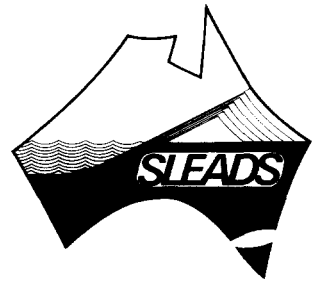


**MAGNESIUM CONTENT OF NON-MARINE
OSTRACOD SHELLS: A NEW
PALAEOHALINOMETER AND
PALAEOETHERMOMETER**



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ABSTRACT

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Ostracods are microcrustaceans with calcitic carapaces (each consisting of two valves or shells) that grow by moulting and regeneration of sequentially larger valves up to nine times before reaching maturity. The Mg content of these valves is species-dependent and is a function of their growth stage and the temperature, salinity, Mg content and Mg/Ca ratio of their host water.

Newly formed, partly calcified valves of the non-marine nektic ostracod *Mytilocypris henricae* have high Mg contents (100,000 ppm Mg in CaCO₃ at individual shell weights of 2 µg). This relative Mg content decreases as calcification proceeds, until shell weights exceed 120 µg, whereupon the Mg content is constant and useful as an indicator of the ostracod's environment.

Mg/Ca ratios in individual ostracod valves from several species of the genera *Mytilocypris* and *Australocypris* from culture experiments and a series of Australian lakes indicate that the valve's Mg content increases as a function of increasing temperature and salinity. Within the range 11–25°C and for waters containing 24–2325 ppm Mg, the molar Mg/Ca ratio in these ostracods' fully calcified valves increases by 0.0015 (or 370 ppm Mg in CaCO₃) per 1°C and per change of 125 ppm Mg in solution. For most mainland Australian lakes, a change in water composition of 125 ppm Mg corresponds to a change of 3.5‰ in salinity. For a given Mg content of a lake, the Mg/Ca ratio of the water may vary within the range of common lacustrine values without significantly affecting Mg uptake in the ostracod valves.

These relationships can provide palaeosalinities and/or palaeotemperatures for ostra-

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cods recovered from continental sediments. For Mg partitioning, an increase in temperature and salinity produce increased Mg content in ostracods, whereas for ^{18}O fractionation in biogenic calcite an increase in temperature produces a decrease in $\delta^{18}\text{O}$ of the ostracod and an increase in salinity leads to an increase in $\delta^{18}\text{O}$ of the ostracod. Thus a combination of $\delta^{18}\text{O}$ and Mg measurements on non-marine ostracods should enable unique resolution of palaeotemperature and palaeosalinity variations.

INTRODUCTION

Salt lakes are ideal sites for the investigation of past climates. A change in water regime and salinity in such lakes, which usually occur in arid or semi-arid regions, directly result from a change of climatic conditions, specifically a change in the evaporation and, or precipitation over the lake. The lacustrine sedimentary record and fossil aquatic biota will therefore testify to changes of conditions in the lakes. Our aim has been to study one member of the aquatic fauna, the ostracod, to determine whether any information on lacustrine environments can be obtained from it, as has been achieved for foraminifers in marine studies (Emiliani, 1955; Shackleton, 1967; Shackleton and Opdyke, 1973; Shackleton et al., 1983). Ostracods are essentially the only abundant calcareous microfossils in the sedimentary records of continental waters. Furthermore, because nektonic ostracods live above the sediment-water interface, their compositions relate directly to the water conditions whereas the chemical or isotopic compositions of sediments or authigenic minerals are commonly the products of diagenetic reactions.

In this study we seek to determine information on the aquatic environment recorded by the partitioning of trace elements within the calcareous shell of ostracods. To this end, we performed experiments in which ostracods were grown in waters of known temperature and chemical composition.

Ostracods were chosen because they are small (0.5–7 mm for adults), ubiquitous aquatic organisms (De Deckker, 1981) whose body is enclosed between two calcareous valves (a carapace). In contrast to organisms such as molluscs or foraminifers which retain carbonate throughout their lifetime, ostracods grow incrementally by moulting; shedding the old and redundant valves and then forming a new pair. The calcium used in the lattice of their low-Mg calcite valves is taken up entirely from the water in which the animals live and only at the time of moulting (Turpen and Angell, 1971). This process is fairly rapid; full calcification is achieved within a few days (Turpen and Angell, 1971; Chivas et al., 1983).

An advantage of studying ostracods is that any "information" on the lacustrine environment recorded in their valves relates to conditions prevailing at the time of moulting and formation of a new shell. Therefore, for an individual ostracod which moults up to eight or nine times within a year, different environmental conditions are recorded in the successively shed valves. Data on seasonal differences of the environment are potentially available.

PREVIOUS WORK AND PRESENT STRATEGY

As early as 1954, Chave suggested that the Mg content of ostracod shells varies with temperature, although his material consisted of six mixed assemblages of Holocene marine ostracods, (Chave, 1954). Cadot and Kaesler (1977) later showed that Mg content varies considerably among ostracod subfamilies.

Our preliminary experimental work (Chivas et al., 1983) suggested a strong positive correlation between the Mg content of the shell from a single ostracod species and increasing water temperature. These experiments were restricted to salinities of 3‰ and 9‰, but in this study are expanded to cover a salinity range up to 73‰. Our approach has been to cultivate ostracods in a series of waters with low salinities and with a narrow range of Mg/Ca ratios. To obtain information for higher salinities and Mg concentrations, ostracods were collected from a series of Victorian lakes which provide data on a broad range of natural conditions. We have thus been able to examine Mg partitioning in the ostracod valve as a function of temperature, salinity (i.e. Mg content), and Mg/Ca ratio of the water.

MATERIALS AND METHODS

The large ostracod *Mytilocypris henricae* (length \approx 3 mm) used in the laboratory experiments was collected from Lake Bathurst, some 75 km N of Canberra. This species occurs in slightly saline lakes (commonly 5–10‰) in eastern Australia (De Deckker, 1978, 1983) especially those which have extensive beds of the halobiont macrophyte plants *Ruppia* and *Lepilaena* spp.

Individual A-1 juvenile (adult minus one stage) specimens of *M. henricae*, were collected from the lake, washed in distilled water before being placed in 25-ml conical flasks filled with filtered (0.45 μ m) saline water. After being washed in distilled water and rapidly dried on tissue paper, one or two fragments of halophytes from Lake Bathurst were placed in each flask and upon which the ostracods grazed. Water used in the experiments was also collected from Lake Bathurst and subsequently diluted with de-ionized water or evaporated to reach the following salinities: 3, 9, 13.9 and 17.8‰. During the experiments, the sealed flasks were kept in a constant-temperature waterbath. For experiments at 3 and 9‰ salinity, temperatures of 15 and 25°C were monitored; at 13.9 and 17.8‰ a temperature of 25°C was maintained.

After the juvenile (A-1) ostracods moulted to adults, the discarded juvenile valves lying at the bottom of the flasks were pipetted out, washed in de-ionized water and stored in ethanol. At a later stage, adults were commonly killed and the separated valves subsequently also stored in ethanol.

Laboratory experiments indicate (Chivas et al., 1983; Martens, 1985) that the intermolt period for juvenile *M. henricae* is one to two weeks. Therefore it is possible to collect juvenile ostracods from lakes and assume with confidence that the water temperature and chemistry of the lakes at the time

of collecting would have been similar to those at the time of the last moult of the ostracods. Thus, juvenile specimens of *M. henricae* collected from Lake Bathurst and immediately preserved in ethanol at different times of the year were also used for chemical analyses of their shell. Times of collection were selected to obtain specimens grown at temperatures different from those used in the experiments.

ANALYTICAL PROCEDURE

Ca, Mg and Sr analyses were performed on individual ostracod valves. The other valve from each specimen was stored for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analysis. Dried ostracod valves were immersed in 10 ml 2% HCl for at least 24 hr in acid-washed polypropylene bottles. Merck "Suprapur" HCl and water from a "Milli-Q" de-ionizer were used. We have shown (Chivas et al., 1983) that this acid attack does not leach trace elements from the chitinous sheath, (visible in suspension in some solutions), which has a different Mg/Ca ratio to that of the calcite carapace.

The solutions were analysed using a very high resolution inductively-coupled argon-plasma atomic emission spectrometer (ICPAES) (Shelley and Taylor, 1981). The limits of detection (2σ , in $\mu\text{g/l}$, or ppb) in solution are Ca 0.02 (wavelength 3933.6 Å), Mg 0.04 (2795.5 Å) and Sr 0.03 (4077.7 Å). Concentrations encountered were all greater than an order of magnitude above the detection limits. Corrections were made for contaminant (blank) concentrations in the solvent acid.

RESULTS

Analytical results for Mg, and Sr are expressed as ppm by weight of CaCO_3 . In practice, the valves are not weighed but the Ca, Mg and Sr contents of the dissolutions are determined and expressed as μg of the element present in each valve. We refer to the calculated CaCO_3 weight as the nominal shell weight, because ostracod valves are typically $\sim 90\%$ CaCO_3 . Final presentation of data is commonly in the form of atomic ratios (Mg/Ca, Sr/Ca) for both ostracods and waters.

Growth history

The Mg content of *Mytilocypris henricae* from both Lake Bathurst and the culture experiments varies as a function of calcification. Newly formed valves are thin and soft and have a high Mg content, even higher than the Ca content, until calcification proceeds. Figure 1 shows how the relative Mg content decreases with increasing shell weight. From these data and from earlier experiments (Chivas et al., 1983) we estimate that shells reach constant Mg content at a nominal shell weight of 120 μg . Adult valves of this species commonly reach 200–300 μg . The time taken to calcify to a shell

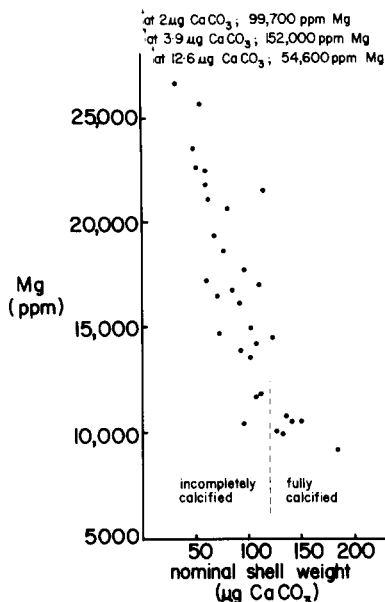


Fig.1. Plot of Mg content of individual *Mytilocypris henricae* valves as a function of the weight of CaCO_3 in their shells. These data derive from an experimental culture at 13.9‰ salinity and 25°C.

weight in excess of 120 μg is temperature dependent: approximately 11 days at 15°C and 5 days at 25°C (Chivas et al., 1983).

The initial very high Mg contents of ostracods indicate high values of the distribution coefficient ($K_D = [\text{Mg}/\text{Ca}]_{\text{CaCO}_3} / [\text{Mg}/\text{Ca}]_{\text{H}_2\text{O}}$) during the early stages of calcite formation. Such behaviour has been reported for other trace elements in inorganic CaCO_3 precipitation (e.g. for Zn, Tsusue and Holland, 1966; and for Sr and Ba, Kitano et al., 1971). Our results are the first to indicate this phenomenon is present in biogenic carbonates. Caution should perhaps prevail in the interpretation of the trace-element contents of other calcareous organisms because of the possible preferential uptake of Mg during the early stages of calcification.

The Mg and Sr contents of fragments broken from a single adult right valve were compared with those from the whole left valve (Table I) from the same specimen to indicate uniform trace-element contents for small samples of a fully calcified shell. This also confirms that the high Mg content of poorly calcified valves is not due to analytical difficulties in dealing with very small samples.

The variability of the Mg and Sr contents of a series of ostracods collected at a single sampling from Lake Bathurst was also examined (Table I). Juvenile shells display less analytical scatter than do adults, because the juveniles' compositions reflect temperature and salinity variations during an interval of 10 days or less immediately prior to sampling. Individual adults have reached

TABLE I

Analysis of individual valves of the ostracod *Mytilocypris henricae* from a single sampling (4 October 1982) of Lake Bathurst, New South Wales (lat. 35°03'S; long. 140°41'E)

Analysis number	CaCO ₃ (μ g)	Mg (ppm)	Sr (ppm)	Ca (μ g)	Mg (μ g)	Sr (μ g)	Mg/Ca ^a	Sr/Ca ^a
<i>juvenile shells</i>								
1	158.7	4850	3480	63.6	0.770	0.552	0.020	0.0040
2	157.8	4350	3370	63.2	0.686	0.532	0.018	0.0038
3	147.3	3730	3440	59.0	0.549	0.507	0.015	0.0039
4	59.1	5030	3240	23.7	0.297	0.192	0.021	0.0037
9	142.8	4130	3060	57.2	0.590	0.437	0.017	0.0051
11	49.4	4150	3000	19.8	0.205	0.148	0.017	0.0034
12	182.2	3340	3390	73.0	0.609	0.618	0.014	0.0039
14	127.1	3600	2500	50.9	0.458	0.318	0.015	0.0029
16	187.2	3210	3135	75.0	0.601	0.587	0.013	0.0036
18	131.8	4120	2700	52.8	0.543	0.356	0.017	0.0031
20	140.7	3910	3110	56.3	0.550	0.438	0.016	0.0036
average of 11 shells		4038 \pm 570(1 σ)	3130 \pm 310(1 σ)					

<i>new, uncalcified shell</i>														
10	0.35	398,000	5240	0.14	0.139	0.0018	1.64	0.0059						
<i>adult shells</i>														
5	224.9	6490	5780	90.1	1.46	1.30	0.027	0.0066						
6	164.5	3760	3170	65.9	0.619	0.522	0.016	0.0036						
7	234.7	5020	3810	94.0	1.18	0.894	0.021	0.0044						
8	98.3	8140	5780	39.4	0.80	0.568	0.034	0.0066						
13	283.7	6180	5520	113.6	1.75	1.57	0.025	0.0063						
15	204.6	4290	3340	81.9	0.88	0.683	0.018	0.0038						
17	188.7	6050	4090	75.6	1.14	0.772	0.025	0.0047						
19	271.1	5950	6240	108.6	1.61	1.69	0.025	0.0071						
average of 8 shells		$5735 \pm 1370(1\sigma)$	$4716 \pm 1240(1\sigma)$											
<i>fragment experiment</i>														
21 whole left valve	242.0	3600	2970	96.9	0.87	0.719	0.015	0.0034						
22 ventral portion of right valve	58.3	3950	3080	23.4	0.230	0.180	0.016	0.0035						
23 posterior portion of right valve with fragment of dorsal attached	50.2	4270	3230	20.1	0.214	0.162	0.018	0.0037						
24 anterior + portion of dorsal of right valve	20.8	4170	3350	8.3	0.087	0.070	0.017	0.0038						

^aMg/Ca and Sr/Ca expressed as atom ratios.

maturity and thus ceased further calcification at any time during several months prior to sampling, when water conditions could have been quite variable.

Laboratory experiments and temperature-dependence of Mg partitioning

Laboratory experiments using diluted or evaporated Lake Bathurst water were performed at 5, 15 and 25°C, with nominal salinities of 3, 9, 14 and 18‰. Experiments at 18‰ were unsuccessful, because 74 ostracods died before moulting and only two moulted successfully, but these died shortly afterwards without significant calcification. In this case an insufficient period of acclimatization during the change from 3.5‰ (natural Lake Bathurst water) to 18‰ salinity is the likely cause, rather than intolerance to this salinity, because the same species of ostracod has been reported from a lake with a salinity of 19.5‰.

No ostracods moulted at 5°C during a period of 50 days (at salinity 3‰) although their survival rate was greater than for that of other experiments. The ostracods were sluggish at 5°C, with apparently reduced metabolism. Several moulted within a day of their temperature being increased to 15°C.

The composition of the experimental waters is shown in Table II and Fig.2 reports the atomic Mg/Ca ratios of those ostracods that reached nominal valve weights of greater than 120 µg. The experimental results at 15°C and 25°C are supplemented by analysis from two collections directly from Lake Bathurst, which had a salinity of 3.5‰, and whose ostracods can be compared with the experiments at 3‰. These results indicate a temperature

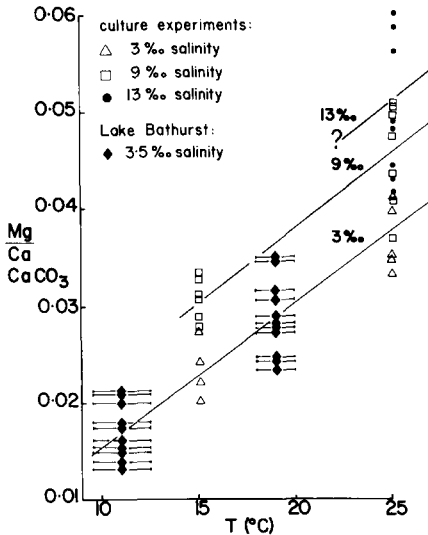


Fig.2. Plot of atomic Mg/Ca ratio in the calcitic portion of *Mytilocypris henricae* valves as a function of temperature of growth. Results are indicated for experimental cultures at 3, 9, and 13‰ salinity and for Lake Bathurst (3.5‰ salinity) samples.

TABLE II

Chemical composition of natural and experimental waters for ostracod growth experiments. Contents of trace elements in mg/l (ppm)

	Typical natural water from Lake Bathurst	Experimental Waters				
		for 15°C expt.		for 25°C expt.		
Salinity at 18°C (‰)	~3.5	2.89	8.99	2.88	8.94	13.95
pH	8.95	9.25	9.35	9.45	9.25	9.1
Na	1240	1095	3460	1050	3185	
K	68	60	176	57	163	
Li	0.004					
Rb	0.003					
Ca	20.7	13.1	17.3	12.4	11.5	
Mg	118	104.6	287	100.5	279	515
Sr	0.82	0.62	1.71	0.65	1.61	3
Ba	0.19	0.16	0.41	0.15	0.32	0.6
F	2					
Cl	1730	1750	5385	1745	5390	
Br	0.5					
B	0.35					
SO ₄	20					
P	0.8					
Mg/Ca (atoms)	9.4	13.2	27.4	13.4	40.0	

dependence for Mg partitioning corresponding to 0.0015 Mg/Ca per °C (or 370 ppm Mg in CaCO₃ per °C). The Mg/*T* slope at 9‰ salinity is parallel to that at 3‰ salinity and is offset to higher Mg/Ca values by 0.008 Mg/Ca units (Fig.2).

Lake Bathurst water is saturated with respect to CaCO₃ so that further evaporation to higher salinities produced no increase in Ca content because of CaCO₃ precipitation. Thus the waters for the higher salinity experiments have progressively higher Mg contents and higher Mg/Ca ratios. The higher Mg contents of the experimentally grown ostracods at higher salinities might be influenced by either or both variations; these are tested separately by expanding the range of salinities and Mg/Ca ratios using ostracods from a series of lakes.

Ostracods from lakes and salinity-dependence of Mg partitioning

After reconnaissance analyses of the water chemistry of many lakes were completed, a sequence of 13 lakes, mostly volcanic crater lakes, from western Victoria and South Australia were chosen to provide a range of solute compositions with salinities varying between 1.3‰ and 73‰ (Table III). The lakes were sampled at three periods of the year to provide further variations in water temperature and chemical composition (due to seasonal variations

TABLE III

Chemical and physical properties of some western Victorian and South Australian lakes from which ostracods were harvested

Name of lake	Number assigned to lake	Date of sampling	Salinity ^a (‰)	Conductivity K ₁₅ (mS/cm)	Temperature (°C)	Ca	Mg	Sr	Ba	Na	K	Cl	HCO ₃ ^b	Atomic Mg/Ca
Edward (SA)	LE	B. 7 Aug. 1983	1.3	1.951	12.5	49.1	97	0.72	0.04	332	45.3	460	35	3.3
		C. 9 Dec. 1983	1.4	2.049	21	56.7	80	0.84	0.04				30	2.3
Goldsmith	KP-21	B. 5 Aug. 1983	1.5	2.214	4.8	25.7	63	0.5	0.05	479	3.9	734	326	4.0
		C. 9 Dec. 1983	1.9	2.780	14.5	34.0	51	0.55	0.04				390	2.5
Toolorook	KP-18	A. 10 Oct. 1982	2.1	3.081	15.5	42.2	154	0.8	0.05	625	16.8	1240		6.0
Coragulac	KP-1	A. 7 Oct. 1982	4.3	5.674	16.6	1.05	194	0.02	<0.01	1930	123	2190	3000	305
		B. 6 Aug. 1983	6.0	8.718	7.2	2.7	267	0.06	0.01	2370	161	2630	3000	163
Purdigulac	KP-2	A. 7 Oct. 1982	5.0	7.179	15.8	2.8	187	0.09	<0.01	2290	140	2370		110
		C. 7 Dec. 1983	6.9	9.463	17.5	6.9	190	0.17	0.05				3400	45
Rosine	KP-9	C. 8 Dec. 1983	7.2	9.854	22.0	49.1	303	2.21	0.20	2470	31.1	6430	315	10.2
Unnamed pond near Skipton ^c	KP-20	A. 10 Oct. 1982	10.0	13.947	19.5	19.8	1310	3.8	0.2	1750	16.1	4430	330	12
		B. 5 Aug. 1983	7.1	9.756	8.5	96.3	720	1.6	0.03				440	11
		C. 8 Dec. 1983	5.1	7.122	19-22	50.6	328	0.8	0.02				3200	3.3
Lesser Twin	KP-5	C. 7 Dec. 1983	11.0	14.634	20.0	11.6	24	0.29	0.05					7.9
Unnamed lake near Coorong	9DDG	24 Oct. 1983	21.5	26.927	29	143	688	13.1	0.03					
Lagoon (SA) ^d														
Bookar	KP-17	A. 9 Oct. 1982	23.7	30.810	13.4	18.8	617	1.9	0.16	7780	66.3	12,990	54	54
		B. 5 Aug. 1983	21.9	27.317	11.7	12.9	529	1.5	0.08	8020	56.4	12,320	1225	68
East Basin	KP-28	B. 6 Aug. 1983	54.3	58.927	10.2	36.8	1285	3.4	0.18	16,700	439	28,370	2255	58
		C. 7 Dec. 1983	53.3	58.049	19.0	40.2	1020	3.3	0.19				2255	42
Gnotuk	KP-10	A. 9 Oct. 1982	67.3	73.488	12.8	125	2325	8.4	0.44	18,990	597	33,670	31	31
		B. 5 Aug. 1983	63.5	70.244	12.1	125	2260	8.2	0.44	17,920	424	33,190	940	30
		C. 8 Dec. 1983	63.5	70.244	17.0	132	1730	8.2	0.56				925	22
Kellambete	KP-29	A. 11 Oct. 1982	74	79.452	13.5	21.1	1290	3.6	0.22	22,740	500	35,900	112	112
		B. 6 Aug. 1983	71.5	77.073	10.2	21.2	1300	3.6	0.22	23,090	418	36,860	2180	89
		C. 8 Dec. 1983	72.7	78.049	18.0	21.4	990	3.5	0.22				2100	79

^aSalinity equated to the total dissolved solutes measured from Williams' (1966) formula based on conductivity measurement. ^bBicarbonate determination by field alkalinity titration after method of Barnes (1964). ^cPond on east side of road, 7.2 km south of Carranballac on road to Pura Pura. ^dLake 9 of De Deckter and Geddes (1980). All lakes are located in Victoria except those followed by (SA) which are in South Australia.

TABLE IV

Representative chemical analyses of single ostracod valves from some southern Australian lakes

Lake, date of collection and sample number	Nominal shell weight ($\mu\text{g CaCO}_3$)	Mg (ppm) ^a	Sr (ppm) ^a	Ca (μg)	Mg (μg)	Sr (μg)	Mg/Ca ^b	Sr/Ca ^b	Mg/Sr ^b
Lake Toolorook (10 Oct. 1982)									
<i>Mytilocypris splendida</i>									
KP18-A	A	2700	1510	105.7	0.713	0.399	0.0111	0.0017	6.53
	B	2450	1440	128.4	0.786	0.462	0.0101	0.0016	6.31
	C	2420	1270	82.1	0.496	0.260	0.0100	0.0015	6.67
	D	2220	1370	123.5	0.684	0.422	0.0091	0.0016	5.69
	E	3250	1330	109.6	0.889	0.364	0.0134	0.0015	8.93
	F	2190	1560	108.8	0.595	0.424	0.0090	0.0018	5.00
	G	2240	1070	91.4	0.511	0.244	0.0092	0.0012	7.67
<i>Mytilocypris henricae</i>									
KP-18A	H	2080	1330	136.9	0.711	0.455	0.0086	0.0015	5.73
	I	2180	1580	138.0	0.751	0.544	0.0090	0.0018	5.00
	J	2610	1290	128.7	0.839	0.414	0.0107	0.0015	7.13
	K	2410	1320	94.7	0.570	0.312	0.0099	0.0015	6.60
	L	2750	1440	157.3	1.080	0.566	0.0113	0.0016	7.06
	M	2400	1370	92.3	0.553	0.316	0.0113	0.0016	7.06
Lake Edward (7 Aug. 1983)									
<i>Mytilocypris mytiloides</i>									
LE-B	1	2260	1270	40.24	0.227	0.128	0.0093	0.0015	6.41
	2	1765	1120	38.28	0.169	0.107	0.0073	0.0013	5.67
	3	1940	1285	40.19	0.195	0.129	0.0080	0.0015	5.44
	4	2030	1245	45.09	0.229	0.140	0.0084	0.0014	5.89
	5	1890	1160	39.21	0.185	0.114	0.0078	0.0013	5.86
	6	2195	1240	39.76	0.218	0.123	0.0090	0.0014	6.37
	7	1900	1340	108.2	0.513	0.363	0.0078	0.0015	5.10
	8	2335	1260	170.2	0.992	0.536	0.0096	0.0014	6.67
Lake Keilambete (6 Aug. 1983)									
<i>Australocypris robusta</i>									
KP-29B	1 juvenile	12,650	6150	5.95	0.188	0.091	0.0521	0.0070	7.41
	2 juvenile	9150	5500	2.87	0.066	0.039	0.0377	0.0063	6.00
	3	6930	5195	52.52	0.909	0.681	0.0285	0.0059	4.81
	4	7370	5550	44.57	0.820	0.618	0.0303	0.0063	4.78
	5	6440	5440	56.72	0.912	0.771	0.0265	0.0062	4.26
	6	6090	5200	59.24	0.901	0.769	0.0251	0.0059	4.22

^aMg and Sr expressed as ppm of the nominal shell weight ($\mu\text{g CaCO}_3$). ^bAtom ratios.

in precipitation/evaporation). In some lakes, several species of ostracod co-exist allowing consideration of species-dependent magnesium partitioning. Not all lakes were sampled on each occasion because ostracods were not always present.

Approximately six individual fully calcified ostracod valves were analysed for Ca, Mg and Sr content for each sampling. Table IV lists some representative analyses and all Ca and Mg analyses are shown on the accompanying diagrams.

Effect of Mg/Ca ratio of the water on the Mg/Ca ratio in the ostracod valve

From the lakes examined several can be selected with a narrow range of Mg content (154–267 ppm) but a large variation in the Mg/Ca ratio. These are shown in Fig.3 which is a plot of the Mg/Ca ratio of the host water versus the same ratio for the ostracod shells. Adjacent to the data for each lake is the Mg content (in ppm) of the water. The Mg/Ca ratio, or the Mg content of the ostracod is only slightly affected by variations in the Mg/Ca ratio of the waters even at very high values (Mg/Ca \sim 300). The Mg/Ca ratios of lake waters are commonly in the range 0.1–20. The Mg/Ca ratios reported in Fig.3 reach very high values, and yet the Mg/Ca value of the ostracods from these lakes shows little response.

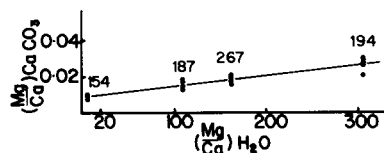


Fig.3. Plot of atomic Mg/Ca ratio in the calcitic portion of ostracod valves as a function of atomic Mg/Ca ratio of host water. The lakes chosen (KP-18, 2A, 1B, 1A) are those with similar magnesium contents (154–267 ppm), which are labelled in ppm.

Effect of Mg content of the water on the Mg/Ca ratio in the ostracod valve

The data for ostracods and waters from all 13 lakes are plotted in Fig.4, where the Mg/Ca ratio of the shell is compared to the Mg content of the water. In this case there is a strong correlation and a considerable variation of (Mg/Ca) shell, from 0.1 to 0.4 as the Mg content of the water varies from 25 to 2300 ppm. Variation in water temperature for these latter data has not been taken into account, but its effect on the Mg content of the ostracod shells compared to the effect due to variation of the Mg content of the water is clearly subordinate.

It is worth noting the effect that could be induced by a 5°C change in water temperature (from the experimental data of Fig.2; see bar in Fig.4) and that the scatter of Mg/Ca data for shells from a single sampling is equivalent to that which could be produced by a variation of 2–4°C alone. The water temperatures tabulated in Table III are misleading; each is a single observation on different days, and at different times of the day, and some

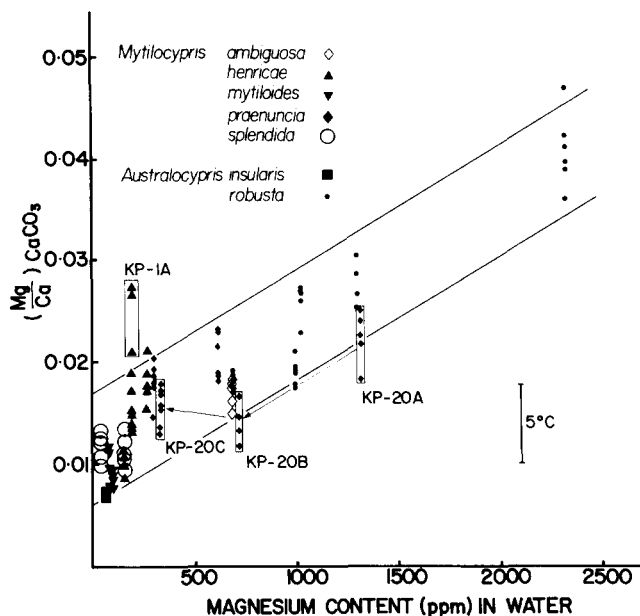


Fig. 4. Graph of atomic Mg/Ca ratio in the calcitic portion of ostracod valves as a function of Mg content of their host waters. The vertical bar labelled "5°C" indicates the change in Mg/Ca ratio of an ostracod valve that would be caused by a change in temperature of 5°C (from the relationship of Fig. 2) of the host water. The arrows show the changing composition of *M. praenuncia* from the pond near Skipton (KP-20A, B, and C). *M. henricae* from KP-1A, which lies outside the general trend, derives from a lake with an extremely high Mg/Ca ratio (305).

lakes are very shallow. For example the lowest temperature, 4.8°C at Lake Goldsmith-B was recorded at 9.20 am. We estimate that the mean temperature of each lake is within a range of approximately 5°C throughout the year.

The largest change in water composition for a single lake is displayed by the shallow (~20 cm) pond near Skipton (KP-20) where progressive changes in water chemistry, combined with a low temperature for the B sampling lead to first a reduction, then a slight increase in the Mg/Ca of the ostracod shells. These changes are indicated by the arrows on Fig. 4.

Species-dependence of Mg partitioning

Our experiments and collections from natural waters involve ostracods of two genera, *Australocypris* and *Mytilocypris* that are morphologically similar and of similar size. We have examined several species of each, namely, *A. robusta*, *A. insularis* and *M. henricae*, *M. mytiloides*, *M. splendida*, *M. praenuncia*, *M. ambiguosa*. The shells of coexisting *M. henricae* and *M. splendida*

from Lake Tooliorook have identical Mg contents (Fig.4 and Table IV) and those of *M. ambiguosa* and *A. robusta* from the unnamed lake (9DDG) near the Coorong Lagoon are also similar (Fig.4).

Preliminary results for smaller genera (adults with nominal weights of 0.5–20 μg CaCO_3 per valve) such as *Limnocythere*, *Diacypsis*, *Reticypsis*, *Ilyocypris*, and *Cyprinotus* suggest these contain significantly more Mg than do coexisting *Australocypris* and *Mytilocypris*. In general, it appears that the smaller the species the higher the Mg content of its shell. Thus there is a parallel with the high Mg-contents of small poorly-calcified *Australocypris* and *Mytilocypris*.

DISCUSSION

Calculation of past temperatures and salinities

For the two genera investigated we have provided correlation curves that can be used to estimate past variations in the chemistry of lakes for ostracods recovered by, for example, coring pertinent lake sequences. However, the Mg content of the ostracod shell is a function of both temperature and Mg content of the water. In low-latitude and semi-arid areas with little long-term seasonal temperature fluctuation, the compositional effect significantly outweighs the contribution due to temperature, and the effect of varying the Mg/Ca of the water at constant Mg content is minor.

In some situations, such as the Victorian lakes sampled in this study, and in fact, much of present mainland Australia, the seasonal and long-term temperature changes may be small and thus the Mg content of ostracods could be used to indicate changes of salinity that ultimately reflect changes in the precipitation/evaporation ratio (P/E). In this case, the Mg content of the palaeolake is also a direct indicator of past salinity and thus P/E because virtually all Australian saline lakes have the same chemical "pathway" (in the sense of Eugster and Jones, 1979) in the $\text{NaCl}-\text{SO}_4^{2-}-\text{HCO}_3^-$ system. This is illustrated by a plot of Mg content versus salinity for most published analyses of mainland Australian lakes with salinities up to 100‰ (Fig. 5). This clear relationship is not maintained much beyond salinities of 100‰ where precipitation of evaporite minerals ensues (starting with gypsum in Australian lakes, for example). However, most ostracods cannot tolerate such salinities, and fossil ostracod shells are not useful for investigating high-salinity palaeoenvironments.

A further advantage is that the salinity ranges for the ostracods from our study are well known (Fig.6) and, in some cases, may be used to decide if observed changes in the Mg content of ostracods are due to changes in temperature and/or salinity. Also shown in Fig.6 is the anticipated Mg content of ostracods at different salinities, based on the salinity: Mg relationship of Fig.5 and the ostracod-Mg data of Fig.4.

A more complex pursuit involves comparison of the Mg contents of nektic

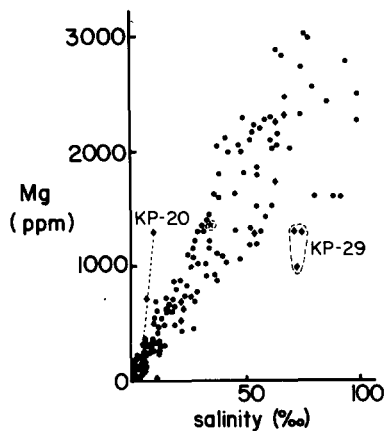


Fig.5. Relationship between Mg content and salinity for some mainland Australian lakes (162 analyses). Data from Williams (1966), Maddocks (1967), Geddes et al. (1981), Williams and Buckney (1976), Bayly and Williams (1966, 1972) and unpublished works of P. De Deckker and W. D. Williams. The star represents the composition of ocean water, and the diamond-shaped symbols represent those lakes from Table III. Two of these lakes, KP-20 and KP-29, have compositions outside the general trend.

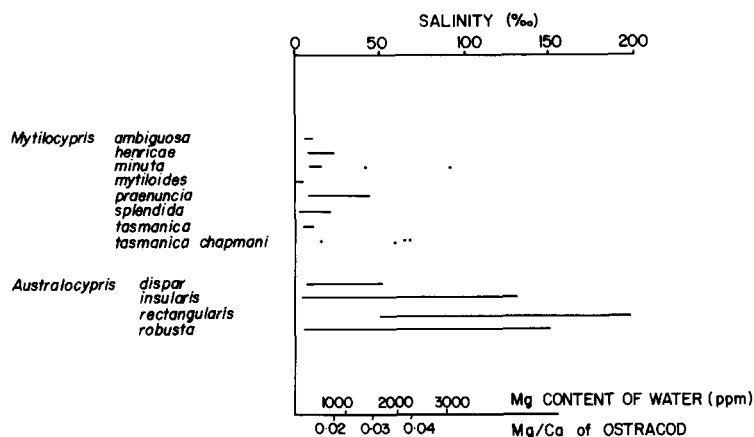


Fig.6. Distribution of the Australian non-marine ostracods *Mytilocypris* and *Australocypris* as a function of salinity (De Deckker, 1983). Also shown is the approximate Mg content of these waters (from the relationship of Fig.5) and the anticipated approximate Mg/Ca ratios of ostracod valves from these lakes (from the relationship of Fig.4).

and benthic ostracods (when suitable calibrations are complete for the latter) from deep lakes, with the aim of setting limits to the proportion of the observed Mg variations due to each of the temperature and salinity effects.

A unique solution to lacustrine palaeotemperature and palaeosalinity using Mg-content and $\delta^{18}\text{O}$

A potential solution to the uncertainty in interpretation of Mg-contents of ostracods in the general situation involves introduction of a second parameter. The oxygen-isotope composition of biogenic calcite varies as a function of water temperature (Epstein et al., 1953; Erez and Luz, 1983) and salinity. The variation of the latter is essentially due to changing bulk $\delta^{18}\text{O}$ content of a lake with progressive evaporation or dilution by rainwater or fresh-water runoff. Importantly, the $\delta^{18}\text{O}$ responses are not in the same direction as those for Mg-partitioning. An increase in temperature and/or salinity of a lake produces an increase in Mg-content of the constituent ostracod, whereas an increase in temperature produces a decrease in $\delta^{18}\text{O}$ of the ostracod and an increase in salinity leads to an increase in $\delta^{18}\text{O}$.

These combined variations and also the case for unchanged salinity and temperature are illustrated in Fig.7. There appears the potential to uniquely solve independent variations in salinity and temperature for ostracods from cored lacustrine sequences. This resolution need not be merely qualitative (as for the curves of Fig.7) but may be solved for paired Mg/Ca and $\delta^{18}\text{O}$ analyses from the same sample with simultaneous equations of the form:

for Mg-partitioning: $x(m, T) + y(m, S) = z$

for $\delta^{18}\text{O}$: $x'(m, T) + y'(m, S) = z'$

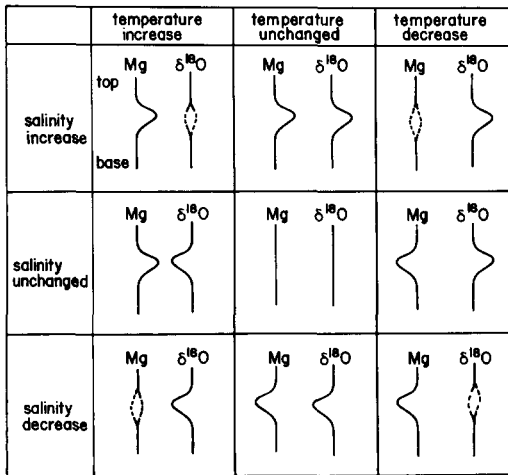


Fig.7. Combined variations of Mg and $\delta^{18}\text{O}$ in ostracod carapaces in response to a matrix of conditions representing increasing, unchanged, and decreasing water temperature and salinity. Each curve represents the trend that might be produced from continuous sampling of ostracods from a stratigraphic sequence such as that recovered in drill core. (Note "top" and "base" in the top-left segment, refer to this stratigraphic order.) In this generalized example, the single and synchronous perturbation in temperature and/or salinity is followed by a return to initial conditions. Dashed lines indicate those cases where salinity and temperature changes produce compositional shifts in opposite directions and where the resultant trend depends upon the magnitude of these individual changes.

where m , T and m , S represent the known "slopes" of Mg/Ca and $\delta^{18}\text{O}$ response per $^{\circ}\text{C}$ and per ‰ salinity change, respectively. z and z' represent respectively the measured Mg-content and $\delta^{18}\text{O}$ value of the ostracod and x and y are the relative contributions of the temperature and salinity variations. This paper provides those factors for Mg/Ca (m , $T = 0.0015$; m , $S = 0.0006$) for two genera of nektic ostracods. We are currently investigating the $\delta^{18}\text{O}$ fractionation for the same ostracods from experimental and natural conditions. The $\delta^{18}\text{O}$ variation as a function of salinity change can be calculated from evaporation curves given by Gilath and Gonfiantini (1983). At very high salinities there would be uncertainties associated with the use of these curves, due to the possibility of unpredictable variations of past relative humidity. However, these high salinities are largely beyond the range of ostracod tolerance.

In a companion paper, we (Chivas et al., 1985) have described the Sr contents of the living ostracod *Australocypris robusta* from Lake Keilambete (lake KP-29, Table III). The Sr uptake is a function of the Sr content of the host water (i.e. salinity, in a closed-system lake), with little variance contributed by temperature changes. For Lake Keilambete, a 10,000-year palaeosalinity record based on the Sr-content of ostracods (*A. robusta* and *M. praenuncia*) is in striking agreement with independent salinity estimates derived from sediment texture alone. Thus a further estimate of both lacustrine palaeosalinity and palaeotemperature records is available by coupling the results of Mg- and Sr-analyses of ostracods.

CONCLUSIONS

(1) The Mg content of poorly calcified and newly formed *Mytilocypris henricae* shells is very high, up to 100,000 ppm Mg. Only after growth to an individual shell-weight of $>120 \mu\text{g CaCO}_3$ is the Mg content of *Mytilocypris* species and of a related genus *Australocypris* indicative of conditions of growth. Several smaller genera of ostracods with adult shell-weights of 0.5–20 $\mu\text{g CaCO}_3$, typically contain proportionately more Mg than do coexisting larger adult species.

(2) Increasing water temperature and Mg content produce ostracod shells with higher Mg-content. At a constant Mg content, the Mg/Ca ratio of the water only marginally affects Mg uptake in the bicarbonate-dominated systems studied.

(3) In many lacustrine systems, variations of the Mg-content in ostracods will largely reflect changes in water composition rather than temperature, because the temperature partitioning effect is subordinate to that caused by changes in the Mg content of the water. In lakes with limited major-solute variability like the $\text{NaCl-SO}_4^{2-}\text{-HCO}_3^-$ systems of mainland Australia, variations in the Mg-content of lake water are a function of total salinity and thus a record of Mg-contents of fossil ostracods may provide a record of past salinities, and in turn, precipitation/evaporation changes. The corollary is that changes of chemical pathways during the evolution of lakes involving

changes of Mg concentrations in solution might be recorded by ostracods.

(4) In general, the relative contributions of temperature- and salinity-induced changes to the Mg-content of ostracods may be difficult to deduce. A unique solution is potentially available by combining Mg-content and $\delta^{18}\text{O}$ measurements, or by coupling Sr- and Mg-contents, of ostracods.

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