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Holocene lake salinity changes in the Wimmera, southeastern Australia, provide evidence for millennial-scale climate variability

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ABSTRACT

Palaeosalinity records for groundwater-influenced lakes in the southwest Murray Basin were constructed from an ostracod-based, weighted-averaging transfer function, supplemented with evidence from *Campylodiscus clypeus* (diatom), charophyte oogonia, *Coxiella striata* (gastropod), *Elphidium* sp. (foraminifera), *Daphniopsis* sp. ephippia (Cladocera), and brine shrimp (*Parartemia zietziana*) faecal pellets, the $\delta^{18}O$ of ostracods, and >130 μm quartz sand counts. The chronology is based on optically stimulated luminescence and calibrated radiocarbon ages. Relatively wet conditions are marked by lower salinities between 9600 yr and 5700 yr ago, but mutually exclusive high- and low-salinity ostracod communities suggest substantial variability in effective precipitation in the early Holocene. A drier climate was firmly in place by 4500 yr and is marked at the groundwater-dominated NW Jacka Lake by an increase in aeolian quartz and, at Jacka Lake, by a switch from surface-water to groundwater dominance. Short-lived, low-salinity events at 8800, 7200, 5900, 4800, 2400, 1300 and 400 yr are similar in timing and number to those recorded on Australia's southern continental shelf, and globally, and provide evidence for the existence of the ~1500-yr cycle in mainland southern Australia. We surmise that these are cool events associated with periodic equatorward shifts in the westerly wind circulation.

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Introduction

Millennial-scale climate variability has been a major focus of Quaternary research for the last decade (Clark et al., 1999) and there has been a call for evidence from marine and terrestrial sites in the Southern Hemisphere (Alley et al., 1999). In the Northern Hemisphere, the pattern of change is now reasonably well understood (Mayewski et al., 2004; Wanner et al., 2008), but the Southern Hemisphere remains a problem because of the high spatial variability and low resolution of available records (Seager and Battisti, 2007). Limited evidence for Holocene climatic variability has emerged in Australia (Chivas et al., 1986, 1993; De Deckker et al., 1991; Gell et al., 1994; Stanley and De Deckker, 2002; Turney et al., 2004; Donders et al., 2007; Gouramanis et al., 2010), and the Southern Ocean (Charles et al., 1996; Ninnemann et al., 1999; Gingele et al., 2007; Moros et al., 2009), and is recorded in Antarctic ice cores (Masson et al., 2000; Masson-Delmotte et al., 2004; Marino et al., 2008; Gabrielli et al., 2010) and glacial advances (Allen et al., 2010). Consequently, it is expedient to explore the potential of other proxies for extracting detailed information from the sediment records of Australian lakes.

Transfer functions calibrated from modern datasets define a mathematical relationship between the composition of a group of aquatic organisms (e.g., cladocerans, diatoms, ostracods) and abiotic variables. All of these have revolutionised palaeolimnology by allowing the relative magnitudes of chemical signals to be quantified (Birks, 1995, 2003), often with a high degree of accuracy, and can yield more finely resolved records compared to broad trends inferred by lake level studies or pollen analysis (e.g., Fritz et al., 1991, 1994). Despite the demonstrated reliability of ostracods for inferring broad salinity changes in southeastern Australian lakes (De Deckker, 1982; Chivas et al., 1985), and the effectiveness of ostracod-based quantitative reconstructions in North America (Delorme, 1971a, 1971b; Delorme et al., 1978; Smith, 1991), the use of ostracod-based transfer functions for inferring chemical changes in lake records has been underutilised in Australia until recently (see Chivas et al., 1986; Gouramanis and De Deckker, 2010; Gouramanis et al., 2010; De Deckker et al., 2011). This paper redresses this gap and presents high-resolution palaeosalinity records for the Holocene based on lake sediment cores from a semi-arid region of southeastern Australia.

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The Mt. Arapiles Lake Complex

The Wimmera lakes (centered on 36°48' S, 141°48' E; 132 m a.s.l.) occupy a ~100-km-long, 4–5 km wide relict valley, mostly infilled with <30 m of sediment (Fig. 1). To the northwest, a quartz arenite monolith at Mt. Arapiles rises >200 m above the plain. The water table lies close to the surface or outcrops in a chain of brackish to hypersaline lakes, which are groundwater-dominated in solute terms (Brownbill, 1995). Lakes are particularly abundant in the recharge zone around the margins of Mt. Arapiles, and include Jacka Lake and Northwest (NW) Jacka Lake.

The Wimmera experiences a Mediterranean-type climate with hot summers and cool winters. Mean annual rainfall near the study area is 400 mm and falls dominantly in winter from fronts embedded in the Southern Hemisphere Westerlies. Evaporation averages 1600 mm yr^{-1}, substantially exceeding precipitation except, intermittently, in winter months. Recharge at Mt. Arapiles is estimated at 30–100 mm yr^{-1} (McAuley et al., 1992). Rainwater enters Mt. Arapiles through fractures in the sandstone or through the porous colluvium at its margins. These two groundwater components can be differentiated hydrochemically, because the deeper flow system does not acquire alkalinity (Alk) through weathering reactions to the same extent as groundwater entering the colluvium (Radke and Howard, 2007). Consequently, the hydrochemistry of the fracture system closely resembles that of seawater (Ca>Alk; herein referred to as Path 1), whereas the hydrochemistry of the colluvial system follows a solute evolutionary pathway in which alkalinity equivalents exceed those of Ca (herein referred to as Path 2). Regional groundwaters of the Path 2 chemical-type also move northward in the valley and interact with the chain of lakes (Radke and Howard, 2007). Significantly, the monolith provides the hydraulic head that sustains many of the lakes at its periphery. The estimated transit time of the groundwater from the outcrop to the lakes is ~200 yr (K. Howard, personal communication). During storm events, surface runoff generated at Mt. Arapiles can dilute solutes that have evaporatively concentrated in some of the lakes. West of the lakes, the Lowan Sand is an outlier of the Mallee continental dunefield, which consists of (now vegetated) longitudinal dunes last mobilised ~13,800 yr ago (Wasson, 1984). Sand from this area can be transported into both lakes by wind and major flooding events, and into Jacka Lake also by running water.

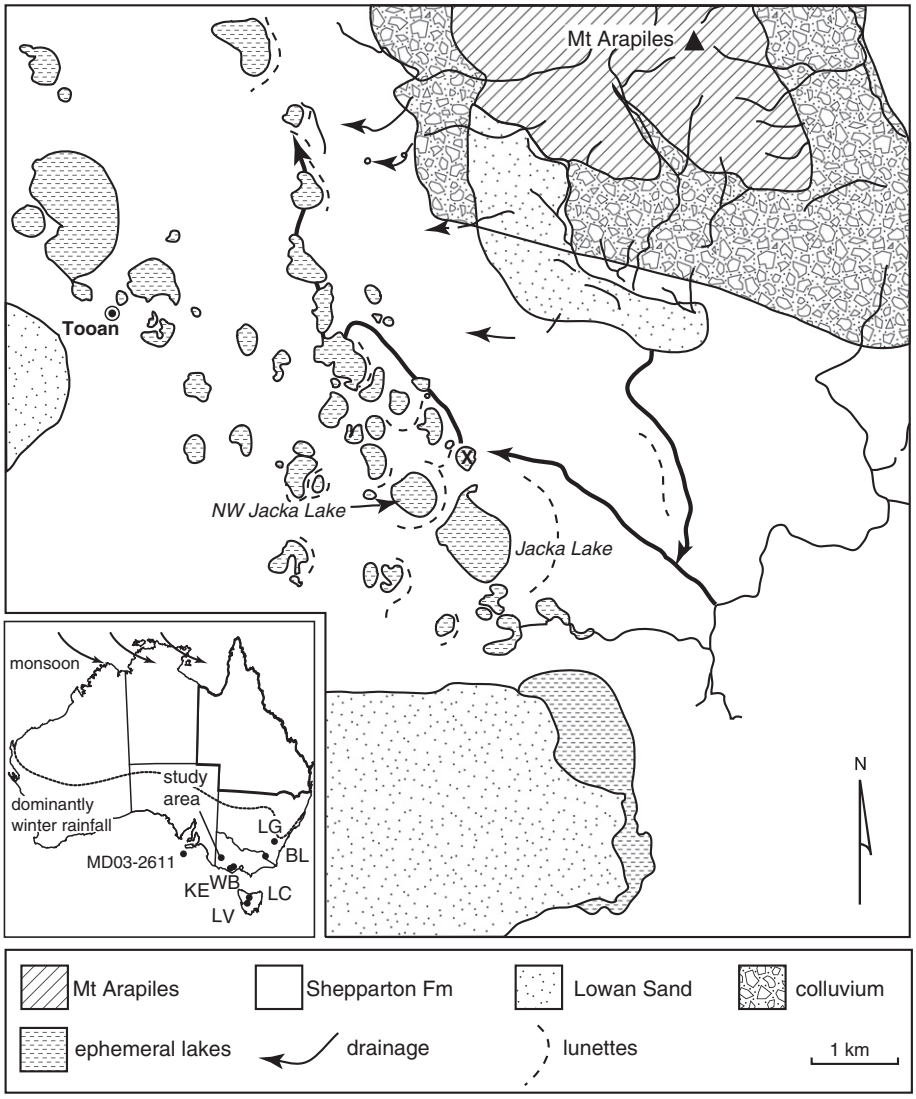


Figure 1. Map showing the proximity of Jacka Lake and NW Jacka Lake to Mt. Arapiles. The dark arrows indicate the main pathways followed by modern runoff. The main system by which runoff enters the lakes is marked with an "X", and was determined by air-photo interpretation. NW Jacka Lake does not receive runoff generated at the monolith because it is separated from the system of depressions by a local topographic feature. Map (inset) shows the location of the study site, weather systems, and localities mentioned in the text: LG = Lake George; BL = Blue Lake; LC = Lynd's Cave; LV = Lake Vera; KE = Lake Keilambete; WB = West Basin Lake; and marine core MD03-2611. Dotted line shows the boundary of dominantly winter rainfall derived from the Westerlies.

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Under modern conditions, Jacka Lake is semi-permanent, drying every 4–5 yr, and follows a Path-2 solute evolutionary pathway (Radke and Howard, 2007). NW Jacka Lake, by comparison, has a calcium-to-alkalinity ratio (Ca/Alk) that approximates unity, and models suggest that it gets a 30–40% contribution from the groundwater system that is conducted by fractures (Radke and Howard, 2007). The lake currently enters a seasonal cycle of winter wetting with the dissolution of a minor salt crust, followed by summer drying with salt crust deposition. The higher stage at Jacka Lake allows throughflowing waters to enter NW Jacka Lake (Brownbill, 1995).

Methods

Core extraction and processing

Cores ~1.5 m in length were obtained from Jacka Lake and NW Jacka Lake in 1994 by hammering PVC pipes fitted with a piston and an anvil into the sediments, and removed with a winch. In the laboratory, the cores were split lengthwise and 0.5–1.0 cm samples were taken for ostracods at ≤5-cm intervals. Sample preparation followed methods described in De Deckker (1982). Samples were weighed into 100-ml glass jars. Three percent hydrogen peroxide was added to facilitate clay separation and the dissolution of organic matter. When the reaction was complete, the samples were washed through 150-μm sieves, oven dried at <40°C, and transferred to glass scintillation vials for storage prior to identification and counting. Samples for water content, taken from the same horizons as the ostracod samples, were determined by weight-loss after oven drying at 90°C for 24 h.

Fossil ostracods

Adult ostracod valves were identified, counted, and stored on micropalaeontological slides. Samples were often split with a standard micro-splitter prior to counting and the final count was determined proportionally. Adult valves of large species were often found broken and instars (juveniles) of an identical size and species were counted in their place. Counts were converted to valves per gram dry weight for presentation by correcting for water content, and to percentages for use in transfer functions. Ostracod species that could not be distinguished to species level by shell characteristics were grouped as species complexes or at higher taxonomic levels (e.g., *Reticypris* sp., *Mytilocypris praenuncia–M. mytiloides*, and *Australocypris* sp.). In addition, *Diacypris dictyote* was found in the NW Jacka core, but was not represented in the modern dataset. The median salinity (40 g L^{-1}) for the occurrence of this species was close to the optimum of *D. dietzi* (Radke et al., 2003). Consequently, counts of this species were pooled with those of *D. dietzi* for use in transfer functions. Sand grains (predominantly quartz) and biological remains that could be readily identified in the 150-μm sieve fraction were also enumerated. The biological evidence included the tests of foraminifera, a group of predominantly marine microorganisms also found in salt lakes in Australia that have Na–Cl dominant waters (see De Deckker and Geddes, 1980; Cann and De Deckker, 1981), together with charophyte oogonia, diatom *Campylodiscus clypeus* frustules, shells of the gastropod *Coxiella striata*, cladoceran epphipia belonging to *Daphniopsis* sp., brine shrimp (*Parartemia zietziana*) faecal pellets, and limbs of the oniscoid *Haloniscus* sp.

Ostracod transfer function

119 samples of living ostracods and water chemistry were collected seasonally from 73 lakes between August 1993 and December 1994 by methods outlined in Radke et al. (2003). Ostracod-based transfer functions for log salinity (g L^{-1}) were developed from this dataset by applying weighted averaging regression and calibration (ter Braak and van Dam, 1989; Birks et al., 1990) with tolerance down-weighting (WAT) using C2 version 1.5 (Juggins, 2007). Tolerance downweighting was used because it yielded a small but significant reduction in cross-validation prediction error ($p = 0.03$) assessed using a randomisation *t*-test (van der Voet, 1994). Salinity was reconstructed because (i) it was the main control on ostracod distributions in the modern dataset (Radke et al., 2003); and (ii) ion concentration is coupled to climate through the water balance, allowing inferences to be made about change in past effective precipitation (P/E). Outliers were identified in trial runs as samples having a residual (observed − inferred) and were omitted from subsequent analysis. Transfer function performance was measured by the squared correlation (r^2) between observed and inferred values, the root mean square error (RMSE) (observed − inferred), and by the more reliable RMSE of prediction determined under leave-one-out cross validation (RMSEP; ter Braak and Juggins, 1993). Details of the WAT regression and calibration for log salinity are available in Radke (2000). The results show a good agreement between observed and estimated log salinity ($r^2 = 0.91$), and the model has low RMSE and RMSEP (0.17 and 0.27 $\log_{10}$ units, respectively).

Geochemistry

Biogenic carbonate samples for isotopic analysis typically weighed between 200 and 250 μg and consisted of tests of the foraminifer genus *Elphidium* and valves of *Diacypris compacta* and *Reticypris* sp. Measurements of $\delta^{18}O$ were made on a Finnigan MAT 251 mass spectrometer with a Kiel microcarbonate device at the Australian National University. Solid carbonate samples were placed into glass reaction vessels and were dosed with 105% phosphoric acid at 90°C for 13 min. The working gas has an isotopic composition of $\delta^{18}O_{V\text{-}PDB} = -1.63‰$; $\delta^{13}C_{V\text{-}PDB} = +2.13‰$. Data were corrected for ^{17}O interference using the method of Santrock et al. (1985) and were normalised such that a sample of solid NBS 19 standard would yield $\delta^{18}O_{V\text{-}PDB} = -2.20‰$; $\delta^{13}C_{V\text{-}PDB} = +1.95‰$. Selected samples were submitted for mineral identification by a random powder X-ray diffraction (XRD) method using a D500 Siemens X-ray diffractometer with θ/2θ geometry, a curved graphite monochromator, a scintillation detector, and Cu Kα radiation at the Australian National University.

Dating

Samples of bulk sediment and ostracods were radiocarbon-dated following procedures outlined in Gupta and Polach (1985) at the Australian National University, or dated using AMS techniques at the Australian Nuclear Science and Technology Organisation. AMS samples were graphitised by the late John Head at the ANU and then analysed at ANSTO by Dr. Ewan Lawson. Radiocarbon ages were calibrated using Calib 6.0.1 (Stuiver and Reimer, 1993). Quartz sand samples extracted from the lakes were dated by optically stimulated luminescence (OSL) using the single aliquot regenerative-dose (SAR) protocol. Table 1 provides details on the OSL calculations including water contents, dose rates, burial dose estimates, and calculated burial ages. A full account of the method and

Table 1
Mode of transport, sampling depths, water contents (% of dry weight), dose rates (D_r), burial dose estimates (D_b), and calculated burial ages.

Sample name	Mode of transport	Depth (cm)	Water (%)	D_r (mGy/year)	D_b (Gy)	Burial age (years)
NWJ16	Aeolian	16	40.0	0.82 ± 0.07	1.30 ± 0.13	1590 ± 215
NWJ 68	Aeolian	68	51.1	0.88 ± 0.05	4.40 ± 0.30	5000 ± 470
NWJ 105	Aeolian	105	54.3	1.28 ± 0.14	8.60 ± 0.12	6750 ± 800
JL23	Aeolian	23	59.9	2.09 ± 0.17	0.06 ± 0.01	29 ± 15
JL46	Aeolian	46	49.2	1.63 ± 0.11	1.00 ± 0.20	615 ± 130
JL66	Aeolian	66	56.3	1.86 ± 0.11	1.83 ± 0.10	985 ± 85
JL139	Aeolian	139	49.0	2.43 ± 0.31	18.2 ± 0.8	7500 ± 1000
JL150	Aeolian	150	33.0	3.53 ± 0.50	24.8 ± 0.8	7000 ± 1000

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background on the OSL ages used in this study is provided in Olley et al. (2004). The calibrated ^{14}C age ranges, together with the OSL ages (Table 2), were used to develop age–depth relationships for the cores (Fig. 2). The calibrated ^{14}C age for the sample collected from a depth of 23 cm from the Jacka Lake core is 520 ± 160 yr; this compares with an OSL age for the same depth increment of 29 ± 15 yr. The anthropogenic fallout radionuclide ^{137}Cs is also present at this depth, and indicates an age of less than 45 yr (Olley et al., 1991), supporting the OSL age. We interpret the disparity between the OSL and calibrated radiocarbon age as indicating that at the time of deposition older carbon was present, resulting in a carbon age offset from the true burial age of 490 ± 160 yr. In developing the age–depth relationships for both lakes, we have assumed this offset is present in all of the radiocarbon ages and have corrected the radiocarbon burial ages accordingly (Fig. 2). The two radiocarbon ages from the bottom of the NW Jacka core (ANU-9811, and OZAO35) are clearly out of stratigraphic order. With the exception of these two samples, all the corrected radiocarbon ages and OSL dates were used in developing the age–depth relationships. The data were fitted with linear regression models with an inverse weighting on the associated age uncertainties. The relevant equations are shown in Figure 2.

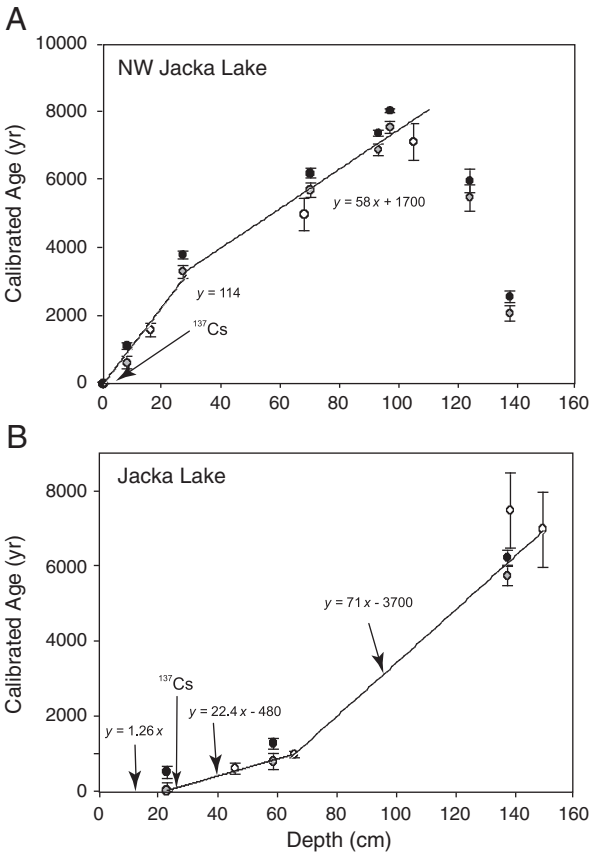


Figure 2. Age–depth chronology for NW Jacka Lake and Jacka Lake. The OSL dates (open circles) are shown with uncertainties equivalent to one standard error, while the radiocarbon dates are presented as midpoint and range (black [uncorrected] and gray [offset-corrected] closed circles). The calculations assume constant sedimentation rates between samples. However, intervals without dates between ~70 cm and ~140 cm (Jacka) and between ~40 cm and ~70 cm (NW Jacka) increase chronological uncertainties in these sections of the record. Radiocarbon calibrations were performed using Calib 6.0.1 (Stuiver and Reimer, 1993). The least significant figures in the equations indicate the associated uncertainties equivalent to one standard error.

Results

Biostratigraphy

Counts of ostracod valves ranged from 0 to 2000 individuals per gram dry weight and are shown in their stratigraphic contexts in Figures 3 and 4.

NW Jacka Lake

The record from NW Jacka Lake is divided into four zones (Fig. 3) based on the salinity reconstructions.

Zone I (168–135 cm; >9640 yr)

Brine shrimp (*P. zietziana*) faecal pellets, which are recognised by their length, width, and broken ends (De Deckker, 1988), are the main biological evidence in the early part of the record. The sediments in this interval consist of laminated dolomitic mud alternating with organic-rich clay layers consisting of montmorillonite, illite, and minor kaolin.

Zone II (135–50 cm; 9640–4620 yr)

Lithologies are more variable between 130 and 65 cm depth. The sediment is organic-rich, calcareous mud with varying abundances of dolomite and ankerite. Dolomite commonly occurs as intermittent laminae, and crusts, indicating changes in water chemistry and precipitation at the sediment–water interface. Each sample records ~30–60 yr of sediment accumulation, depending on thickness (0.5

Table 2
Radiocarbon and OSL dates and standard errors (SE) for depths in the Northwest Jacka and Jacka Lake cores. Radiocarbon calibrations were performed using Calib 6.0.1 (Stuiver and Reimer, 1993).

Lake	Depth	Material dated	Code	^{14}C age	SE	Calibrated age range	OSL age	Error
Northwest Jacka	8	Bulk sediment	ANU-9808	1130	70	962–1167		
Northwest Jacka	16	Quartz sand	NWJ16				1590	215
Northwest Jacka	27	Ostracod valves	OZAO33	3480	90	3638–3863		
Northwest Jacka	68	Quartz sand	NWJ68				5000	470
Northwest Jacka	70	Bulk sediment	ANU-9809	5410	90	6022–6298		
Northwest Jacka	93	Ostracod valves	OZAO34	6420	100	7261–7428		
Northwest Jacka	97	Bulk sediment	ANU-9810	7200	110	7939–8161		
Northwest Jacka	105	Quartz sand	NWJ105				6750	800
Northwest Jacka	124	Bulk sediment	ANU-9811	5130	320	5587–6279		
Northwest Jacka	137.5	Ostracod valves	OZAO35	2420	110	2349–2699		
Jacka	23	Bulk sediment	ANU-9805	460	140	317–632		
Jacka	23	Quartz sand	JL23				29	15
Jacka	46	Quartz sand	JL46				615	130
Jacka	59	Bulk sediment	ANU-9806	1350	130	1191–1385		
Jacka	66	Quartz sand	JL66				985	85
Jacka	138	Bulk sediment	ANU-9807	5430	170	5999–6395		
Jacka	139	Quartz sand	JL139				7500	1000
Jacka	150	Quartz sand	JL150				7000	1000

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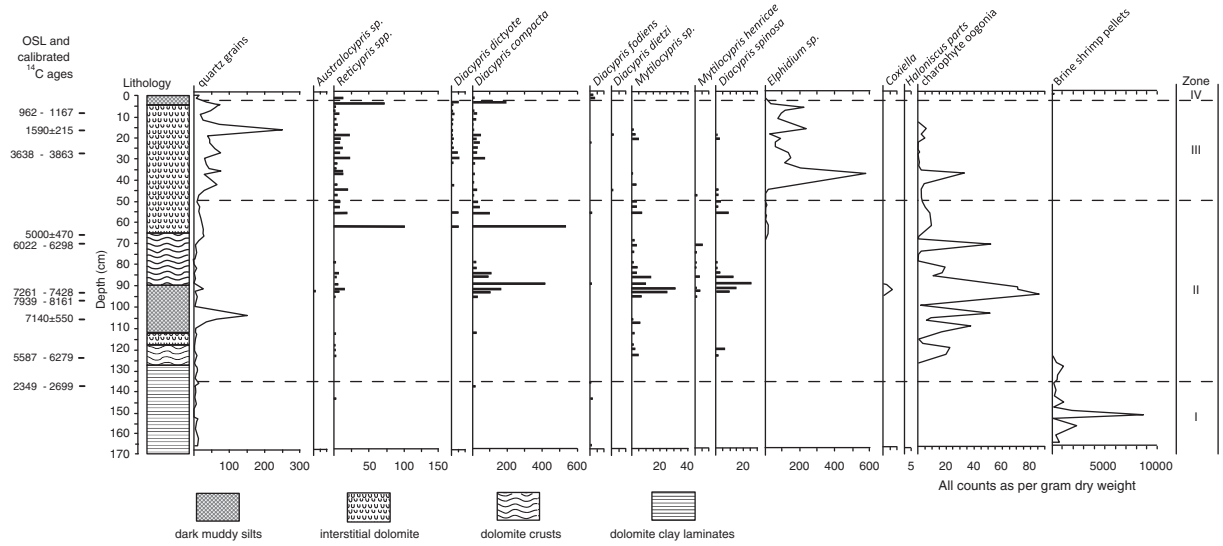


Figure 3. Lithostratigraphy and biostratigraphy of NW Jacka Lake, listing the presence and counts of key organisms and sediments used for palaeoenvironmental reconstructions. Refer to Table 2 for dating details.

or 1 cm), and most show evidence for mutually exclusive higher or lower salinity ostracod communities. The higher salinity ostracod assemblage consists of *Reticypris* sp. and *D. compacta*, with occasional *Diacypris fodiens* and *Australocypris* sp., whereas the lower salinity ostracod assemblage consists of *M. praenuncia*/*mytiloides*, *Diacypris spinosa* and *M. henricae*. A large quartz sand spike at 110–100 cm corresponds to a period of low ostracod productivity.

Zone III (50–3 cm; 4620–340 yr)

The lower salinity ostracods disappear from the record, or are found in low abundance, while *Reticypris* sp. and *D. compacta* dominate. Significantly, *D. dictyote* and the foraminifer *Elphidium* sp. become dominant. The sediments comprise massive dolomitic mud. The dolomite sometimes infills ostracod valves suggesting that some valves may have been lost to the dolomitisation process. Quartz sand abundances are high throughout the zone.

Zone IV (3–0 cm; 340 yr–present)

Brine shrimps inhabited the lake at the time of this study from September 1993 to December 1994, and their faecal pellets were found in the surficial sediments of this zone. Halite dominates the XRD traces but could be the result of interstitial waters that dried up since the core was obtained.

Jacka Lake

The biostratigraphical zones at Jacka Lake (Fig. 4) corresponds to those at NW Jacka Lake, although Zone I is not present.

Zone II (158–116 cm; <7770–4620 yr)

The sediments at the lower part of Zone II are mottled and consist of clay lumps with abundant sand. The diatom *C. clypeus* and the gastropod *C. striata* are found in the upper part of the zone. Ostracod preservation is poor.

Zone III (116–30 cm; 4620–190 yr)

Zone III (116–30 cm; 4620–190 yr) consists of organic-rich silts with abundant microscopic pyrite framboids. The ostracods preserved in this zone consist mainly of *M. henricae* and *D. spinosa*, with occasional freshwater (*Limnocythere mowbrayensis*, *L. dorsosicula*, *Ilyodromus viridulus*, *Sarscypridopsis aculeata*, and *Candonocypris novaezelandiae*) and halophilous/halobiont (*D. compacta*, *D. dietzi*, and

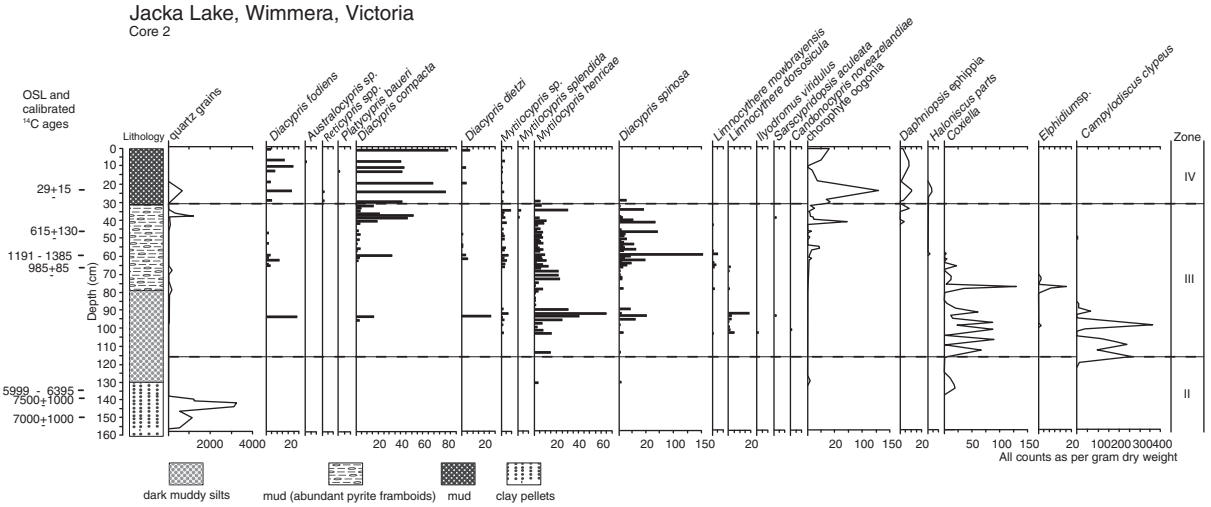


Figure 4. Lithostratigraphy and biostratigraphy of Jacka Lake listing the presence and counts of key organisms and sediments used for palaeoenvironmental reconstructions. Refer to Table 2 for dating details.

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D. fodiens) species. The diatom *C. clypeus* and the gastropod *C. striata* also alternate in abundance throughout.

Zone IV (30–0 cm; 190 yr–present)

D. compacta dominates the ostracod fauna of Zone I, while *M. henricae* and *D. spinosa* drop out of the record. The sediments are organic-rich and muddy.

Holocene hydrology and salinity reconstructions

The salinity reconstructions for NW Jacka Lake and Jacka Lake derived using the WAT ostracod transfer function are shown in Figures 5 and 6, together with the $\delta^{18}O$ values for *Elphidium* sp., *D. compacta* and *Reticypris* spp., and quartz sand grain counts.

Zone I (prior to 9600 yr ago)

The presence of laminated sediments and brine shrimp faecal pellets in Zone I (Fig. 3) suggests that NW Jacka Lake was a permanent hypersaline lake prior to 9600 yr ago. Hatching of *P. zietziana* in large quantities occurs at salinity levels between 50 and 180 g L^{-1} ($10^{1.7}$–$10^{2.3}$ g L^{-1} on a log scale) (Geddes, 1976). The general absence of ostracod valves throughout this zone suggests that either $CaCO_3$ preservation was compromised, as is often the case in the high salinity range (Radke, 2000), or that salinities never dropped to ranges permissible for the hatching of ostracod eggs. Hatching of ostracod eggs seldom occurs at salinities above ~130 g L^{-1} ($10^{2.1}$ g L^{-1}) (Geddes, 1976; De Deckker and Geddes, 1980). Sediments at the base of the Jacka Lake core were mottled, suggesting that the lake was elevated above the water table at this time and experienced intermittent drying.

Zone II (9600–4600 yr)

Salinity started to decrease at NW Jacka Lake after ~9600 yr (event 7; Fig. 5A), and alternated between ~20 and ~50 g L^{-1} (log $10^{0.3}$ to $10^{1.7}$) throughout this zone. Higher salinities occurred between ~8300 and 7800 yr, and a large spike of presumably aeolian sand was also observed (~7800 yr). The sand spike was not evident in Jacka Lake (Fig. 5E), potentially because the lake was dry.

Salinity levels were low between ~7300–7100 yr (event 6; Fig. 5A) and between ~6050–5700 yr (event 5) and at 4800 yr (event 4). The occurrence of *Mytilocypris henricae* during the low salinity periods (Fig. 3) suggests that the lake followed a path 2 solute evolutionary pathway (Radke et al., 2003), while the presence of charophyte oogonia suggests that the lake held water for at least 3 months at a time. This is the time required for most charophyte species to complete their growth cycle (Soulié-Marsche, 1991).

The low-salinity periods were probably caused by increased local runoff and higher water tables around Mt. Arapiles. Regional groundwater levels may have also increased, but the effect would probably have been minor. This is because the most recent period of significant recharge in the region occurred before 20,000 yr ago (Leaney and Herczeg, 1999). Ostracod preservation was poor because Jacka Lake was under-saturated with respect to $CaCO_3$. The onset of $CaCO_3$ precipitation occurs at salinity levels of ~1.2 g L^{-1} (log $10^{0.1}$) in southeastern Australian lakes (Radke et al., 2002), so we may assume that salinities were below this level. However, Jacka Lake was a repository for sediment, and the abundant sand grains in the interval from ~7500–6200 yr were probably transported by running water (Figs. 4 and 7). High stages at Jacka Lake may have been conducive to enhanced throughflow of water to NW Jacka Lake.

The influx of water that was pre-evolved in the up-gradient lake may help to explain why $\delta^{18}O$ values (*D. compacta*) in NW Jacka Lake are relatively heavy at ~8900 yr when salinity was relatively low. However, a more likely explanation is that *D. compacta*, which has a salinity optimum of ~40 g L^{-1} (log $10^{1.6}$), occurred towards the end of annual/decadal cycles of evaporation (and salt concentration) in the early Holocene. There is little overlap in the modern 25th to 75th percentile salinity ranges of *Reticypris* sp., *D. compacta*, *D. fodiens* and *Australocypris* sp. and *M. praenuncia/mytiloides*, *D. spinosa* and *M. henricae* (Radke et al., 2003) which form the high-salinity and low-salinity groups respectively of the fossil assemblages (comprising 30–60 yr accumulation) in this part of the record (Fig. 5). The species belonging to these groups generally do not coexist because they occur on either side of a major hydrochemical transition (at ~10 g L^{-1}) which is marked by significant ion-pair formation (Radke et al., 2003). By comparison, optimal salinity conditions for *D. compacta* were likely attained by the re-solution of salt crusts during wet events in the late Holocene, accounting for less evolved $\delta^{18}O$ values at this time. This interpretation is supported by the earliest Holocene

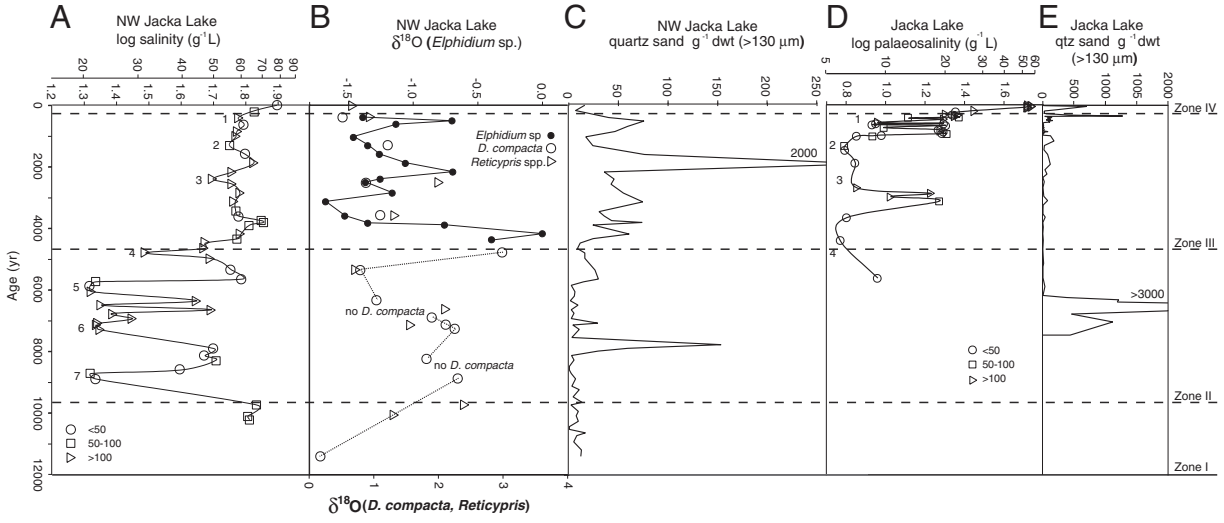


Figure 5. Palaeoenvironmental record from NW Jacka and Jacka Lakes showing (A) NW Jacka log salinity reconstruction and raw counts; (B) NW Jacka $\delta^{18}O$ records based on ostracods and foraminifera; (C) NW Jacka quartz sand counts; (D) Jacka Lake log salinity reconstruction and raw counts and E) Jacka Lake quartz sand counts. Four zones were recognised on the basis of salinity reconstructions in Jacka and NW Jacka Lakes.

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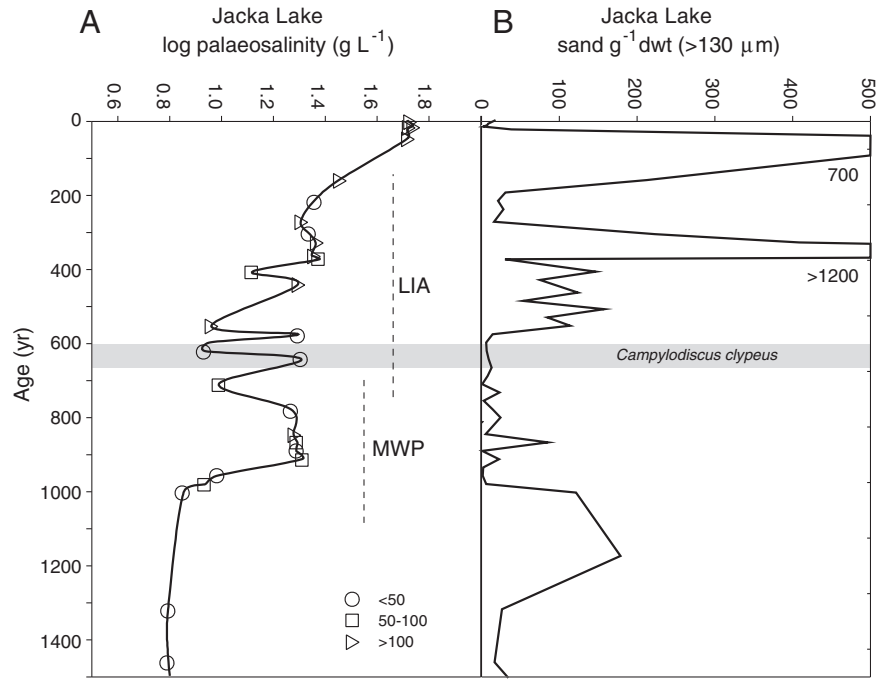


Figure 6. (A) Ostracod-inferred palaeosalinity reconstruction for the last 1500 years in Jacka Lake showing the age ranges of Medieval Warm Period (MWP) and the Little Ice Age (LIA) recognised in Europe, and (B) Jacka Lake quartz sand counts over the same period. Raw counts of ostracod valves are shown using symbols in A. The occurrence of diatom *Campylodiscus clypeus* around 600 yr suggests an interval of higher runoff.

sediments at Lake Keilambete (Fig. 1), which show low $\delta^{18}O$ values concurrent with high salinities, and which were attributed to the dissolution of salt crusts emplaced during previous dry conditions (Chivas et al., 1993, see Fig. 8).

Zone III (4600–~300 yr)

A trend towards lower effective moisture started at ~5800 yr and was firmly in place by ~4600 yr (Fig. 5A). Ostracod assemblages cycled between *D. compacta* and *Reticypris* spp. dominance throughout this zone (Fig. 7), with the *Reticypris* peaks corresponding to higher salinity levels. The aeolian sand counts (Fig. 5C) and the *Elphidium* $\delta^{18}O$ values (Fig. 5B) also co-varied with inferred salinity. Indeed, the prevalence of the foraminifera *Elphidium* sp. during the high salinity events (Figs. 3 and 8) suggests that the lake followed a Path-1 solute evolutionary pathway at these times. Therefore, the lake was likely dominated by fracture flow from Mt. Arapiles during dry periods, as the colluvial water table contracted (Fig. 7). Driest conditions probably occurred at ~4200 yr, as judged by the heavy *Elphidium* sp. $\delta^{18}O$ values. Lower-salinity events as indicated by higher *D. compacta* percentages (Fig. 7) were centred on 2400, 1300, and 400 yr.

The change to a muddy facies at ~5600 yr (130 cm; Fig. 4), the abundant occurrence of the brackish water diatom *C. clypeus* (global salinity optimum 4.4 g L^{-1}; Carvalho et al., 1995) and more consistent preservation of ostracods heralds the onset of drier conditions (less runoff) at Jacka Lake. The inferred salinity between ~5600 and 1000 yr averaged ~6.3 g L^{-1}, except for the short period between ~2900 and 3100 yr when it rose to ~16 g L^{-1}. This salinity change was less evident at NW Jacka Lake, most likely due to lower sedimentation rates. The occurrence of *C. striata* shells (Fig. 4) in the absence of ostracod valves suggests that salinity levels varied from fresh (<1.2 g L^{-1}) to brackish, potentially in response to seasonal runoff events. *C. striata* can be found over a wide salinity range [2–80 g L^{-1}; Williams and Mellor (1991)], and its aragonitic shells are more robust than ostracod valves owing to their greater thickness.

Good preservation of ostracod valves and a change to higher sedimentation rates at 66 cm (Fig. 2) allows for a relatively high-resolution account of salinity changes during the last 1000 yr at Jacka Lake (e.g., samples represent an average of 36 yr depending on their thickness)

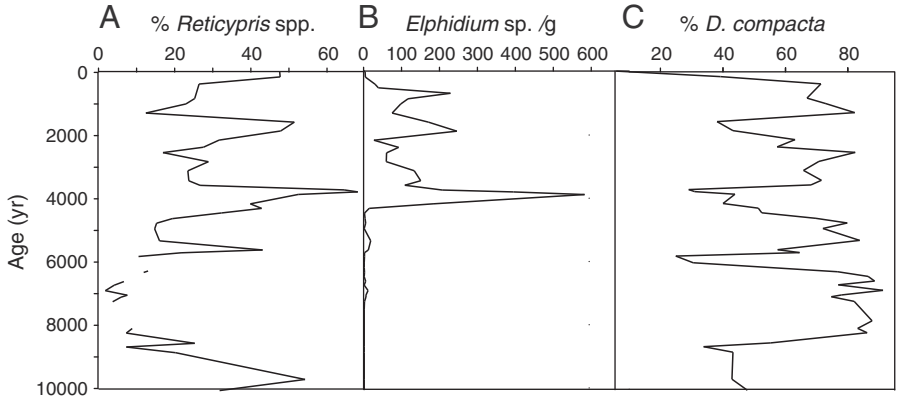


Figure 7. Distributions of various taxa, showing clear cycles of (A) % *Reticypris* ssp., (B) *Elphidium* sp., and (C) % *Diacypris compacta* in NW Jacka Lake.

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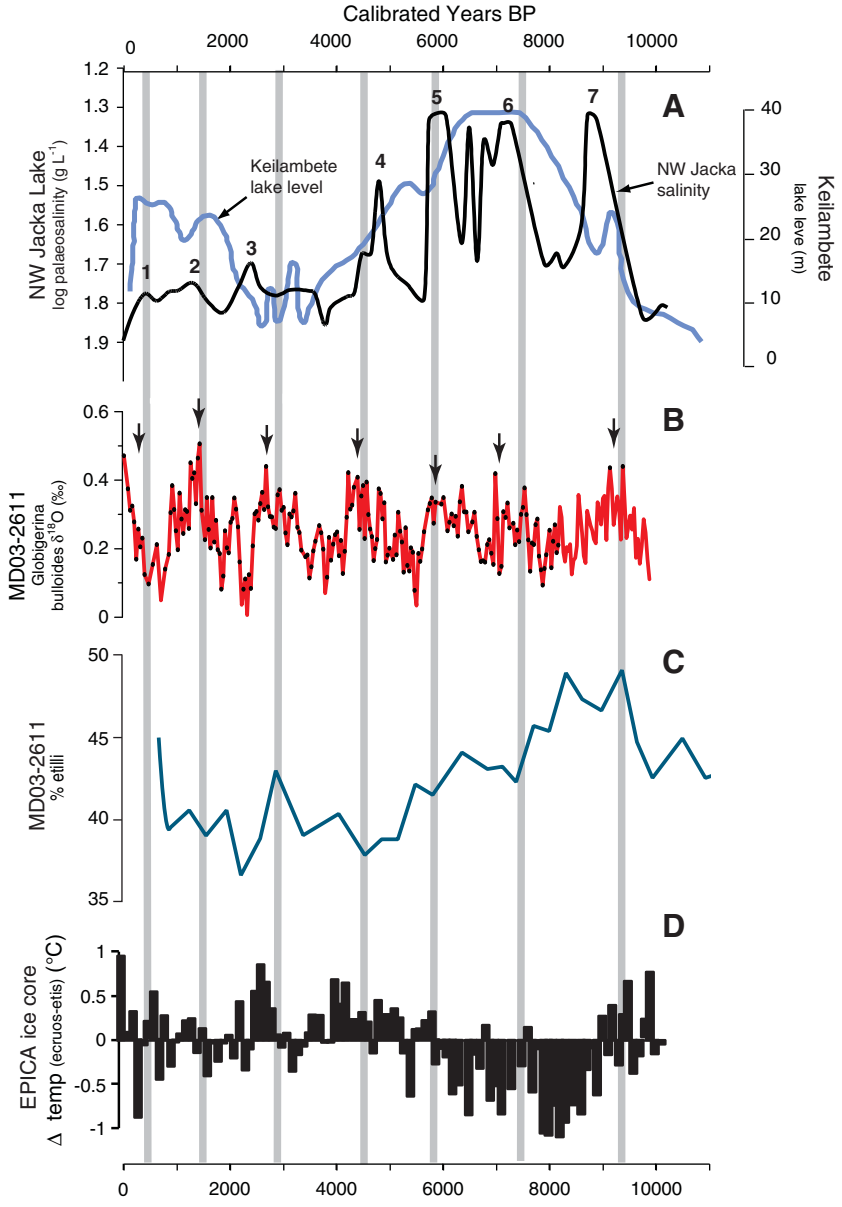


Figure 8. (A) NW Jacka palaeosalinity reconstruction and low-salinity events compared with Keilambete lake-level record (Bowler, 1981 with calibration by P. De Deckker), (B) percentage *Globigerina bulloides* record at site MD03-2611 offshore the Murray River mouth (Fig. 1) with arrows showing the occurrence of isotopically heavy spikes interpreted as cold events by Moros et al. (2009), (C) percentages of fluvial illite in core MD03-2611 interpreted as a record of fluvial discharge for the Murray–Darling Basin (Gingele et al., 2007), (D) deuterium and deuterium excess temperature reconstruction (site–source) from Antarctic EPICA core (Moros et al., 2009 using data from V. Masson-Delmotte). Shaded lines correspond to peaks in the percentage of haematite-stained grains in the North Atlantic (Bond et al., 1999).

(Fig. 6). These conditions were promoted by: (i) an increase in the calcite saturation state of the lake water due to the salinity increase; and (ii) the initiation of highly productive biological communities, which promoted sediment accumulation. The valves of *M. henricae* were often observed in association with microscopic pyrite framboids in this part of the record (Fig. 4). Both lines of evidence suggest that sulphate reduction was an important process occurring in the lake sediments (Radke et al., 2003), reflecting high reactive carbon loads (Berner, 1984), which are consistent with *M. henricae* being found in low-salinity lakes that support abundant aquatic vegetation.

Salinity increased abruptly at ~1000 yr and remained high until ~780 yr. The interval between ~780 yr and 380 yr (AD 1220–1620) is marked by extreme salinity variability, although the overall picture is one of generally wetter conditions. The occurrence of the diatom *C. clypeus* may indicate a freshening, though brackish, event at 600 yr caused by higher runoff (Fig. 6). This wetter period is matched in the NW Jacka Lake record by a low-salinity sample at 400 yr (AD 1600). High and stable salinities occurred between ~380 and ~330 yr (AD 1620–1670) and were followed by a brief return to relatively wetter conditions centred on ~270 yr (AD 1730). Quartz sand deposition was high between ~440 and 550 yr, and between 360 and 310 yr, and it was presumably mainly waterborne at these times.

Zone IV (~300 yr to present)

By ~210 yr, brine shrimps had returned to NW Jacka Lake as interpreted from their faecal pellets, and the lake had entered its current mode of hydrological function characterised by winter filling and re-solution of a halite crust formed upon drying during the summer months (Fig. 3). The final salinity rise in Jacka Lake (~270 yr) preceded European settlement (Fig. 6), which began between 1913 and 1920, but after ~220 yr (AD 1780) salinities were higher than any observed previously in the Holocene. Consequently, the widespread

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clearing of native vegetation may have mobilised salts stored in the unsaturated zone at around this time.

Post-glacial climate changes in Southeast Australia

Palaeosalinity records at the groundwater-dominated NW Jacka and Jacka Lakes are interpreted as indicators of Holocene runoff and effective precipitation in southeastern continental Australia. During wet periods, runoff generated from Mt. Arapiles increased, accompanied by an expansion of the fresh groundwater zone at its periphery, and greater throughflow from Jacka Lake to NW Jacka Lake. During dry periods, the system may have been dominated by fracture flow. These records are compared to a range of proxy records from SE Australia that fall in the dominantly winter rainfall zone today, and which receive most of their effective precipitation through the passage of the westerly winds.

The early Holocene (i.e., before 6000 yr ago) is generally regarded as a wetter and climatically stable period in southeastern Australia (Macumber, 1991; Singh and Luly, 1991; Gell, 1998; Pickett et al., 2004; Donders et al., 2007; Gingele et al., 2007; Fitzsimmons and Barrows, 2010), and the findings here are consistent with greater southerly penetration of the Australian Monsoon associated with a precession-forced reduction in seasonality (Shulmeister, 1999). Compelling evidence for an early Holocene "pluvial" comes from the concordant results obtained from maar lakes in western Victoria, which act as sensitive rainwater gauges due to their small catchment areas. Studies of grain size inferring lake levels (Bowler and Hamada, 1971; Bowler, 1981), vegetation (Dodson, 1974), and palaeosalinity (De Deckker, 1982; Chivas et al., 1993) at Lake Keilambete, suggest a positive water balance between 8000 and 6000 yr (Fig. 1; Fig. 8A), and hydrological modelling indicates that overflow required a wetter climate with P/E ~ 1.1 (Jones et al., 1998).

Fragmented evidence for millennial-scale variability within the early Holocene "pluvial" is apparent from a small number of lake level histories in western Victoria and elsewhere. At Lake Keilambete, a spike of heavier $\delta^{18}O$ values ~8000 yr (Chivas et al., 1993), and an aragonite/calcite facies dated ~7400 yr (from radiocarbon ages of 6640 and 6290 ^{14}C yr BP) (Bowler, 1981) could imply carbonate saturation caused by evaporation. Farther north at Lake Frome, drying caused the brief development of a playa facies at ~7900 yr (Bowler et al., 1986; De Deckker et al., 2011). West Basin Lake also shows an abrupt increase in salinity at ~6800 yr with a modest fall at ~6200 yr (Fig. 1; Gell, 1998) in phase with the record from NW Jacka Lake and an "unexplained" dry phase between ~6800 and 5700 yr exhibited by a range of proxies from Tasmania and Queensland (Harrison, 1993). In Tasmania, this event coincides with a lower precipitation evident from the influx of mineral sediment and expansion of shallow-water diatoms in Lake Vera (Markgraf et al., 1986). High variability in precipitation at Lynd's Cave in northern Tasmania is also noted in speleothem records between 9080 and 8600 yr, ~8000 yr, and a sustained drier period from 7000 to 6600 yr (Fig. 1; Xia et al., 2001).

Salinity increased at NW Jacka Lake between ~5700 yr (Fig. 5A) and ~5600 yr at Jacka Lake. Oscillating lake levels with saline episodes at 5600, 3800, 1700 and 700 yr are suggested by peaks in *Reticypris*/*Elphidium*, but in general lake salinity remains well above levels in the early Holocene. The increase in aeolian quartz sand starting at ~5600 yr and intensifying after 4200 yr at NW Jacka Lake provides evidence for a mid-Holocene strengthening of westerly wind circulation identified from temperate latitudes of New Zealand, South America (Markgraf et al., 1992; Moreno, 2004; Shulmeister et al., 2004; Villa-Martinez and Moreno, 2007; Lamy et al., 2010), and southeastern Australia, where the change in wind regimes is associated with the onset of drier conditions (Stanley and De Deckker, 2002; Gingele et al., 2007; Moros et al., 2009). Regionally, changes at Jacka and NW Jacka Lake are in good agreement with the record at Lake Keilambete, where lake levels relaxed after 5000 yr (Fig. 8A; Bowler, 1981) and changes in oxygen and Sr/Ca ratios indicate increasing salinities (Chivas et al., 1986), implying a decrease of P/E. Changing distributions of forams and ostracods at the mouth of the Murray River suggest decreased fluvial input between 5900 and 3900 yr (Cann et al., 2000), which is corroborated by a decrease in the proportion of fluviatile clay minerals such as illite in favour of aeolian clays observed in marine sediments within the Murray Canyons between 5000 and 2000 yr (Figs. 1 and 8C; Gingele et al., 2007). At Lake George in New South Wales, lake levels are mostly lower after 5000 yr with brief returns to high lake levels suggesting the development of a drier and more variable climate (Fig. 1; Fitzsimmons and Barrows, 2010).

Evidence for millennial-scale variability in Holocene paleoclimates in Australia

The records from Jacka and NW Jacka Lakes provide a more variable picture of Holocene climates than is generally accepted for southeastern Australia. On millennial timescales, the reconstruction at NW Jacka Lake suggests a variable climate, punctuated by high- and low-salinity events that recur through the Holocene. The recurrent periods of low salinity (nos. 1–7 on Figs. 5A and 8A) have an approximate spacing of 1400 ± 550 yr. This periodicity is indistinguishable from climatic instabilities with a period of ~1500 ± 500 yr observed in glacial and interglacial records from around the world (Mayewski et al., 2004). With the exception of events 3 and 7, which may deviate because of dating uncertainties, lower salinity episodes indicative of higher effective precipitation coincide in timing and number with cool events in the North Atlantic (Fig. 8; Bond et al., 1999). Good agreement is also found in the number and timing of isotopically heavy events identified in marine core MD03-2611 at 9200, 7300, 5800, 4300, 2700, 1400 and ~200 yr ago (Fig. 8B; Moros et al., 2009) and interpreted as cool episodes caused by episodic, stronger influence from Southern Ocean fronts moving north and an associated reduction in the depth of the oceanic thermocline. Higher lake levels are evident from the lake-level construction at Lake Keilambete at events 7, 4, 3, 2 and 1 with events 5 and 6 appearing as a single mid-Holocene wet phase (Fig. 8A). Wet–dry cycles in the late Holocene are also evident in Sr/Ca ratios from ostracod carbonates at this site (Chivas et al., 1986).

Evidence from other sites suggests southern Australia and the wider region experienced cooler conditions at intervals through the Holocene. Lower salinities between 8300 and 7900 yr overlap with an abrupt cooling event recorded in a return to glacial dust signatures in the Antarctic EPICA ice core between 8300 and 7500 yr (Gabrielli et al., 2010) and ascribed to the 8.2 ka event, which is widely documented and global in extent, falling between 8400 and 7800 yr in most records (Alley and Agustsdottir, 2005). At NW Jacka Lake, saline conditions were also associated with a peak in quartz sand deposition, reflecting drier conditions that destabilised the regional dunefield. Long-term trends in temperature reconstructed from deuterium and deuterium excess in the EPICA Dome C (Fig. 8) core also suggest an abrupt cooling in continental Antarctica at 8000 yr, together with a change in the dominant precipitation source from the subtropical to the temperate Indian Ocean (Masson et al., 2000; Masson-Delmotte et al., 2004). This peak is superimposed on generally lower temperatures apparent in the EPICA core between 9000 and 6000 yr and ascribed to lower obliquity and an associated reduction in high-latitude insolation (Fig. 8D; Masson-Delmotte et al., 2004). Small-scale variations in deuterium indicate temperature reductions in continental Antarctica at 7200, 2300 and 600 yr (Masson et al., 2000; EPICA Community Members, 2004). These events find close correlatives with events 6, 3 and 1 at NW Jacka (Figs. 8A and D). Cooler conditions during wet events 3 and 2 coincide with speleothem evidence for neoglacial conditions occurring at ~3200 yr (Goede et al., 1996), and with radiocarbon dates on periglacial deposits in the Snowy Mountains, which cluster

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around 3200 yr, 2270 yr and 1400 yr (Costin, 1972). All of these times were characterised by cooler summer temperatures indicated by the Huon Pine tree ring record in Tasmania (Cook et al., 2000). The most recent wet event (1) at NW Jacka Lake and variably wet conditions from ~AD 1290 to 1450 at Jacka Lake correspond with the most recent episode of high lake levels at Lake George ~AD 1400–1700 (Fitzsimmons and Barrows, 2010). Tentatively, this event aligns with the Little Ice Age (LIA) in Europe, the most recent of the 1500-yr events (Bond et al., 1999). A period of high salinity at Jacka Lake from AD 1040–1220 corresponds with the Medieval Warm period (MWP) in Europe (Briffa, 2000; Crowley, 2000). There is supporting evidence for the MWP from tree-ring (Cook et al., 2002) and speleothem (Williams et al., 2005) evidence in New Zealand.

The cause of ~1500-yr cycles in the Holocene remains obscure (Rahmstorf, 2003; Debret et al., 2007; Wanner and Butikofer, 2008), although a solar origin is favoured by some workers (Bond et al., 2001; Mayewski et al., 2004; Versteegh, 2005; Dima and Lohmann, 2009; Helama et al., 2010). Evidence for 1500-yr cycles in northern (Turney et al., 2004) and southern Australia (Moros et al., 2009) has been attributed to modulations in the amplitude and/or frequency of El Niño variability, but the influence of El Niño is small in southern Australia (Nicholls, 1989; Risbey et al., 2009), and the events recorded here may be better explained by equatorward shifts in the position of the Westerlies. Evidence suggests that variations in solar output may have caused the position of the westerly flow to vary at centennial to millennial timescales in the late Holocene (Varma et al., 2010). This interpretation is consistent with climatic excursions during the Holocene recorded in South America (Lamy et al., 2001; Moreno, 2004; Kaiser et al., 2005; Moreno et al., 2009) and in glacial surges in New Zealand's South Island (Gellatly et al., 1988; Suggate, 1990), both linked to varying westerly influence (Fitzharris et al., 1992; Hooker and Fitzharris, 1999), and which are in good agreement with the records obtained here.

Conclusions

Weighted averaging regression and calibration were used to construct an ostracod-based transfer function for inferring log salinity from ostracod assemblages in sediment cores from ground-water dominated lakes in semi-arid southeastern Australia, and the model performed well under cross-validation. The records at NW Jacka and Jacka Lakes provide a detailed account of Holocene changes in salinity and effective precipitation in the region. Salinity decreased at NW Jacka around 9600 yr and reached its Holocene minimum between 8900 and 5700 yr, in good agreement with regional evidence for an early Holocene pluvial. The results suggest that the Holocene was more variable than previous studies have shown, and provide evidence for the existence of ~1500-yr cycles in mainland southern Australia. Lower salinity phases at ~8800, 7200, 5900, 4800, 2400, 1300 and 400 yr probably represent cooler intervals with more intense westerly circulation. The timing of these intervals agrees well with cool episodes identified in the region and elsewhere in the southern hemisphere.

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