to those from Mulurulu indicating that the fish lived in the Willandra lakes system for nearly all its life. However, none of these otoliths can be directly associated with human activity.

Conclusions

The geochemical records preserved in fish otoliths from Lake Mungo represent a largely untapped resource for understanding lake level changes, chronology and aquatic exploitation by humans. There is also the potential to obtain further environmental data. As we have only analysed otoliths from a short time period around the Last Glacial Maximum, we have not attempted to use the O isotope compositions to reconstruct average temperatures. This would better be done using clumped isotope analysis. The next logical step will be to investigate otoliths spanning the whole history of the Mungo lunette from well before 50,000 years to the final drying out of the lakes around the end of the Pleistocene.

Radiocarbon dating of hearth otoliths can clearly resolve short time spans of human presence at the lake. Focusing on otoliths avoids some of the contamination problems that interfere with the reliable dating of shells and bones. Although otoliths contain little uranium, the closed system behaviour for radiocarbon implies that U-series dating has a potential to extend the dating range for otoliths back to several hundreds of thousands of years.

Acknowledgments

This research was undertaken with permission from the Elders Council of the Two Traditional Tribal Groups of the Willandra Lakes Region World Heritage Area and the Technical and Scientific Advisory and Community Management Committees of the WLRWHA. The otoliths were collected under a Cultural Heritage Impact Permit issued by the New South Wales Office of Environment and Heritage (No. 1131516), with the approval of the Elders' Council. We thank the Elders from the Paakantyi (Barkindji), Ngyiampaa and Mutthi Mutthi tribes for welcoming us into their country and for their participation in this work. The research was funded by an Australian Research Council Linkage Project grant (LP0775058) and Discovery Project grant (D1092966) and supported by La Trobe University, the Australian National University and the University of Wollongong. Some aspects of this research were funded through ARC Discovery Project DP110101415 to R. Grün. For their assistance in the field we are indebted to Daryl Pappin, the project's Cultural Heritage Officer, and Paul Kajewski, Rudy Frank and a dedicated group of student volunteers from La Trobe University. Fig. 1 was prepared by Rudy Frank.

References

- Alibert, C., Kinsley, L., Fallon, S.J., Mc Culloch, M.T., Berkelmans, R., McAllister, F., 2003. Source of trace element variability in Great Barrier Reef corals affected by the Burdekin flood plumes. *Geochim. Cosmochim. Acta* 67, 231e 246.
- Allen, G.R., Midgley, S.H., Allen, M., 2002. *Field Guide to the Freshwater Fishes of Australia*. Western Australian Museum, Perth.
- Allen, H., 1974. The Bagundji of the Darling Basin: cereal gatherers in an uncertain environment. *World Archaeol.* 5, 309e322.
- Allen, H., 1998. Reinterpreting the 1969e1972 Willandra Lakes archaeological surveys. *Archaeol. Ocean.* 33, 207e220.
- Anderson, J.R., Morison, A.K., Ray, D.J., 1992. Validation of the use of thin-sectioned otoliths for determining the age and growth of golden perch, *Macquaria ambigua* (Perciformes: Percichthyidae), in the Lower Murray-Darling Basin, Australia. *Aust. J. Mar. Freshw. Res.* 43, 1103e1128.
- Andrus, C.F.T., Crowe, D.E., 2002. Alteration of otolith aragonite: effects of prehistoric cooking methods on otolith chemistry. *J. Archaeol. Sci.* 29, 291e299.
- Aubert, M., Williams, I.S., Boljkovac, K., Moffat, I., Moncel, M.-H., Dufour, E., Grün, R., 2012. In situ oxygen isotope micro-analysis of faunal material and human teeth using a SHRIMP II: a new tool for palaeo-ecology and archaeology. *J. Archaeol. Sci.* 39, 3184e3194.
- Balme, J., 1995. 30,000 years of fishery in western New South Wales. *Archaeol. Ocean.* 30, 1e21.
- Barrows, T.T., Stone, J.O., Fifield, L.K., 2004. Exposure ages for Pleistocene periglacial deposits in Australia. *Quat. Sci. Rev.* 23, 697e708.
- Boljkovac, K., 2009. In Situ SHRIMP d18O and Laser Ablation ICP-MS Sr/Ca and 87Sr/86Sr Measurements in Fossil otoliths for Palaeoclimate Reconstructions at the Willandra Lakes

World Heritage Area. Unpublished Honours Thesis. Australian National University, Canberra, p. 91.

Bowler, J.M., Jones, R., Allen, H., Thorne, A.G., 1970. Pleistocene human remains from Australia: a living site and human cremation from Lake Mungo, Western New South Wales. *World Archaeol.* 2, 39e60.

Bowler, J.M., 1971. Pleistocene salinities and climate change: evidence from lakes and lunettes in southeastern Australia. In: Mulvaney, D.J., Golson, J. (Eds.), *Aboriginal Man and Environment in Australia*. Australian National University Press, Canberra.

Bowler, J.M., 1998. Willandra Lakes revisited: environmental framework for human occupation. *Archaeol. Ocean.* 33, 120e155.

Bowler, J.M., Johnston, H., Olley, J.M., Prescott, J.R., Roberts, R.G., Shawcross, W., Spooner, N.A., 2003. New Ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421, 837e840.

Bowler, J.M., Gillespie, R., Johnston, H., Boljkovac, K., 2012. Wind v Water: Glacial maximum records from the Willandra Lakes. *Terra Aust.* 34, 271e296.

Bronk Ramsey, C., 2009a. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337e360.

Bronk Ramsey, C., 2009b. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51, 1023e1045.

Campana, S.E., 1999. Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Mar. Ecol. Prog. Ser.* 188, 263e297.

Campana, S.E., Thorrold, S.R., 2001. Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? *Can. J. Fish. Aquatic Sci.* 58, 30e38.

Casteel, R.W., 1976. *Fish Remains in Archaeology and Palaeo-environmental Studies*. Academic Press, London, New York.

Degens, E.T., Deuser, W.G., Haedrich, R.L., 1969. Molecular structure and composition of fish otoliths. *Mar. Biol.* 2, 105e113.

Disspain, M., 2009. Using Archaeological Otoliths to Determine Paleoenvironmental Change and Ngarrindjeri Resource Use in the Coorong and Lower Murray, South Australia. Unpublished Honours thesis. Flinders University, Adelaide, p. 145.

Disspain, M., Wallis, L.A., Gillanders, B.M., 2011. Developing baseline data to understand environmental change: a geochemical study of archaeological otoliths from the Coorong, South Australia. *J. Archaeol. Sci.* 38, 1842e1857.

Elsdon, T.S., Gillanders, B.M., 2002. Interactive effects of temperature and salinity on otolith chemistry: challenges for determining environmental histories of fish. *Can. J. Fish. Aquatic Sci.* 59, 1796e1808.

Elsdon, T.S., Gillanders, B.M., 2004. Fish otolith chemistry influenced by exposure to multiple environmental variables. *J. Exp. Mar. Biol. Ecol.* 313, 269e284.

Fallon, S.J., Fifield, L.K., Chappell, J.M., 2010. The next chapter in radiocarbon dating at the Australian National University: status report on the single stage AMS. *Nucl. Instruments Methods Phys. Res. Sect. B: Beam Interact. Mater. Atoms* 268, 898e901.

Faure, G., Mensing, T.M., 2005. *Isotopes Principles and Applications*. John Wiley and Sons, Hoboken.

Fitzsimmons, K., Stern, N., Murray-Wallace, C.V., 2014. Depositional history and archaeology of the central Mungo lunette, Willandra Lakes, southeast Australia. *Journal of Archaeological Science* 41, 349e364.

Gillanders, B.M., 2005. Otolith chemistry to determine movements of diadromous and freshwater fish. *Aquat. Living Resour.* 18, 291e300.

Gillespie, R., 1998. Alternative timescales: a critical review of Willandra Lakes dating. *Archaeol. Ocean.* 33, 169e182.

Gillespie, R., Roberts, R.G., 2000. On the reliability of age estimates for human remains at Lake Mungo. *J. Hum. Evol.* 38, 727e732. Gillespie, R., Fink, D., Petchey, F., Jacobsen, G., 2009. Murray-Darling basin freshwater shells: riverine reservoir effect. *Archaeol. Ocean.* 44, 107e111.

Higham, T.F.G., Horn, P.L., 2000. Seasonal dating using fish otoliths: results from the Shag river Mouth site, New Zealand. *J. Archaeol. Sci.* 27, 439e448.

Høie, H., Folkvord, A., Otterlei, E., 2003. Effect of somatic and otolith growth rate on stable isotopic composition of early juvenile cod (*Gadus morhua* L) otoliths. *J. Exp. Mar. Biol. Ecol.* 289, 41e58.

Ickert, R.B., Hiess, J., Williams, I.S., Holden, P., Ireland, T.R., Lanc, P., Schram, N., Foster, J.J., Clement, S.W., 2008. Determining high precision, in situ, oxygen isotope ratios with a SHRIMP II: analyses of MPI-DING silicate-glass reference materials and zircon from contrasting granites. *Chem. Geol.* 257, 114e128.

Ireland, T., Clement, S., Compston, W., Foster, J., Holden, P., Jenkins, B., Lanc, P., Schram, N., Williams, I., 2008. Development of SHRIMP. *Aust. J. Earth Sci.* 55, 937e954.

Johnston, H., 1993. Pleistocene shell middens of the Willandra Lakes. In: Smith, M., Spriggs, M., Faunkhauser, B. (Eds.), *Sahul in Review: Pleistocene Archaeology in Australia, New Guinea and Island Melanesia*, pp. 197e203. Canberra.

Kalish, J.M., 1991. Oxygen and carbon stable isotopes in the otoliths of wild and laboratory-reared Australian salmon (*Arripis trutta*). *Mar. Biol.* 110, 37e47.

Kefous, K.C., 1977. We Have a Fish with Ears and Wonder if it Is Valuable?. Unpublished honours thesis ANU, Canberra, p. 76.

Kemp, J., Rhodes, E.J., 2010. Episodic fluvial activity of inland rivers in southeastern Australia: palaeochannel systems and terraces of the Lachlan River. *Quat. Sci. Rev.* 29, 732e752.

Kennedy, B.P., Blum, J.D., Folt, C.L., Nislow, K.H., 2000. Using natural strontium isotopic signatures as fish markers: methodology and application. *Can. J. Fish. Aquatic Sci.* 57, 2280e2292.

King, A., Tonkin, Z., Mahoney, J., 2008. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Res. Appl.* 25, 1205e1218.

Kraus, R.T., Secor, D.H., 2004. Incorporation of strontium into otoliths of an estuarine fish. *J. Exp. Mar. Biol. Ecol.* 302, 85e106.

Langdon, J., 1987. Active osmoregulation in the Australian Bass, *Macquaria novemaculeata* (Steindachner), and the golden perch, *Macquaria ambigua* (Richardson) (Percichthyidae). *Aust. J. Mar. Freshw. Res.* 38, 771e776.

Lintermans, M., 2007. Fishes of the Murray-Darling Basin: an Introductory Guide. MDBC Publication, 10/07.

Lomax, J., Hilgers, A., Radtke, U., 2011. Palaeoenvironmental change recorded in the palaeodune fields of the western Murray Basin, South Australia. New data from single grain OSL-dating. *Quat. Sci. Rev.* 30, 723e736.

Long, K., 2012. 'An Ear to the Ground': Fish Otolith Geochemistry, Environmental Conditions and Human Occupation at Lake Mungo., ANU. B.A (Hons), pp. 1e129 (website).

Maillet, G.L., Checkley Jr., D.M., 1990. Effects of starvation on the frequency of formation and width of growth increments in sagittae of laboratory-reared Atlantic menhaden (*Brevoortia tyrannus*) larvae. *Fish. Bull. U.S.* 88, 155e165.

Mallen-Cooper, M., Stuart, I.G., 2003. Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system. *River Res. Appl.* 19, 697e719.

Meredith, K.T., Hollins, S.E., Hughes, C.E., Cendón, D.I., Hankin, S., Stone, D.J.M., 2009. Temporal variation in stable isotopes (^{18}O and ^2H) and major ion concentrations within the Darling River between Bourke and Wilcannia due to variable flows, saline groundwater influx and evaporation. *J. Hydrol.* 378, 313e 324.

Montagna, P., McCulloch, M., Mazzoli, C., Silenzi, S., Odorico, R., 2007. The nontropical coral *Cladocora caespitosa* as the new climate archive for the Mediterranean: high-resolution (weekly) trace element systematics. *Quat. Sci. Rev.* 26, 441e462.

Morales-Nin, B., 2000. Review of the growth regulation processes of otolith daily increment formation. *Fish. Res.* 46, 53e67.

Panfili, J., Pontual, H.D., Troadec, H., Wright, P.J. (Eds.), 2002. *Manual of Fish Sclerochronology*. Ifremer-IRD Coedition, Brest, France, p. 464.

Pak, J.H., Liu, C.Y., Huangpu, J., Graham, J.S., Thorrold, S.R., Campana, S.E.,

Jones, C.M., Swart, P.K., 1997. Factors determining $\delta^{13}\text{C}$ and also $\delta^{18}\text{O}$ fractionation in aragonitic otoliths of marine fish. *Geochim. Cosmochim. Acta* 61, 2909e2919.

Patterson, W.P., 1999. Oldest isotopically characterized fish otoliths provide insight to Jurassic continental climate of Europe. *Geology* 27, 199e202.

Payan, P., Borelli, G., Priouzeau, F., De Pontual, H., Boeuf, G., Mayer-Gostan, N., 2002. Otolith growth in trout *Oncorhynchus mykiss*: supply of Ca^{2+} and Sr^{2+} to the saccular endolymph. *J. Exp. Biol.* 205, 2687e2695.

Payan, P., Pontual, H.D., Boeuf, G., Mayer-Gostan, N., 2004. Endolymph Chemistry and otolith growth in fish. *C. R. Palevol.* 3, 535e547.

Radtke, R.L., Showers, W., Mokesness, E., Lenz, P., 1996. Environmental information stored in otoliths: insights from stable isotopes. *Mar. Biol.* 127, 161e170.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G.,

Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R.L., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0e50,000 years cal BP. *Radiocarbon* 51, 1111e1150.

Robertson, A.I., Bunn, S.E., Walker, F., Boon, I., 1999. Sources, sinks and transformations of organic carbon in Australian floodplain rivers. *Mar. Freshw. Res.* 50, 813e829.

Sadekov, A., Eggins, S.M., De Deckker, P., Ninnemann, U., Kuhnt, W., Bassinot, F., 2009. Surface and subsurface seawater temperature reconstruction using Mg/ Ca microanalysis of planktonic foraminifera *Globigerinoides ruber*, *Globigerinoides sacculifer*, and *Pulleniatina obliquiloculata*. *Paleoceanography* 24. PA3201, 17p.

Sadekov, A.Y., Eggins, S.M., De Deckker, P., 2005. Characterization of Mg/Ca distributions in planktonic foraminifera species by electron microprobe mapping. *Geochem. Geophys. Geosyst.* 6. Q12P06, 14p.

Scholz, O., Gawne, B., Ebner, B.C., Ellis, I., 2002. The effects of drying and re-flooding on nutrient availability in ephemeral deflation basin lakes in western New South Wales, Australia. *River Res. Appl.* 18, 185e196.

Secor, D.H., Rooker, J.R., 2000. Is otolith strontium a useful scalar of life cycles in estuarine fishes? *Fish. Res.* 46, 359e371.

Shawcross, W., 1998. Archaeological excavations at Mungo. *Archaeol. Ocean.* 33, 183e200.

Stern, N., Tumney, J., Fitzsimmons, K.E., 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., Lawrence, S. (Eds.), *Archaeology in Environment and Technology: Intersections and Transformations*. Routledge, New York, London, pp. 31e50.

Stuart, I.G., 2006. Validation of otoliths for determining age of Golden perch, a long lived freshwater fish of Australia. *North Am. J. Fish. Manag.* 26, 52e55.

Tabouret, H., Lord, C., Bareille, G., Pécheyran, C., Monti, D., Keith, P., 2011. Otolith microchemistry in *Sicydium punctatum*: indices of environmental condition changes after recruitment. *Aquat. Living Resour.* 24, 369e378.

Tohse, H., Murayama, E., Ohira, T., Takagi, Y., Nagasawa, H., 2006. Localization and diurnal variations of carbonic anhydrase mRNA expression in the inner ear of the rainbow trout *Oncorhynchus mykiss*. *Comp. Biochem. Physiol. Part B: Biochem. Mol. Biol.* 145, 257e264.

Walther, B.D., Thorrold, S.R., 2006. Water, not food, contributes the majority of strontium and barium deposited in the otoliths of a marine fish. *Mar. Ecol. Prog. Ser.* 311, 125e130.

Wells, B.K., Rieman, B.E., Clayton, J.L., Horan, D.L., Jones, C.M., 2003. Relationships between water, otolith, and scale Chemistries of Westslope Cutthroat Trout from the Coeur d'Alene river, Idaho: the potential application of Hard-Part Chemistry to describe movements in freshwater. *Trans. Am. Fish. Soc.* 132, 409e424.

Woodcock, S., Munro, A., Crook, A., Gillanders, B., 2012. Incorporation of magnesium into fish otoliths: determining contribution from water and diet. *Geochim. Cosmochim. Acta* 94, 12e21.

Woydack, A., Morales-Nin, B., 2001. Growth patterns and biological information in fossil fish otoliths. *Paleobiology* 27, 369e378.

Wurster, C.M., Patterson, W.P., 2001. Late Holocene climate change for the eastern interior United States: evidence from high-resolution $\delta^{18}\text{O}$ values of sagittal otoliths. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 170, 81e100.