Journal of Arid Environments 75 (2011) 38–50

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Late Quaternary palaeohydrological changes in the large playa Lake Frome in central Australia, recorded from the Mg/Ca and Sr/Ca in ostracod valves and biotic remains

P. De Deckker [a,*], J.W. Magee [a], J.M.G. Shelley [b]

[a] Research School of Earth Sciences, The Australian National University, #47 Linnaeus Way, Canberra ACT 0200, Australia
[b] Formerly of Research School of Earth Sciences, The Australian National University, Australia

A R T I C L E I N F O

Article history:
Received 29 December 2009
Received in revised form
22 July 2010
Accepted 11 August 2010
Available online 22 September 2010

Keywords:
AMS ^{14}C dating
Aquifer
Gypsum
Halobiont
Mg/Ca
Na/Ca
Paleoclimates
Paleohydrology
Radiocarbon dating
Saline playa
Sr/Ca
Trace element ratios

A B S T R A C T

The last 42,000 years of hydrological history of Lake Frome, a large playa located in the arid part of northern South Australia, which is hypersaline and most often dry today, is reconstructed using a combination of ostracod assemblages, other microfossil remains, and the trace elemental composition of the selected halobiont ostracod species of *Diacypris* and *Reticypris*.

The Mg/Ca and Sr/Ca of ostracod valves from 2 cores relate to significant hydrological changes that affected the lake over time. The reconstruction of the Sr/Ca of the lake's waters, based on the Sr/Ca of ostracod shells, shows that when the lake fills the waters originate mostly from runoff, *not* from hypersaline waters located below the lake or the surrounding aquifers. The Last Glacial Maximum saw gypsum deflation from the lake.

Prior to 25K yBP, Frome had a stable hydrological regime, permanent water and low salinities, with occasional freshwater conditions between 42 and 33K yBP. From 25 to 20.3K yBP, salinities fluctuated and ephemeral conditions operated. After that, until ~14.8K yBP, a brine pool was located below the lake and was therefore under a different hydrological regime. Between 13 and 11.2K yBP, wet conditions occurred, but such conditions were not seen again during the Holocene.

1. Introduction

Australia is the most arid inhabited continent, with a large portion of this landmass characterised by extensive dune fields and dry-lake beds. Many of the latter show obvious evidence of a wetter past, with ample palaeohydrological evidence of the presence of significant surface water. Many of the large playa lakes are presently covered, in parts, by a halite and/or gypsum crust resulting from the interaction of atmospheric conditions and the brine pool which occurs below lake surfaces. Under the present-day climatic conditions prevailing in the arid part of Australia, evaporative pumping, in particular during the summer months, causes highly concentrated solutes to reach the lake floor and either salts such as halite precipitate at the surface, or other minerals, such as discoidal gypsum, precipitate interstitially near the surface of the lake (Bowler and Teller, 1986; Magee, 1991). Deflationary processes also occur at this stage, and much material (including 'puffy' lacustrine clays and gypsum crystals) is deflated from the lake floor. Sand-sized clay pellets form at this stage and can also be transported downwind to form lunettes (for review, see Bowler, 1983).

We undertook here to reconstruct the palaeohydrological history of the large playa Lake Frome in northern South Australia using a combination of techniques to unravel events that affected the lake. Examination of satellite imagery of the lake floor and surroundings (see Fig. 1) indicates ancient shorelines, some of which have been transgressed by aeolian deposits, and also the presence of large islands on the lake floor that have formed during periods of deflationary processes. Unlike many lakes in Australia which have a record of low sedimentation due to the low topographical relief so characteristic of the continent, Lake Frome is adjacent to the Flinders Ranges (Fig. 1) which, during wet periods, must have supplied a substantial amount of sediments to the 'terminal' portion of the basin.

* Corresponding author. Tel.: +61 2 6125 2070; fax: +61 2 6125 5544.
E-mail address: patrick.dedeckker@anu.edu.au (P. De Deckker).

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doi:10.1016/j.jaridenv.2010.08.004

2. Site description

2.1. Lake Frome

Lake Frome is a large playa, approximately 100 km long and 45 km wide (Figs. 1 and 2) and covers an area of ~2700 km^2. The lowest part of the lake is ~2 m below sea level. It is a terminal lake lying within a closed basin that covers ~40,000 km^2, when it is filled with water. The south-central part of the playa is now covered with a thin halite crust below which interstitial discoidal gypsum crystals abound within the dark brown clayey sediments. In places, the sediment is black due to the high concentration of interstitial sulphate-reducing bacteria (*Desulfovibrio*) as documented by Bowler and Teller (1986) at Lake Tyrrell, in western Victoria.

Lake Frome is bounded to the west by the Flinders Ranges (see Fig. 1) with peaks reaching up to 1100 m. A number of large stream beds (ephemeral today) rise in the Flinders Ranges and end at the edge of the lake. Those streams must be the largest supplier of clay to the lake floor. All other sides of the lake are covered by a large, recently inactive longitudinal dune field, which contains several salt pans (Fig. 1). Several other streams flow into the lake, and the most important one is the salt creek which connects Frome with Lakes Blanche and Callabonna to the north (Fig. 1) (Callen, 1981).

The average rainfall in the region ranges between 180 and 200 mm whereas potential evaporation exceeds 2200 mm (Draper and Jensen, 1976). Nevertheless, rainfall is sporadic and this bears much relevance for any biota found living in any lake in arid Australia, as predictability of rainfall is vital for numerous invertebrate species (for further details, refer to De Deckker, 1983a).

The surface and groundwater hydrologies of Lake Frome are a complex function of both local and continental-scale factors. In addition to the local Flinders Ranges tributaries, Lake Frome can receive surface inflow from Cooper Creek, a large catchment (306,000 km^2) which is a major part of the Lake Eyre drainage basin, via the Strzelecki Creek, a distributary channel branching off the Cooper at Innamincka. In the largest historic flood of 1974, water from the Strzelecki Creek flooded Lakes Gregory, Blanche and Callabonna but did not reach Lake Frome (Fig. 1). However, Bowler (1981, 1986) in an analysis, for a number of Australian lakes, of the relationship between lake area/catchment area ratio and climate and runoff, concluded that the local (Flinders Ranges) catchment of Lake Frome was insufficient to fill the lake to the beach level 15–20 m above the playa floor (see Fig. 2).

When Lake Eyre to the north stood at +10 m Australian Height Datum, it was connected to Lakes Frome and Gregory, and covered ~35,000 km^2 and held ~430 km^3 of water (DeVogel et al., 2004). This possibility had already been suggested by Kotwicki (1986) and provides an additional complication for the surface water hydrology of Lake Frome because under these conditions, the Frome mega-lake is no longer a closed terminal basin as is the playa today.

Lake Frome can receive groundwater inflow from local sources, most significantly the Tertiary and Quaternary fluvial and alluvial fan sediments marginal to the Flinders Ranges which interfinger laterally with the Frome lacustrine and playa sediments. But Lake Frome lies at the SW margin of the Great Artesian Basin (GAB) and it can also receive groundwater inflow from that continental-scale source. The GAB is a very large artesian groundwater basin (1,700,000 km^2) with deep aquifers, mostly of Jurassic age, and recharge sources mostly in the Australian Eastern Highlands (Habermehl, 1980). GAB inflow to Lake Frome occurs both from general leakage and through mound springs on the playa floor. The absolute and relative contributions from these two sources is unknown and may have varied through the past, in concert with climatically-controlled changes in aquifer pressure and flow rates.

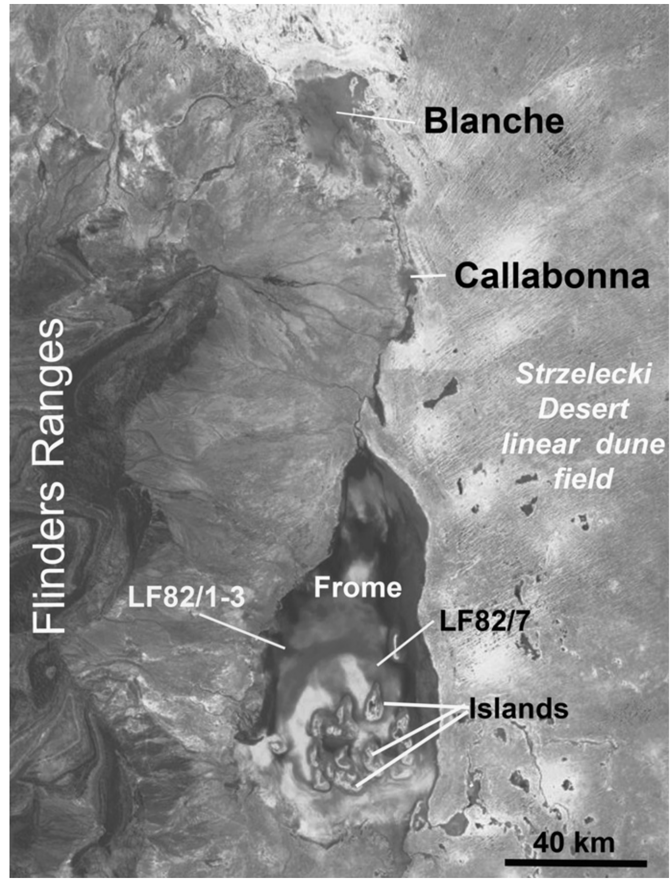

Fig. 1. Satellite image of Lake Frome and the Flinders Ranges to the west. Reproduced from Landsat 7, Path 97, Row 81 taken on February 1, 2001. The surface area represented by the photograph is ~135 km by ~160 km. Image provided through the courtesy of M. Thankappan of AUSLIG, Geoscience Australia, Canberra. Note the linear dunes that are most obvious in the right hand corner of the photograph, and gypseous islands/dunes in the southern portion of the lake. Of interest too are the extensive alluvial fans on the eastern side of the Flinders Ranges, with the most spectacular one opposite Lake Callabonna. These fans are the major conduits of surface water from the Ranges and that drain onto the lake.

The floor of Lake Frome is located above a brine pool (see Bowler (1986; Fig. 4)) which is characteristically NaCl-enriched, with salinities reaching >250‰, but there is also a regional groundwater feeding the lake, predominantly on its western side originally from the Flinders Ranges (for further details, refer to Bowler (1986; Fig. 4)). At the site of regional groundwater seepage, deflation of lacustrine and fluvial sediments is caused by wind processes combined with evaporative pumping. Efflorescent gypsum crystals characteristically contribute to the deflation processes due to sediment disruption by their expansionary action.

The floor of Lake Frome, in particular its central part, is covered by several large islands (see Fig. 1) which were formed as the result of the deflation and redeposition of gypsum-rich sediments during very arid periods, the most significant one possibly corresponding to the Last Glacial Maximum, ~23,000–19,000 cal. years ago [Note from now on, in this paper, all reported ages are in calibrated years BP and will be referred to as "yBP", *unless stated*]. During that time, the longitudinal dunes, best visible on the eastern side of the lake, were active; today, they are fixed and sparsely vegetated (Callen, 1983). Bowler (1983) indicated that the Frome islands consist of aeolian deposited material, dominantly sand-sized discoidal gypsum and clay pellets, derived from saline groundwater-controlled deflation of adjacent lake floor sediments. The islands sit on a pedestal of lacustrine sediment approximately 1 m above the playa floor, which marks the pre-deflation level of the lake floor. The aeolian sediments of the

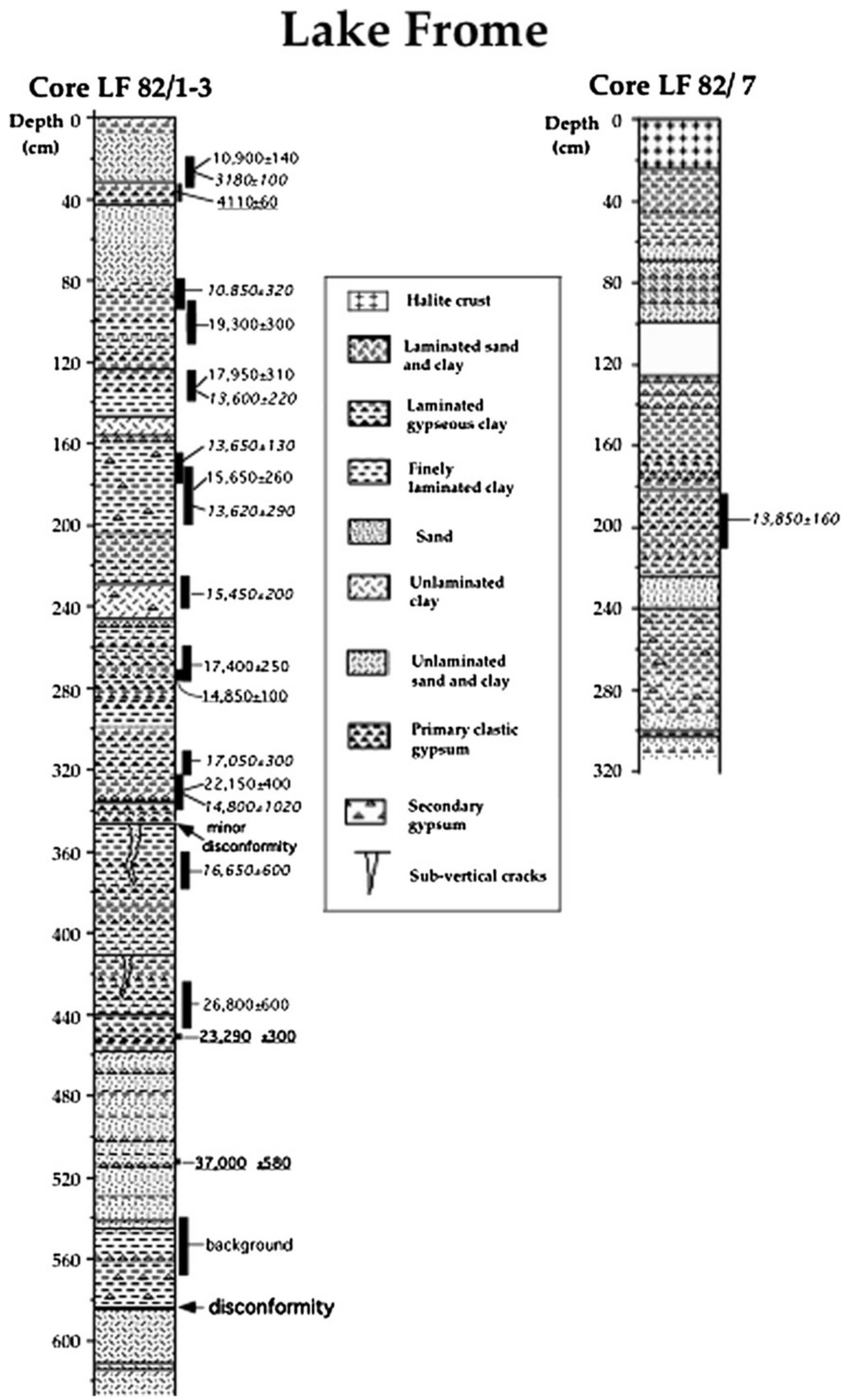

Fig. 2. Detailed log showing the main lithological units and sedimentary structures for the main core LF82 1/3. The position of the levels dated by radiocarbon are also presented. For more details on the analysed samples, refer to Table 1. Radiocarbon dates in normal fonts were made on bulk carbonates; those in italics were done on the organic fraction of the bulk sediments; those underlined are AMS dates done by Luly and Jacobson (2000), and those in bold are AMS dates done for this study.

islands are capped by a well-developed pedogenic profile, including a surface gypcrete and are gullied and trimmed by wave cut shorelines from post-deflation lacustrine events. Bowler et al. (1986) published radiocarbon dates from the aeolian sediments from one island, which indicated a deflation event around the time of the LGM.

2.2. Water chemistry

Sodium and chloride are the major solute ions in the lake water as well as in the brine below the lake. The lake water salts are derived from a mixture of brine waters and dissolution of the halite crust when surface waters invade the Lake Frome depression. Sulphate also dominates over bicarbonate ions.

Detailed information on the chemistry of the lake's surface waters, brines and regional aquifers are available in Draper and Jensen (1976) and Ullman and Collerson (1994).

Gypsum readily precipitates interstitially in surficial sediments, and this explains the "calcium sink" that is so characteristic of playa lakes commonly found in arid Australia. This phenomenon could be one of the principal reasons for Mg to be in higher concentration than Ca in most saline lacustrine environments in Australia. Nevertheless, the waters are close to saturation with respect to calcite and this explains why the calcitic biogenic remains found in the cores studied here show no evidence of calcareous overgrowth.

3. Previous work

3.1. Sediments

Draper and Jensen (1976) provided a thorough overview of the sediments found at the surface of Lake Frome. They also augered several holes across the lake floor, and recognised three main lithological units; a muddy unit lying between two sandy units. These are capped by a salt crust in the south-central portion of the lake. They also obtained several radiocarbon dates for samples from the auger holes, and from short cores which established a good chronology with one minor age reversal.

Bowler et al. (1986) provided the first comprehensive attempt at dating the Lake Frome cores, which highlighted the difficulties inherent in dating lacustrine sequences in Australia that contain little carbon. Examination of the data from Bowler et al. (1986), replotted in Fig. 4 (see also Fig. 6), show the discrepancy between radiocarbon dates done on the organic fraction of lacustrine material in comparison with the carbonate fraction.

3.2. The Lake Frome SLEADS cores

A total of 15 cores in two transects were taken from Lake Frome in 1982–1983 during the SLEADS program (for further details see acknowledgements section) and two of them from the southern transect were selected for this study. The most studied and best dated core is LF82/1-3 because it yields the most comprehensive representation of all the youngest facies recognised across the lake. We studied a second core LF82/7, for comparative purposes, and because it shows the best microfossil preservation (for location of both cores, see Fig. 1). Both cores have been studied here for their biological remains and ostracod valve chemistry. A description of the cores is available in Bowler et al. (1986) and is summarised below (see also Fig. 2 for log description).

The upper 346 cm of the lake sediments lie above a minor disconformity, probably resulting from a period of deflation. The *upper 120 cm* consist of reddish-brown sandy clays, below which, from *120 to 346 cm*, dark-grey silty clays with displacive (discoidal) gypsum. Radiocarbon dates for those 2 units (published by Bowler et al., 1986) are presented in Fig. 3 and Table 1 and were obtained on both the bulk carbonate fraction and bulk organic carbon. The percentage of carbonates in the Lake Frome sediments is quite low and the origin of much of the carbonate material is uncertain, and consequently the carbonate dates need to be considered with caution (Table 2).

Below the disconformity, from 346 to 560 cm, very fine-grained, bluish grey clays grade down to a sandy facies near 5 m (see Fig. 2, and Bowler et al., 1986). There is another, more pronounced disconformity at around 578 cm.

Subsequent studies mentioned below were performed on the same core LF82/1-3.

3.3. Previous investigations on core LF82/1-3

Several types of studies have been performed on many of the cores obtained during the SLEADS coring program at Lake Frome, but effort has concentrated on core LF82/1-3 because of the availability of a radiocarbon chronology. Using this chronology, Bowler et al. (1986) reconstructed the hydrological budget of Lake Frome and identified "an early lacustral phase that gave way 18,000 yBP to drying and aeolian activity. Water had returned to the system by 16,000 yBP and lacustrine conditions persisted through early Holocene with development of playa facies about 7000 yBP. After a brief return to lacustrine conditions between 6000 and 4000 yBP,

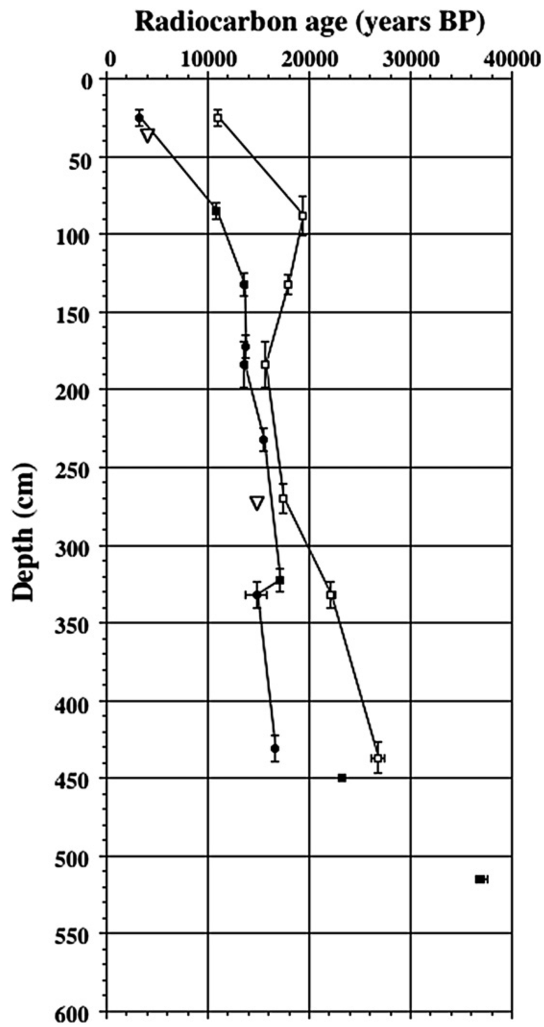

Fig. 3. Diagram to show the (uncalibrated) radiocarbon ages obtained for all the samples measured on core LF82/1-3, which are presented in Table 1. ● refer to standard radiocarbon dates on bulk organic fraction; □ on bulk carbonate samples; ▽ refers to AMS radiocarbon dates on bulk sediments; and ■ refers to AMS radiocarbon dates on ostracods. Note the 'rapprochement' of the ages for the 180–350 cm portion of the core, suggesting a hydrological change in the lake. For more details, refer to text.

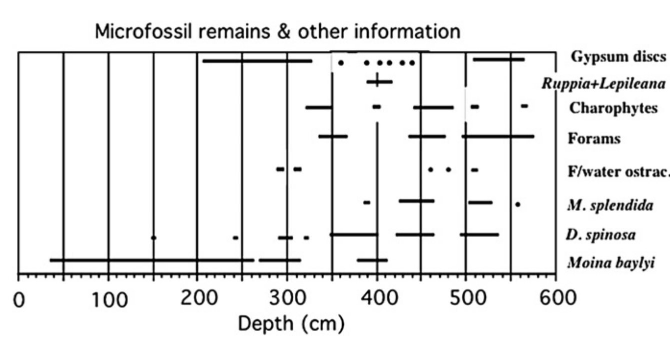

Fig. 4. Representative sketch to show the distribution of key taxa recovered in core LF82/1-3 as well the main occurrence of gypsum discs in this core. For the palaeoenvironmental significance of these remains, refer to text.

Table 1
List of all the samples analysed for radiocarbon dating from the Lake Frome cores LF82/1-3 and LF82/7. All dates with an ANU code were taken from Bowler et al. (1986), the 2 ANSTO dates from Luly and Jacobsen (2000) and the others were provided courtesy of G.H. Miller, University of Colorado. The calibrated ages were calculated using the polynomials available in Bard et al. (1998).

Core Depth (cm)	Laboratory where dated	Material	Age yBP	1σ	Calibrated age yBP
LF82/1-3					
20–30	ANU-2926	carbonate	10,900	140	12,694
20–30	ANU-3147	organic C	3180	100	3426
35–38	ANSTO-OZD-055	bulk gypseus clay	4110	60	4609
86–111	ANU-2927	carbonate	19,300	300	22,762
80–90	ANU-3148	organic C	10,850	320	12,634
126–139	ANU-2928	carbonate	17,950	310	21,173
125–140	ANU-3149	organic C	13,600	220	15,976
169–199	ANU-2929A	carbonate	15,650	260	18,439
169–199	ANU-2929B	organic C	13,620	290	16,001
165–180	ANU-3150	organic C	13,650	130	16,037
225–240	ANU-3151	organic C	15,450	200	18,200
261–280	ANU-2930	carbonate	17,400	250	20,522
272–275	ANSTO-OZD-056	bulk sediment	14,850	100	17,481
310–325	ANU3152	organic C	17,050	300	20,107
324–340	ANU-2931A	carbonate	22,150	400	26,082
324–340	ANU-2931B	organic C	14,800	1020	17,421
360–377	ANU-3153	organic C	16,650	600	19,632
427–447	ANU-2932	carbonate	26,800	600	31,393
450	NSRL-11119	ostracods	23,290	300	27,396
515	NSRL-11120	ostracods + *Coxiella*	37,000	580	42,586
542–572	ANU-2933	carbonate	background	–	–
LF82/7					
183–213	ANU-3156	organic C	13,800	150	16,220

a dry playa has continued to the present-day" [These are uncalibrated radiocarbon years].

Using the same chronology, Ullman and McLeod (1986) investigated the content of Na^+ in stratigraphically-preserved gypsum in core LF82/1-3 and reconstructed a salinity record for Lake Frome which is consistent with Bowler et al.'s (1986) reconstructions reported above. Zheng and Bowler (1986) also made a preliminary study of the clay minerals from the same core and, once again, concurred with Bowler et al.'s (1986) original reconstructions.

Singh and Luly (1988) provided a vegetation record which extended further back in time than the one which Singh (1981) had provided for the Holocene using a one-metre core for which 3 radiocarbon dates were available.

Ullman and Collerson (1994) examined the Sr-isotope record obtained from gypsum crystals from LF82/1-3 and concluded that *"periods of high rainfall ('wet') were identified at 3–6 Ka, 12–15 Ka, and >17 Ka and dry periods at ̃10 and ̃17 Ka"* [These are radiocarbon years, uncalibrated]. Overall, their results were fairly consistent with the other palaeoclimatic inferences reported above.

Finally, Luly and Jacobsen (2000) reported on two additional AMS dates obtained on bulk sediments from the same core LF82/1-3 core to check the validity of the original dates obtained on organic residue by Bowler et al. (1986).

4. Methods

4.1. Sediment core and extraction of biotic remains

Coring was carried out in 1982 when the Lake was completely dry, following severe drought conditions over much of the continent in the early 1980s. Two light four wheel drive vehicles and trailers, equipped with wide low-pressure tyres, were used to transport a small Jacro-350 drilling rig and drill string across the playa floor. Coring was accomplished by two methods. Where sediments were sufficiently soft, 80 mm PVC tube was driven into the sediment, past a piston, in lengths of up to 2.5 m. After extraction of the core tube, the hole was then widened to the same depth by drill-rig auger flights and another sample tube driven into the underlying sediment. Where sediments were too hard for PVC core tube penetration, 50 mm diameter thin-walled metal tubes were driven into the sediment ahead of the hollow augers which acted as casing.

The larger PVC cores were sealed and returned to the laboratory for opening, logging and sub-sampling. The shorter 50 mm cores were extruded, scraped clean for initial field logging and then wrapped in polythene for transport back to the laboratory where they were stored in a cold room while waiting to be logged in detail and sub-sampled.

A detailed log of the representative core (LF82/1-3) is presented in Fig. 2. The second core (LF82/7; see detailed log in Fig. 2) was taken some 30 km east of the longer one and a shorter section sampled for comparative purposes. For location of both cores, refer to Fig. 1.

Subsamples, on average weighing 5 g, were taken from specific levels in both cores, especially on either sides of obvious lithological changes. To disaggregate the often hard and dry samples, they were placed in glass jars and immersed in 3% H_2O_2 for several weeks. Those samples were then washed, using a gentle water jet, through a 150 µm sieve, and the fraction >150 µm was dried in an oven. Microfossil remains were then separated under a binocular microscope for

Table 2
Salinity ranges and other relevant ecological characteristics of the ostracod taxa found in the Lake Frome cores.

	salinity range[‰]	other characteristics
Saline taxa		
Australocypris robusta	7–145	
Diacypris compacta	8–132	
Diacypris fodiens	21–114	1 record at ~190
Diacypris spinosa	6–41, +1 record at ~50 and ~90	most commonly at <20
Mytilocypris splendida	~2–21	
Reticypris kurdimurka	1 record at 21.3 and 40	
Reticypris pinguis	4–35.4	
Reticypris walbu	1 record at ~2, 10 and 87.6	
Sarscypridopsis sp.	usually low salinity	*S. aculaeata* <1–24
Repandocypris sp.		
Freshwater taxa		
Bennelongia sp.		usually in ephemeral pools
Candonocypris sp.		likes eutrophic environments
Gomphodella sp.		
Limnocythere dorsosicula		
Limnocythere mowbrayensis	<1 to ~5	likes filamentous algae
Limnocythere porphyretica		

examination, and material was stored in standard micropalaeontological slides. Observations on the nature of the coarse sediment fraction were also noted, especially with respect to the presence of discoidal gypsum and platy micaceous minerals.

4.2. Ostracod shell chemistry

For the subsamples, single valves of the small ostracods *Diacypris* and *Reticypris* were selected from the samples for chemical analysis and analysed for their Ca, Mg and Sr content. Extremely well-preserved, transparent valves were selected by microscopic examination and cleaned of any adhering sediment particles by immersion in a small vial in ethanol, and scratched with fine tungsten needles and fine (triple 000) paint brushes (No ultrasonic cleaning could be used for this material as *Diacypris* specimens are too brittle to undergo such treatment). On average, valves weighed 5 μg, but analysed material varied between 1 and 15 μg. Samples were dissolved in 2% Merck Suprapur HCl and MilliQ® water. Analyses were performed on a built-in-house Inductively-Coupled Argon Plasma Emission Spectrometer (ICPAES) at the Research School of Earth Sciences at the Australian National University (Shelley and Taylor, 1981), following the same procedures documented in De Deckker et al. (1999). Detection limits for Ca^{2+} are 0.02 ppb, for Mg^{2+} 0.04 ppb and Sr^{2+} 0.03 ppb in solution.

4.3. Biogenic samples for AMS ^{14}C dating

Two samples consisting of biogenic carbonates have been analysed in order to determine whether the sediments below the disconformity at 346 cm were definitely below background ages as shown by Bowler et al. (1986) for bulk sediment. The sample from level 450 cm consisted of well-preserved, transparent valves of the following ostracods: *Diacypris fodiens*, *Reticypris, Mytilocypris splendida, Trigonocypris* and *Australocypris* fragments. The sample from level 515 cm contained valves and fragments of *Mytilocypris* and those of the aquatic, halobiont gastropod *Coxiella*.

Target preparations for the 2 samples were made at the University of Colorado in Boulder at the INSTAAR Laboratory for AMS Radiocarbon Preparation and Research. The quoted ages in radiocarbon years use the Libby 1/2 life following the convention of Stuiver and Polach (1977). Calibrated ages were obtained for all samples discussed here using the polynomials available in Bard et al. (1998).

5. Palaeoecological and palaeoenvironmental information from biotic remains

5.1. Ostracoda

A number of ostracod taxa were recovered from the 2 cores and these taxa are discussed below. Of importance to this study are the salinity ranges for each extant taxon as water salinity can be informative of conditions of the lake (Fig. 4); in addition, salinity is of particular relevance to climatic conditions when conditions change from arid to less arid conditions. For example, a dry or ephemeral playa, which may be under the influence of a brine pool below it, should relate to an arid phase; a permanent, saline lake would exist under less arid conditions; a low salinity lake [less than sea water salinity] is engendered by either a wetter climate or less solar radiation or a combination of both; and a freshwater lake is definitely related to even wetter conditions than the previous situation. The presence of various ostracod taxa recovered in the cores is given in Appendix available as supplementary information.

Numerous fragmented remains of the large ostracods belonging to the Australian endemic tribe Mytilocypridini (for more information, refer to De Deckker (1978) and Halse and McRae (2004)) were found in the examined cores. These ostracods are large, with adult sizes reaching 3 mm, but often, because of their fragility, their valves are not preserved as complete specimens. Compaction of the sediment during the coring process, and even careful laboratory handling can cause much breakage of the valves and, consequently, identification at the species level becomes difficult. Nevertheless, the characteristic pointed posterior extremity of *M. splendida* permits identification of some of its fragments. Similarly, the recognition of specimens belonging to the recently described genus *Repandocypris* by Halse and McRae (2004), known to occur at Lake Annean in central northern WA [De Deckker, personal observation], and Lakes Eyre and Torrens (for further details, refer to Williams et al. (1998) and Halse and McRae (2004)) has been made possible. Fragments of *Repandocypris* are characterised by a very broad inner lamella as seen all along the periphery of the valve, except in the hinge area, and its broadly curved posterior area. The less common of the halobiont taxa is *Diacypris compacta*, and this is a surprise as in many other lakes in temperate Australia such as the Victorian lakes district, it accompanies *Australocypris robusta* in huge numbers. Obviously, different ecological conditions at Lake Frome must have prevented this association from developing. In addition, *Reticypris pinguis* is also found in low numbers at a few levels in core LF82/1-3 (Appendix).

Of interest, is that most of the species mentioned above have been recorded at both Lakes Eyre and Torrens during modern-day ephemeral wet periods (Bayly, 1976; Williams et al., 1998; Williams, 1990).

At some levels in the cores, around 300 cm and between 460 and 520 cm in core LF82/1-3, a few significant ostracod specimens representative of freshwater conditions have been found. These are *Bennelongia* sp. *Candonocypris* sp., *Darwinula* sp., *Gomphodella* sp., *Limnocythere mowbrayensis, and Limnocythere porphyretica* (Appendix). These latter species are occasionally found in association with the halobiont taxa but principally occur with *Diacypris spinosa* which prefers low salinity conditions (e.g. ~5‰; see De Deckker et al., 1982; De Deckker and Williams, 1988). An alternation of fresh to slightly saline conditions must be postulated, or the freshwater taxa from nearby streams, or possibly springs, may have been mixed into the saline facies during periods of substantial flooding of the lake. There are also a few specimens of *Sarscypridopsis*, but their lack of identification down to species level cannot confirm freshwater conditions as one species *S. aculeata* can occur in quite saline conditions (De Deckker, 1983b).

The lack of obvious secondary calcareous 'coatings' on the ostracod valves indicates low saturation levels of the interstitial waters with respect to calcite. This is obviously an advantage for the chemical analysis of an ostracod valve as we can be assured of minimal post-depositional alteration of the primary chemical signature.

5.2. Cladocera

Until now, cladoceran remains have not been recovered from playa lake sediments in Australia. De Deckker (1988) was the first to record ephippial (=egg case) remains of *Daphnia* as well as *Daphniopsis* from crater lake sediments. Kokkin and Williams (1987) later described a new *Daphniopsis* taxon, originally identified from fossil material. The recovery of numerous ephippia of *Moina* in nearly the entire upper half of both Lake Frome cores (LF82/1-3 and 7) confirms the tolerance of this cladoceran to saline conditions. Hence, we believe the ephippial egg cases are likely to belong to *Mytilocypris baylyi* as it is widely distributed in saline environments in arid Australia (Williams and Kokkin, 1988; Williams et al., 1998). The ephippium of *Moina* is characterised by its almost circular periphery and its reticulated texture. Overall, its presence should indicate a saline lake that is filled ephemerally. The salinity range of

M. baylyi (originally called *M. mongolica*) was 7–27‰ (Bayly, 1976) at Lake Eyre, and consequently 25.3–86.7‰ at the same lake and at Lake Torrens 16–30‰ (Williams et al., 1998).

5.3. Foraminifera

Following the investigations of Cann and De Deckker (1981) and De Deckker (1982) on the occurrence of foraminifera in saline lakes in Australia, it is not surprising to find tests of these organisms with the Lake Frome sediments. These organisms require NaCl dominated waters, and are often found at salinities averaging sea water values (~35‰), but can occur over a salinity range from close to fresh to 80‰. In order to survive desiccation, *Elphidium* seeks refuge below dead halophyte mats during drought. *Ammonia beccarii,* on the other hand, needs permanent water to survive and does best between 20 and 40‰, although it can be found with the 7–67‰ range (see De Deckker, 1981a). One specimen of *Trochaminna* further confirms the presence of halophytes upon which they usually rest (see Cann and De Deckker, 1981 for further details).

The presence of these foraminifera at Lake Frome must indicate different climatic conditions from today as no live forams have so far been found in ephemeral lake fillings in the central, arid part of Australia. De Deckker (1983a) postulated that this must be the result of the frequency/predictability of rainfall. The erratic filling of those lakes today does not allow the survival of those halobiont organisms. Similarly, the presence of foraminifera in some horizons at Lake Frome implies more frequent rains in the region than today.

5.4. Gastropoda

Only a few remains of aquatic gastropods have been found in the cores. These are believed to belong to the ubiquitous halobiont *Coxiella*. It is of no surprise to find so few specimens as aquatic gastropods usually occur on the margins of saline lakes, and upon death they either float or are windblown during dry-lake phases to the shore of the lake where they accumulate in large concentration. No attempt was made to identify the gastropods down to species level. One specimen was used for AMS radiocarbon dating in the sample at 515 cm depth.

5.5. Charophyta remains

Lake Frome is well known for some of its older formations which consist of large concentrations of charophyte remains (Callen, 1977). These, however, must have been produced during extremely wet phases. Nevertheless, the gyrogonite remains of *Lamprothamnium papulosum* in saline lakes has been substantially documented by Burne et al. (1980), the calcified reproductive organs of this species in the Lake Frome cores are to be expected. In any case, their presence must indicate low salinity conditions, as required for regeneration, even though *L. papulosum* has been found alive up to 69‰ salinity (Burne et al., 1980).

5.6. Other remains

Fish scales and vertebrae have also been recovered in the cores. Only sparse fish remains are likely to be found unless the core penetrated through an ancient shore line of the lake, where fish accumulate during fish kills, as well documented at Lake Eyre by Ruello (1976). It is not surprising to find fish remains even though Lake Frome is a playa because it is connected to an extensive fluvial system.

A few beetle remains have also been found, and it is likely that insects are often blown into a lake and die there due to the toxic nature of saline water. The presence of one specimen of the aquatic weevil *Bagous* can be explained as it is known to tolerate saline conditions (Williams, 1980).

Numerous seeds have been encountered in the cores, but little attempt has been made to identify them, except for the characteristic seeds of the halophytes *Ruppia* and *Lepilaena*. Although these aquatic grasses can tolerate high salinities (Brock, 1981), the presence of their seeds indicates low salinities (30‰ or less) and shallow water conditions.

A few microscopic egg remains (on average 1–2 mm in diameter) have also been recognised, especially for what is considered to be the most saline and ephemeral episode of the lake, and a tentative attribution to the brine shrimp *Parartemia* is made.

6. Palaeoecological and palaeoenvironmental information obtained from ostracod valve chemistry

The two elements Mg and Sr can be fairly easily measured in the calcitic valves of ostracods and vary according to the Mg/Ca and Sr/Ca of the water in which the ostracod formed its valve at the time of moulting and also with water temperature. A good summary of the conditions that control ostracod valve chemistry with respect to Mg and Sr is available in De Deckker et al. (1999). For more information on how these elements relate to conditions in a lake, refer to the synopsis of De Deckker and Forester (1988). In the case of Lake Frome, the analyses are made on the halobiont ostracods *Diacypris* spp. and *Reticypris* spp. because they are ubiquitous and well-preserved in the cores.

6.1. Magnesium

The partition coefficient for magnesium (K_D [Mg]) of either *Diacypris* or *Reticypris* species has never been calculated from field collections of live material because it has not been possible to obtain temperature measurements for the time of ostracod valve calcification and temperature plays an important role in the uptake of Mg in ostracods (Chivas et al., 1983, 1986; De Deckker et al., 1999). Nevertheless, it is assumed that being congeneric taxa, which are grouped in the same subfamily Diacypridinidae (De Deckker, 1981b), species of *Diacypris* and *Reticypris* will have similar K_D [Mg], as they do for the K_D [Sr]; see below.

It is not possible to distinguish the temperature effect on the uptake of Mg in the ostracods from that caused by the waters' Mg/Ca composition because the original water composition of Lake Frome (at the time of growth of the ostracods) is unknown. Nevertheless, by examining the trends in the Mg/Ca in the ostracods and in combination with the Sr/Ca record, it is still possible to decipher some information on lake water changes. In particular, if the Mg/Ca for all the ostracods, for any particular level, are very similar, substantially deep-water conditions can be postulated because shallow conditions would ensure broad temperature fluctuations and engender a broad range of ostracod Mg/Ca values. Similarly, if the Mg/Ca signals for adjacent samples are similar, then a lack of temperature and salinity changes can be postulated, presumably as the Mg/Ca do not change substantially.

Lake Frome as a large playa is different from the crater lake studied for ostracod shell chemistry by Chivas et al. (1986) because the presence of streams reaching Lake Frome would significantly and rapidly alter the lake's water composition with respect to Mg and Ca.

6.2. Strontium

The partition coefficients K_D [Sr] of *Reticypris* and *Diacypris* species have already been calculated by Chivas et al. (1986). Three species of *Diacypris* returned a K_D [Sr] of 0.212 ± 0.020 for 13 analyses and *Reticypris* gave a value of 0.237 ± 0.027 for 7 analyses. Note that within error, these K_D [Sr] values overlap and is very likely that being related taxa, additional analyses would, in fact, return a single K_D [Sr] for both genera. Nevertheless, it is possible to reconstruct the Sr/Ca of the ambient waters of Lake Frome because the thermodependence on the uptake of Sr in ostracods is considered minimal or non-existent (De Deckker et al., 1999). Therefore, the Sr/Ca in the ostracods should provide a good estimate of the Sr/Ca composition of the waters in which they secreted their valves. In this paper, when attempting to reconstruct past Sr/Ca of the lake's water, we use separate K_D [Sr] for the 2 genera.

Of interest to the study here is that gypsum [$CaSO_4 \cdot 2H_2O$] is commonly found in the sediments of Lake Frome and, in particular, displacive gypsum discs occur throughout much of the cores. The distribution of those discs is presented in Fig. 6, and their presence, as well as chemical analyses done on some of them, have also been discussed in Ullman and McLeod (1986) and Ullman and Collerson (1994). The precipitation of gypsum in a lake would increase the Sr/Ca of the lake water. An increase of the water Sr/Ca would be reflected in the Sr/Ca of any ostracods calcified during that period of chemical change. However, because most of the gypsum crystals recovered in the Frome cores are displacive in nature, they must have formed interstially as previously observed by Bowler and Teller (1986) and Magee (1991). Therefore, because the displacive gypsum crystals are post-depositional, we assume that their growth did not change the Sr/Ca of the lake waters at the time of deposition of the sediments containing the displacive gypsum. This hypothesis will be tested later on when comparing the ostracod shell composition results against the analyses done by Ullman and McLeod (1986) and Ullman and Collerson (1994) on the gypsum crystals.

7. Results

7.1. Chronology

Prior to establishing the evolutionary history of physicochemical changes that occurred at Lake Frome, there is a need to establish a reliable chronology of events. Obviously, radiocarbon dating of playa lake sediments is a difficult and painstaking task due to the paucity of datable material, of both organic and carbonate fractions. Bowler et al. (1986) discussed the discrepancy between the radiocarbon dates obtained from organic and inorganic residues in bulk sediments from core LF82/1-3. Their data, reproduced in Fig. 5 (to which the subsequent dates obtained from Lake Frome sediments have been added), show great disparity in ages between the two types of material used except for the middle portion of the core between 180 and 270 cm. Nevertheless, Luly and Jacobsen (2000) analysed 2 samples by radiocarbon Accelerated Mass Spectrometry, which confirmed the original dates obtained by Bowler et al. (1986) for adjacent levels. Two additional AMS dates done on pristine ostracod material (+1 gastropod from the lowest sample – see Table 1) establish ages that are still within the limit of AMS radiocarbon dating, in contrast to the earlier finding of Bowler et al. (1986) that the sample was beyond the limit of conventional radiocarbon dating. All of the dates have herewith been converted to calibrated years (=cal. yBP) using the polynomials of Bard et al. (1998); the calibrated ages are listed in Table 1 and used in Fig. 5. This figure indicates that, despite the minor disconformity at 346 cm in core LF82/1-3, the 4 AMS dates can be used to obtain the following age–depth regression with an r^2 of 0.94:

$$\text{Age(in calibrated years BP)} = 149.92 + 71.743 \times \text{depth(in cm)}$$

This relationship has been used here to reconstruct environmental changes recognised in the core. Note that several of the bulk carbonate ages fit well on the regression line, but that nearly all bulk organic dates are incompatible. We assume that alteration of the sediment by groundwater is more effective for the organic fraction. This is no surprise considering the presence of brines below the lake floor (see the discussion in Bowler (1986)).

Caution will have to be maintained with respect to the chronology of the earliest events recorded in core LF82/1-3 as the oldest AMS date at 515 cm returned an age of 37,000 uncalibrated radiocarbon yBP which is close to the limit of radiocarbon dating. Part of the material analysed for this date consists of aragonite [*Coxiella* fragment], and consequent contamination by younger carbon must be accepted as a possibility.

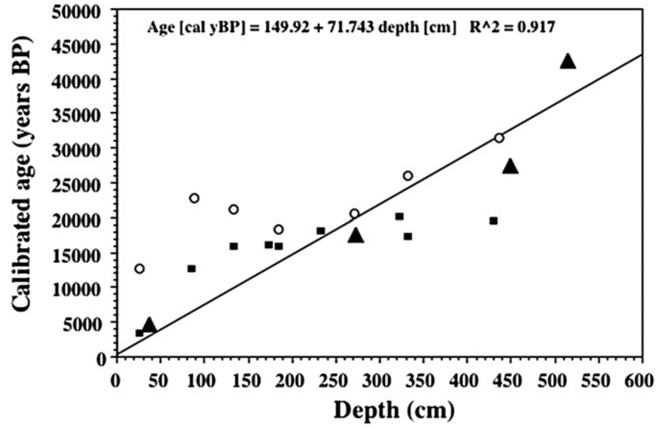

Fig. 5. Diagram showing the calibrated ages [without errors] calculated for all the samples from core LF82/1-3 using Bard et al.'s (1998) polynomial. Note the disparity of the ages away from the regression line for the 16–23k cal. yBP period, signifying a change of hydrological regime (see text for more discussion). ○ represents dates done on carbonates, ■ dates on the organic fraction, ▲ for the date on the organic fraction from core LF82/7 for comparison.

7.2. Ostracod shell chemistry

Results of Ca, Mg and Sr analyses done on the 2 genera *Diacypris* and *Reticypris* are presented in Figs. 6 and 7. All data are presented in molar ratios.

Fig. 6 displays the Mg/Ca and Sr/Ca results obtained from individual ostracod valves from core LF82/1-3. With respect to the Mg/Ca ratios, two broad and distinct patterns appear. In the lower part of the core, below ~400 cm, values are not only lower but, for most individual levels, they form tighter clusters. Above ~400 cm, values first climb progressively and then, for the rest of the core, analyses for individual levels display a broad range of values. Sr/Ca analyses, on the other hand, show the opposite trend. In particular, values for individual levels form a narrow range for the upper portion of the core down to ~260 cm.

Fig. 7 shows the Mg/Ca and Sr/Ca analyses done on ostracods from core LF82/7, located on the eastern side of the lake. Ostracods and fossil remains were better preserved in this core, and there was a need to determine whether chemical trends based on ostracod shell chemistry could be compared in both cores, knowing that sedimentation rates and/or deflation may have affected the records in both cores differently. A radiocarbon date obtained on core LF82/7 (See Table 1) gave a comparable result with the dates from equivalent depths in core LF82/1-3 (see Fig. 2). Comparison of the mean ostracod values for Mg/Ca and Sr/Ca calculated from both cores is also presented in Fig. 8 which shows similar overall trends. This feature further confirms that, using a chemical method, both cores recorded the same broad changes in the lake.

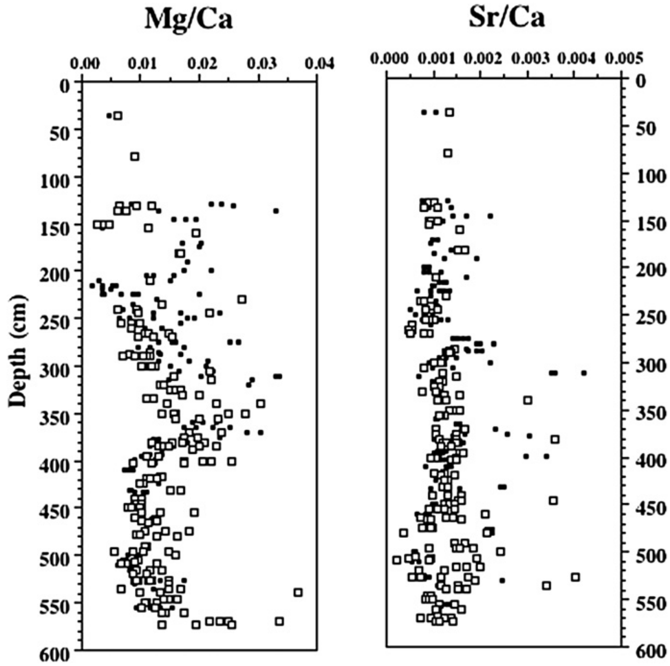

Fig. 6. Mg/Ca and Sr/Ca analyses of individual ostracods form core LF82/1-3 versus depth. ● represent analyses done on single *Diacypris* and □ on *Reticypris* specimens.

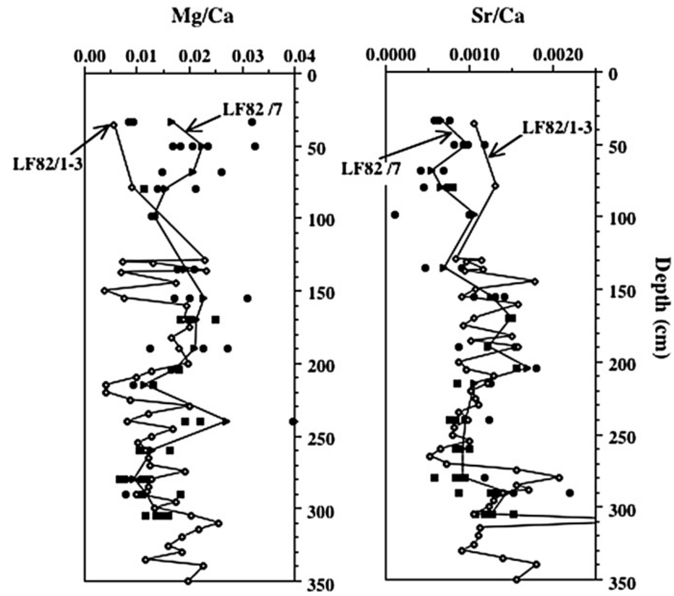

Fig. 7. Superposition of the Mg/Ca and Sr/Ca data done on individual ostracods from core LF82/7 and the mean values from cores LF82/1-3 and LF82/7, all versus depth, to demonstrate the possibility of correlating the cores on chemical trends alone. ● represent Mg/Ca and Sr/Ca from core LF82/7 on Diacypris; ■ on *Reticypris*; ▲ represent mean values of analyses for both *Diacypris* and *Reticypris* combined for core LF82/1-3 and ✧ for the same ratios done on core LF82/7.

Fig. 9 shows the reconstruction of the lake water's Sr/Ca calculated from the respective K_D [Sr] for the 2 dominant genera (*Diacypris* and *Reticypris*) compared against values for various waterbodies and aquifers [the data were obtained from Draper and Jensen (1976), Ullman and Collerson (1994) and unpublished data from Ullman]. This figure shows that prior to 21,000 yBP, the composition of Lake Frome was connected with deep aquifers, mixed with runoff water. Subsequently, the lake's water became disconnected from GAB waters and the Tertiary aquifer, with a return to wetter conditions prior to 11,000 yBP. After that, it appears that the lake's water became more distinct, as a result of he formation of a brine below its floor.

8. Synthesis of the evolutionary hydrological history of Lake Frome

In this section, we combine the palaeoenvironmental interpretation of the biotic remains together with ostracod valve chemistry and sedimentological observations carried out both directly on the core, and also on the samples after treatment for the recovery of biotic remains.

From the lower portion of core, for interval 578 to 560 cm [~41,600 to ~40,300 yBP], several ostracod remains, and charophyte oogonia have been recovered. There is evidence that salinity did fluctuate at some levels, and the fluctuating Mg/Ca values indicate that the lake may have been shallow. This is confirmed by the presence of the ostracod *L. porphyretica* indicative of freshwater conditions, and the foraminifer *A. beccarii* which requires permanent saline conditions, although these salinities could be lower than sea water salinity. *A. beccarii* requires water chemistry with Na and Cl dominance (De Deckker, 1982). The water in the lake originated from runoff as witnessed by the ostracods' Sr/Ca which show no affinity to any of the groundwater Sr/Ca ratios (see Fig. 8). At the contact near the disconformity, several ostracod specimens are deformed, probably resulting from pedogenesis. This is indicative of being much older, possibly preceding the last glacial/interglacial cycle.

Above the disconformity, and for interval 560 to 410 cm [~40,300 to ~29,600 yBP], deep-lake conditions are postulated on the following grounds: Mg/Ca values for the ostracods fluctuate little and are constantly low during this period. This is paralleled, most of the time, by the Sr/Ca ratios, although some ostracods' Sr/Ca show excursions to Tertiary aquifer-Great Artesian Basin (GAB) values (see Fig. 8). Accordingly, there are few gypsum crystals recovered from this interval (gypsum precipitation would induce dramatic changes in the water's Sr/Ca, and probably Mg/Ca as well, - see more discussion below), and platy micas abound in the bluish clays for which Bowler et al. (1986) have postulated a deep-lake facies for the upper part of this section. Several horizons contain freshwater ostracod taxa, and the low salinity *D. spinosa* and *M. splendida* are commonly found. The occasional Sr/Ca fluctuations for a few ostracod valves indicate a greater influence of the deeper aquifers, thus inferring a broad hydrological change on a regional scale with fresh(er) groundwater beneath the lake unlike the brine pool that now exists (refer to Bowler, 1986). Note also that there is an episode of salinity increase, but with permanent water conditions, shown by the presence of *A. beccarii* between 34,500 and 32,000 yBP.

From 410 cm to 346 cm [~29,600 to ~25,000 yBP], just below the disconformity, a large lake persisted, but it was more saline than before as only rare juveniles of the freshwater ostracod *Candonocypris* sp. have been found at 2 levels. The abundance of the low salinity indicators, *D. spinosa*, *M. splendida*, and *Trigonocypris* sp., in conjunction with near-constant ostracod Sr/Ca values support this interpretation. Again, the Sr/Ca of the ostracods indicate a continuing influence of Tertiary aquifer water (see Fig. 8). The ostracods Mg/Ca ratios which register a progressive increase and, at times wide fluctuations, suggest a progressive salinity increase. This phase, between 403 and 385 cm [~29,000 to ~27,700 yBP], coincides with the first occurrence of the ephippia of the halobiont cladoceran *Moina*, possibly indicating ephemeral water conditions as the permanent water indicators are absent. Noteworthy also, is the appearance of gypsum near the top of this sequence and the disappearance of *Moina* and its replacement by foraminifera (nearly always both *A. beccarii* and *Elphidum* sp.) and some charophyte oogonia from 27,700 to 25,000 yBP.

From 346 cm to 285 cm [~25,000 to ~20,200 yBP], the lake registers a change: the very saline ostracod *D. fodiens* is very

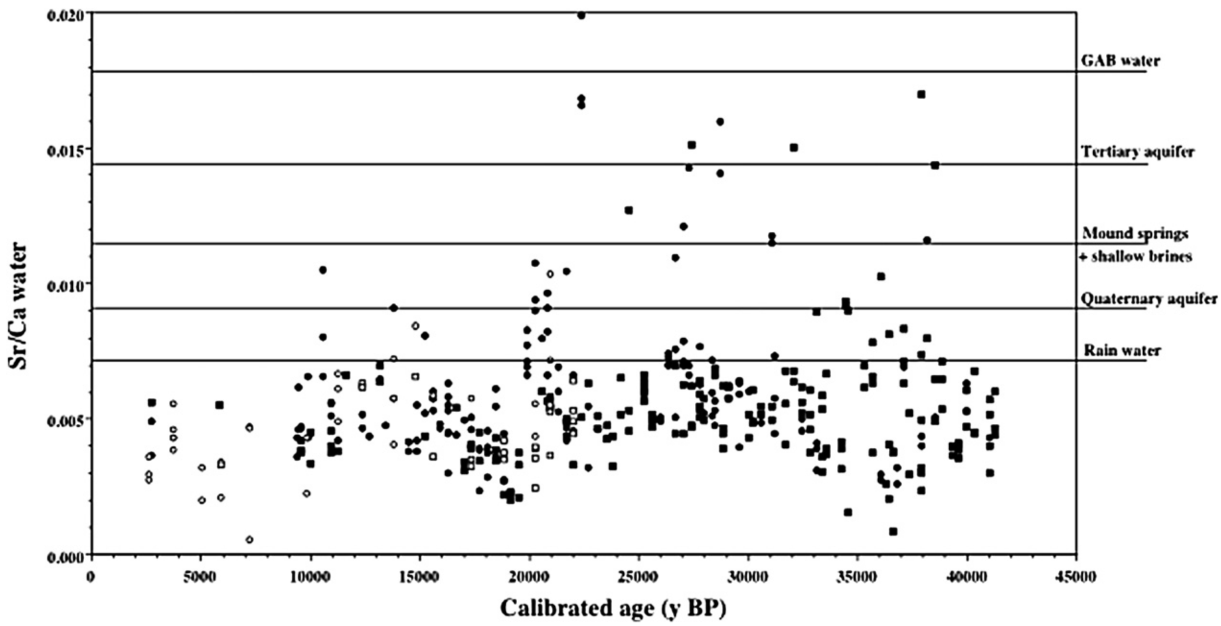

Fig. 8. Reconstruction of the Sr/Ca of the Lake Frome waters in which the ostracods grew against time in calibrated years BP. This is based on Sr/Ca analyses of individual ostracods from cores LF82/1-3 and LF82/7. ● represents analyses done on *Diacypris* from core LF82/1-3 and ■ on *Reticypris* from the same core; ○ represents analyses done on *Diacypris* from core LF82/1-3 and □ on *Reticypris* from the same core. The mean values for the present-day waters in the region [data taken from Ullman and Collerson (1994) and Ullman unpublished data] are also identified on this diagram to demonstrate the disparity of the reconstructed lake waters from regional (mostly ground-) waters. Note the consistent, broad shift in the Sr/Ca values of the lake waters between ~20 and 21.5k cal. yBP. This shift represents a major hydrological change recognised also by a greater influence of groundwater on the lake's surface water afterwards.

common at ~22,000 yBP, although a few rare freshwater ostracods are noticeable in 2 horizons. Nevertheless, all the other low salinity indicators are absent, and water composition changes with an abrupt drop in Sr/Ca, clearly returning to surface runoff values by ~20,500 yBP. There is no evidence of water permanence for this period. From 295 to 285 cm [~21,300 to 20,200 yBP], the low salinity *D. spinosa* is present in the lake and gypsum discs are rare or absent, although at 285 cm there is a mixed assemblage of this species with the high salinity tolerant *D. fodiens*. This must indicate low salinity water in an ephemeral lake some time during this period. The ostracod Sr/Ca point to runoff water filling the lake.

From 285 to 205 cm [~20,200 to ~14,800 cm], the playa is under a very different regime. Freshwater or low salinity taxa are absent and the ephemeral- and moderate salinity indicator *Moina* abounds. The Sr/Ca of the water registers an increase, and gypsum discs are very common in this portion of the core. This also coincides with the abundant presence of *D. fodiens*. It is likely that the lake water was more under the influence of groundwater brine pool and that the latter would have been established by then. This episode ends with the disappearance of gypsum discs in level 200 cm and the presence of *D. spinosa* at 205 cm.

From 205 cm to the top of both cores [~14,800 to the present], the playa Lake Frome is the ephemeral, saline playa lake we recognise today with a groundwater brine pool below it. Between ~13,000 and 11,200 yBP, the climate must have been wetter as low salinity indicators occur in 2 samples covering the 12,000 to 11,600 yBP

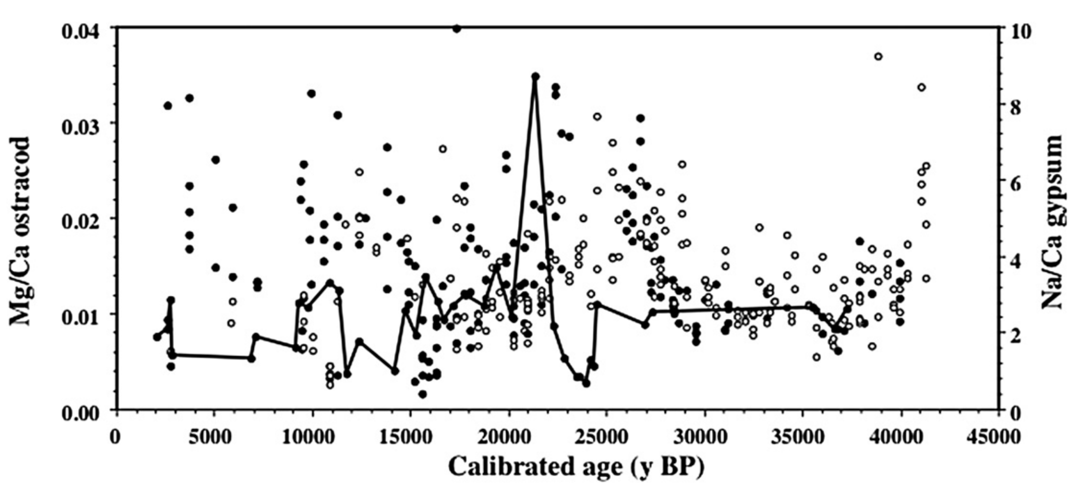

Fig. 9. Plot of the Sr/Ca analyses of individual ostracods [● on *Diacypris* and ○ on *Reticypris*] from cores LF82/1-3 and LF82/7 [assuming that sedimentation rates are similar in both cores] (against time in calibrated years BP) for comparison with the Na/Ca analyses [■ and joined by a line to show overall trend] done on gyspum discs by Ullman and McLeod (1986) from the same cores. The latter analyses were interpreted by these authors as indicating salinity changes. Note the broad trends recognised using both types of chemical analyses.

interval. After that period, the Mg/Ca of the ostracod valves fluctuates widely, thus indicating a saline, shallow and ephemeral lake. The Sr/Ca values show a similar broad range indicating ephemeral runoff waters entering the lake, as occurs today.

9. Comparison with other investigations at Lake Frome

The investigations of Williams (1973) on the piedmont sedimentation on the western side of the Flinders Ranges, some 70 km to the west of Lake Frome, are coincident with our data as debris flow and braided streams were active prior to 30,000 radiocarbon years. The landscape was definitely wetter during that period. The same applies to the Willandra Lakes system further to the SE of Lake Frome in western New South Wales (Bowler et al., 2006), and the well-dated Lake Eyre level curve (Magee et al., 2004).

The palynological investigations of Singh and Luly (1988), were carried out only on the upper 360 cm of core LF82/1-3 from Lake Frome and was thought by these authors to span only the last 18,000 radiocarbon years. Our revised chronology, presented here in calibrated years indicates an age of ~26,000 yBP for their basal depth of 360 cm. Of interest is that the largest abundance of pollen indicative of the presence of *Callitris* woodlands – which occur today in the Flinders Ranges – existed from ~26,000 to ~13,400 yBP. More recently, Luly and Jacobsen (2000) and Luly (2001) re-examined this record and interpreted the decline of *Callitris* after 12,000 cal. yBP (using our revised chronology) possibly as a response to a more active fire regime. This observation needs to be considered in line with the interpretation based on our investigations presented here that climatic conditions deteriorated after ~11,200 yBP.

Comparison of the ostracod trace-element data with the Na/Ca analyses of Ullman and McLeod (1986) done on gypsum crystals raises questions regarding such understanding of the formation of the interstitial gypsum crystals. For example, we envisage 4 possible scenarios regarding the complex relationship between lake sediment and post-depositional displacive gypsum. These are:

1. *Wettest, perennial lake conditions when the lake sediment is constantly deposited and no brine pool exists*. At that time, the lake is recharging the regional groundwater, and consequently no displacive gypsum is forming.
2. *An ephemeral lake, with significant oscillations between lacustrine conditions and playa conditions.* This is the most complex state. Wet phases are marked by sediment influx and deposition. Drier playa phases are marked by development of the brine pool. In this case, the developing brine pool underly a large area of the playa with salinity at gypsum saturation and displacive gypsum is able to grow at the capillary fringe evaporation zone across much of the lake. Gypsum will thus displace lake sediment of the previous wet phase(s) across much of the lake at a specific horizon. If, on the other hand, wet phases are still significant, an equilibrium may be established, where the brine pool evolution and water table lowering are suppressed or delayed and sedimentation exceeds deflation. In this situation, sediments may build up with almost contemporaneous displacive gypsum growth and their palaeoenvironmental signals may be in phase or close to in phase. In this case, ostracod shell chemistry should register similar signals to the gypsum crystals from the same horizons in the cores.
3. *A deflating lake, when dry playa phases dominate.* The brine pool is evolving and the water table is being lowered by evaporation. Gypsum grows displacively at the capillary fringe, initially across much of the playa but the zone of gypsum growth contracts to the margins of the brine pool as its salinity evolves. This is a time of net sediment (and displacive gypsum) loss to lunettes and within-playa islands. It is also known for the zone of displacive gypsum growth to move vertically downward through the sediment pile into successively older sediment and their palaeoenvironmental signals must become more and more out of phase. In this case, the chemical signal registered by the gypsum is out of phase with ostracod data from the same horizon in the cores.
4. *A stable playa phase, such as at present, with minimal ephemeral influx, minimal sediment influx, minimal groundwater lowering and minimal deflation*. Displacive gypsum only forms in a playa-marginal halo where surrounding fresh groundwaters meet the brine pool; during this phase, evaporation is concentrated and a narrow zone of capillary fringe at gypsum saturation occurs. Under this scenario, the chemical signals in the gypsum crystals would be "out of phase" with the ostracod signals.

Examination of Fig. 9 shows a fairly good coincidence between the Sr/Ca of the lake water reconstructed from the ostracods and the Na/Ca in the gypsum crystals. Our interpretation of the gypsum data differs from that of Ullman and McLeod (1986) in that we believe that the sharp increase in the Na/Ca in the gypsum around 21,000 yBP is not caused by a substantial increase in salinity, but a change of water composition and origin. Close examination of the data presented in Fig. 9 indicates that the shift of the Sr/Ca recorded by the ostracods occurs earlier than the Na/Ca shift in the gypsum. This indicates that the surface waters changed composition first due to a change of runoff before groundwaters changed composition. This corresponds to scenario 1 presented above, and the gypsum crystals would have formed at a later stage when salinity increases. Higher in the core, the gypsum and ostracod chemical trends coincide. This is best seen in Fig. 9 and the major shifts in Na/Ca coincide with the ostracod Sr/Ca signals. For this part of the core, scenario 2 is recognised. Unfortunately, Ullman and Collerson's (1994) data on Sr isotopes is insufficient to compare changes in the gypsum crystal formation with the ostracod data; this is particularly relevant for the older lacustrine phase discussed here for Lake Frome.

Of importance also, are the valley-filled deposits in the Flinders Rangers some 100 km to the southwest of Lake Frome that have been studied by Williams et al. (2001). These authors identified that suitable fluvial conditions could have sustained the fluvial wetlands in the Flinders Ranges during the glacial period and that this activity commenced before ~34,000 yBP. This scenario coincides well with the permanently wet conditions recognised here at Lake Frome. The interesting interpretation by Williams et al. (2001) is that overall lower temperatures during the Last Glacial Maximum helped maintain wet conditions in the region, an interpretation confirmed by the Lake Frome record. It is not surprising therefore to find a few (rare) freshwater ostracods in the LGM sediments at Frome. The brine pool below the lake must have been very close to the lake floor so as to enable displacive gypsum discs to form and eventually become deflated to form the islands. At the same time, runoff water from the Flinders Ranges must have occasionally reached the lake while transporting freshwater taxa and mixing them with halobiont organisms.

10. Conclusions

We demonstrate that a combination of trace element (Mg and Sr) analyses of single ostracod valves, together with examination of biotic remains recovered from the lacustrine cores of a large, saline playa lake can help reconstruct the status of a lake through time, even without knowledge of the original composition of the waters in which the organisms lived. Knowledge of the chemical composition of the aquifers in the region, in combination with Na/Ca ratios of gypsum discs from the same cores, have helped further detail the hydrological regime of the lake and confirm the origin of the lake's waters for the last 42,000 yBP. We interpret that prior to the Last Glacial Maximum, Lake Frome did not have a brine pool below it. Instead, it retained permanent, slightly saline and, at times, even freshwater conditions. The waters entering the lake would have originated from surface runoff. During the LGM, the lake did have some surface water, but ephemeral conditions prevailed. It is likely that low temperatures reduced evaporation enabling water to be retained in the lake. The period of deglaciation saw a brine pool forming below the lake and this feature was maintained until the present. The wettest period during the deglaciation occurred between 13,000 and 11,200 yBP.

Acknowledgments

We wish to dedicate this paper to the memory of Professor W. D. [Bill] Williams who initiated, through his very communicative enthusiasm and boundless energy, many studies of salt lakes in Australia and elsewhere. Bill was also a great supporter of palaeolimnology of salt lakes. This dedication is unfortunately long overdue.

We are indebted to Jim Bowler for his foresight in initiating the **S**alt **L**akes **E**vaporites and **A**eolian **D**eposit**S** (SLEADS) project that saw us coring numerous lakes in Australia, and for assembling a long-lasting and very productive, multidisciplinary research team at the Australian National University. We also all benefited from Jim's pioneering work at Lake Frome, and wish to also dedicate this paper to him.

We also wish to thank our valiant driller Jacques Van Roy who returned cores from playa sequences often under very arduous conditions. Dominique Thiriet spent countless hours picking and identifying most of the microfossils and we thank her for her effort of many years ago. We are also grateful to Professor S. R. Taylor for allowing Mike Shelley to conduct the ICP analyses. The 2 AMS dates done on biogenic carbonates were performed through the collaboration with Professor G. Miller, University of Colorado, and were funded by US National Science Foundation Grant ATM-9709806 awarded to G. Miller. Bill Ullman, at the time of his participation in the SLEADS program, provided unpublished groundwater chemical data to PDD which is being used here. Comments by Dr T. Cohen on early draft of the manuscript are appreciated.

Appendix. Supplementary information

Supplementary information associated with this article can be found in online version at doi:10.1016/j.jaridenv.2010.08.004.

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