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Notes

Alkalinity control on the partition coefficients in lacustrine ostracodes from Australia

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ABSTRACT

The partition coefficients (K_D) guiding the uptake of Mg and Sr in the low-Mg calcite valves of ostracodes in Australian saline lakes have been reviewed in line with new information on the bicarbonate content and the $\alpha\text{Mg}/\alpha\text{Ca}$ of the ambient waters. Strongly alkaline and very high $\alpha\text{Mg}/\alpha\text{Ca}$ ($>>20$) waters cause the partition coefficients of ostracodes to differ significantly from those found in other lakes with lower $\alpha\text{Mg}/\alpha\text{Ca}$ values. Water salinity does not affect the uptake of Mg or Sr in ostracode valves, whereas the αHCO_3^- of the water strongly correlates to $K_D[\text{Sr}]$, with high αHCO_3^- resulting in a significant $K_D[\text{Sr}]$ decrease.

INTRODUCTION

Trace metal substitution of Ca in the calcium carbonate system as proxies for reconstructing paleoenvironmental variables has been used wherever biogenic calcium carbonate is preserved. This technique has been used in studies of marine fossils to determine changes in temperature, salinity, terrestrial input, and many other factors, and has been utilized for a great number of calcium carbonate-secreting organisms, including foraminifera (for reviews see Eggins et al., 2003; Lea, 2003; Cusack and Freer, 2008), coccolithophores, molluscs, brachiopods (Cusack and Freer, 2008), corals (for reviews see Lea, 2003; Corrège, 2006; Cusack and Freer, 2008), fish otoliths (Bath et al., 2000), ostracodes (Corrège and De Deckker, 1997; Dwyer et al., 2002; for a review see Lea, 2003), and others. Trace metal substitution for calcium in calcite has been utilized in lacustrine environments using ostracodes (for reviews see Holmes and Chivas, 2002; Ito et al., 2003).

The uptake of bivalent cations replacing some Ca atoms during the calcification process in ostracodes is only beginning to be understood. The pioneering work of Turpen and Angell (1971) showed, using ^{45}Ca as a tracer, that ostracodes obtain Ca for their valves directly from the ambient water, and do not utilize Ca from old (molted) valve material. Following this, Chivas et al. (1983, 1985, 1986a, 1986b) and De Deckker et al. (1988) developed the use of trace metal substitution of Ca in the calcitic lattice as a tool for determining environmental change from limnic ostracodes.

Chivas et al. (1986b) showed that Mg incorporation into ostracode valves is primarily driven by the $\text{Mg}/\text{Ca}_{\text{water}}$ and ambient water temperature, and that Sr incorporation is only related to the $\text{Sr}/\text{Ca}_{\text{water}}$. However, De Deckker et al. (1999) showed that there may be a slight temperature effect guiding the uptake of Sr in ostracode valves, and concluded that water salinity is not the controlling factor in trace element uptake.

Assuming that ostracode calcite forms in thermodynamic equilibrium from a large volume of solution containing low concentrations of trace metals (Katz et al., 1972), then trace metal (Mg, Sr) incorporation at a given temperature (T) is dictated by the partition coefficient (K_D) between the molar trace metal ($[\text{Me}] = \text{any divalent cation } [\text{Mg}, \text{Sr}]$) to Ca ratio (Me/Ca) of the water and the valves (Chivas et al., 1986a). However, in highly saline water, the ions bond temporarily, forming ion complexes that are not available for carbonate production (Hem, 1985). Consequently, it is assumed that the true concentration of ions available is the concentration of the active ions in the solution (activities, α), and follows the relationship

$$K_D[\text{Me}]_T = (\text{Me}/\text{Ca})_{\text{ostracodevalve}} / (\alpha\text{Me}/\alpha\text{Ca})_{\text{water}} \quad (1)$$

Several $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ have been determined for several lacustrine, estuarine, and marine ostracode species (for summary, see Holmes and Chivas, 2002), but only the thermodependence with respect to Mg was established for one species, *Cyprideis australiensis* (De Deckker et al., 1999). Other cations have been used variously to reconstruct environmental variables such as Fe and Mn (see Holmes, 1998) and U (see Ricketts et al., 2001).

Chivas et al. (1986a) proposed that congeneric species have identical $K_D[\text{Sr}]$, and that closely related genera, such as *Australocypris* and *Mytilocypris* from Australian lacustrine environments, share a similar $K_D[\text{Sr}] = 0.208$; however, they found that $K_D[\text{Sr}]$ for *Australocypris robusta* in Lake Keilambete, a volcanic maar lake in western Victoria, has a very different $K_D[\text{Sr}] = 0.082$ (Chivas et al., 1985).

Wansard (1996) and Wansard et al. (1998) showed that *Cyprideis torosa* from European lakes have very different $K_D[\text{Sr}]$ with a high degree of variation (0.602–0.83) from the congeneric *C. australiensis* ($K_D[\text{Sr}] = 0.475$) from Australian waters (De Deckker et al., 1988). De Deckker et al. (1999) showed some variation in the $K_D[\text{Sr}]$ of *C. australiensis* ($K_D[\text{Sr}] = 0.438$) from their previous work (Chivas et al., 1986a). Wansard et al. (1999) showed that in *Herpetocypris intermedia*, a freshwater ostracode, the $D(\text{Mg})$ and $D(\text{Sr})$ ($D[\text{Me}]$) implies a constant solution composition during mineral precipitation) varied with respect to the Mg/Ca of the water. Ito and Forester (2009) urged caution in using ostracode partition coefficients in paleoenvironmental reconstructions, stating a range of hydrological and physiological issues that affect the uptake of both Mg and Sr in ostracode valves.

Our investigation seeks to clarify the Chivas et al. (1985, 1986a) paradox between invariant congeneric Australian lacustrine ostracode partition coefficients and the very different partition coefficients of conspecifics in terms of hydrochemical variability. We reanalyze the Chivas et al. (1985, 1986a) partition coefficients from southeastern Australia (SEA) in light of new data from southwestern Western Australia (SWA) lakes.

METHODS

Because the methods presented in this paper are standard procedures, the methods are presented in the GSA Data Repository.¹

RESULTS

The $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ for the ostracode species belonging to the nektonic *Australocypris*, *Mytilocypris*, *Diacypris*, and *Reticypris* collected from SEA and SWA lakes are presented in Table DR1 in the Data Repository.

For all *Australocypris* and *Diacypris* species collected from SWA and SEA lakes (Table DR1), the $K_D[\text{Mg}]$ from the SWA lakes is larger, as is the variation in $K_D[\text{Mg}]$. Most *Mytilocypris* species, however, have similar $K_D[\text{Mg}]$ values and variation in both SEA and SWA lakes (Table DR1), with the exception of *M. mytiloides*. The $K_D[\text{Mg}]$ values of *Reticypris* spe-

¹GSA Data Repository item 2010091, a description of the sites sampled and the methods used, and Table DR1 (the $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ determined from a number of nektonic ostracode species from southeastern and southwestern Australian lakes), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

cies do not vary at all between regions, and have similar means and variances (Table DR1).

Determination of species $K_D[\text{Sr}]$ for SEA and SWA demonstrates that there is a regional difference in the $K_D[\text{Sr}]$ between *A. insularis* collections (Table DR1). Little variability occurs between Western Australia species of *Mytilocypris*, although a high variability occurs within species from SEA lakes (Table DR1). The overall means of $K_D[\text{Sr}]$ for all *Mytilocypris* species in the two regions are very similar (SEA $K_D[\text{Sr}] = 0.3045 \pm 0.2309$ and SWA $K_D[\text{Sr}] = 0.2924 \pm 0.113$).

The $K_D[\text{Sr}]$ values of *Diacypsis* species determined from SWA lakes are systematically higher than those from SEA lakes (Table DR1). Individual species comparisons show that *D. spinosa* differs significantly between regions; however, there is no significant regional difference in *D. compacta* $K_D[\text{Sr}]$ (Table DR1). The reverse is true of the *Reticypris* species analyzed between the two regions, the specimens analyzed from SEA having systematically, although not significantly, higher $K_D[\text{Sr}]$ values than the SWA species (Table DR1).

DISCUSSION

The variation in $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ suggests that the mechanism of trace metal incorporation in ostracodal calcite may vary between SEA and SWA. Several authors (Xia et al., 1997, for *Candona rawsoni*; Wansard et al., 1998, for several other *Candona* species and *Cyprideis torosa*; Wansard et al., 1999, for *Herpetocypris intermedia*) found that the $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ varied with water chemistry. Xia et al. (1997) found that $\text{Mg}/\text{Ca}_{\text{valve}}$ of *C. rawsoni* varied most with respect to temperature and that $K_D[\text{Sr}]$ increased with higher $\text{Sr}/\text{Ca}_{\text{water}}$ and $\text{Mg}/\text{Ca}_{\text{valve}}$. Wansard et al. (1998),

however, showed that $K_D[\text{Mg}]$ decreased as $\text{Mg}/\text{Ca}_{\text{water}}$ increased for three *Candona* species, and that the $K_D[\text{Mg}]$ for *Cyprideis torosa* differed significantly from De Deckker et al.'s (1999) work on *Cyprideis australiensis*. Wansard et al. (1999) also showed that the $K_D[\text{Mg}]$ of *Herpetocypris intermedia* (a freshwater species) was constant as $\text{Mg}/\text{Ca}_{\text{water}}$ increased above 1, and that the variability and value of $K_D[\text{Mg}]$ increased when $\text{Mg}/\text{Ca}_{\text{water}}$ decreased. De Deckker et al. (1999) clearly showed that the $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ of *C. australiensis* did not vary as a function of salinity.

Chivas et al. (1985, 1986a) suggested that the unique water chemistry of Lake Keilambete in SEA with high salinity (ranging from 71.5 to 74 g/L), high $\text{Mg}/\text{Ca}_{\text{water}}$ (89), high HCO_3^- (2180 meq/L), and negligible SO_4^{2-} may be related to the lower $K_D[\text{Sr}]$ of *A. robusta* found in this lake (0.082 ± 0.0051) compared with the $K_D[\text{Sr}]$ of *Australocypris* and *Mytilocypris* species found in other SEA lakes (0.208 ± 0.048).

Figure 1 shows the variation in water chemical parameters for both SWA and SEA lakes, with very little variation in $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ (Figs. 1A and 1B) and $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$ (Figs. 1C and 1D), with salinity for both regions. Similarly, comparison of $\text{Mg}/\text{Ca}_{\text{valve}}$ (Figs. 1E and 1F) and $\text{Sr}/\text{Ca}_{\text{valve}}$ (Figs. 1G and 1H) with salinity shows no significant relationship. This confirms that, for Australian lacustrine ostracodes, De Deckker et al.'s (1999) suggestion for *C. australiensis* that $\text{Sr}/\text{Ca}_{\text{valve}}$ is not a function of salinity, but is in fact a function of $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$ (Figs. 1K and 1L); similarly, $\text{Mg}/\text{Ca}_{\text{valve}}$ is not a function of salinity, but is weakly a function of $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ (Figs. 1I and 1J) and the high variability is due to the temperature effect on Mg incorporation (Chivas et al., 1986a, 1986b).

As mentioned previously, however, the $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ of ostracodes vary in both value and amplitude for both species and genera

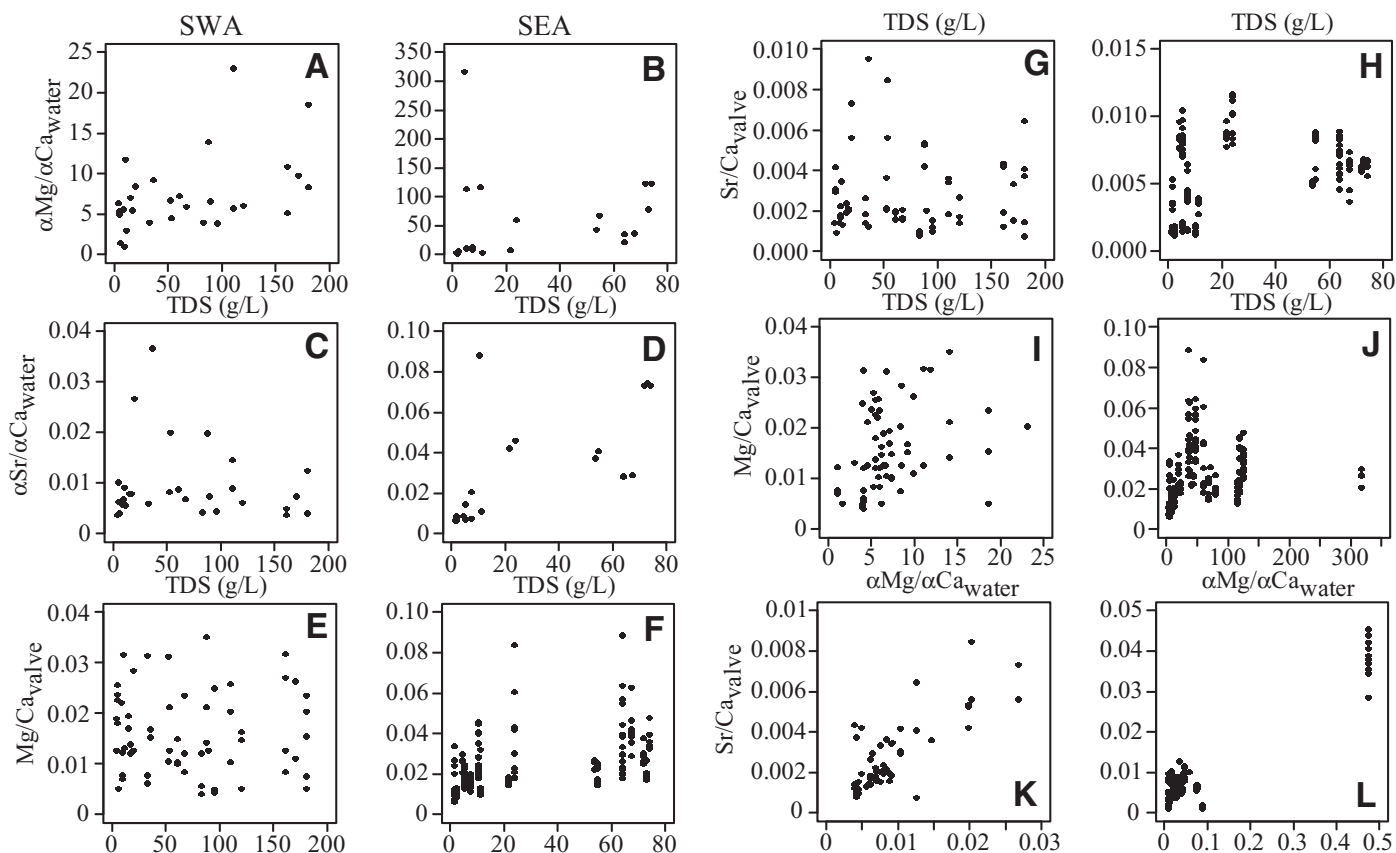


Figure 1. Plots showing various water chemistry and ostracode shell chemistry relationships. Southwestern Western Australia (SWA) lakes are on left, southeastern Australia (SEA) lakes are on right. A, B: $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ vs. TDS (g/L) (TDS—total dissolved solids equivalent to salinity). C, D: $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$ vs. TDS (g/L). E, F: Ostracode $\text{Mg}/\text{Ca}_{\text{valve}}$ vs. TDS (g/L). G, H: Ostracode $\text{Sr}/\text{Ca}_{\text{valve}}$ vs. TDS (g/L). I, J: Ostracode $\text{Mg}/\text{Ca}_{\text{valve}}$ vs. $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$. K, L: Ostracode $\text{Sr}/\text{Ca}_{\text{valve}}$ vs. $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$.

between SWA and SEA. Figure 2 shows combined $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ for both SWA and SEA versus salinity (g/L), $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ and αHCO_3^- (Figs. 2C–2F). Both $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ for all Australian lacustrine species examined here show a weak decrease at first as salinity increases (Figs. 2A and 2B). At low salinity values (<20 g/L), the variability in partition coefficients is high (Figs. 2A and 2B), but then values are scattered. The variability in $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ is relatively uniform above a salinity of 20 g/L. This suggests that uniform $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ can be applied to reconstruct paleoenvironmental variables from ostracode valve chemistry (Chivas et al., 1986a). However, the values and variability of $K_D[\text{Mg}]$ decrease as $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ increases (Fig. 2C).

The decrease in $K_D[\text{Mg}]$ with increasing $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ suggests that the physiological mechanism for secreting low-Mg calcite in Australian lacustrine ostracodes is a tradeoff between the physiological control of Mg uptake in high $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ and the thermodependence on the Mg uptake in low $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$. This implies that the influence of temperature on Mg uptake diminishes as $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ increases, and is replaced by physiological control. A similar result has been found for the freshwater species *Herpetocypris intermedia* in low (<4) Mg/Ca_{water} cultures (Wansard et al., 1999) and *Candona* species in a range of Mg/Ca_{water} (<15) (Wansard et al., 1998).

The value and variability of $K_D[\text{Sr}]$ also decrease with increased $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ as $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ approaches 110 (Fig. 2D). In the two lakes with $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}} > 110$ (Lake Purdigulac $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}} = 115$; Lake Coragulac $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}} = 316$, both in western Victoria, SEA), both of which

have highly evolved waters, the $K_D[\text{Sr}]$ increases substantially ($K_D[\text{Sr}] = 0.566 \pm 0.06$ for Lake Purdigulac and $K_D[\text{Sr}] = 0.956 \pm 0.092$ for Lake Coragulac). This suggests that $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ is not the primary controlling factor in the variability in $K_D[\text{Sr}]$. Wansard et al. (1998) examined $K_D[\text{Sr}]$ variability with respect to Mg/Ca_{water} and found no systematic variation; however, they only analyzed waters with Mg/Ca < 15. Australian lacustrine ostracodes show a similar non-relationship for $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}} < 15$.

Figures 2E and 2F show that with increasing αHCO_3^- , the variability in $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ decreases. SWA analyses are all from waters with a low αHCO_3^- and display very high variability, whereas SEA analyses vary from low to high αHCO_3^- and the variability decreases with increasing αHCO_3^- . Exceptions to this are the analyses of $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ of *M. splendida* in very shallow Lesser Twin Lake in SEA ($\alpha\text{HCO}_3^- = 0.045$) that show a high degree of variability. East Basin Lake and Lake Keilambete in SEA also recorded high αHCO_3^- concentrations on two of the three sampling occasions (East Basin Lake = 0.0195 and 0.0247; Lake Keilambete = 0.018 and 0.0232), and the $K_D[\text{Sr}]$ variability was low in both lakes. This suggests that if the $K_D[\text{Sr}]$ analyses of Lesser Twin Lake are ignored, the αHCO_3^- water appears to influence the $K_D[\text{Sr}]$. Lesser Twin Lake had only 10 cm of water at the time of collection and the water's ionic ratio may have varied between the time of ostracode calcification and water and ostracode collection.

Mechanism for HCO_3^- -Induced Partition Coefficient Variability

A mechanism behind the systematic variation in $K_D[\text{Mg}]$ with αHCO_3^- water documented here was presented by Paquette and Reeder (1995), who described a model of calcite growth in which crystal growth occurs on the $\{10\bar{1}4\}$ face by the spiral mechanism. The spiral mechanism causes a microtopographic relief with randomly distributed pyramidal hillocks that comprise two characteristically similar pairs (a and b, a' and b') of vicinal faces that vary slightly in orientation ($\leq 1^\circ$) from the $\{10\bar{1}4\}$ face; Paquette and Reeder (1995) found that Mg enrichment always occurred on the a' and b' vicinal faces, and Sr enrichment on the a and b vicinal faces. This enrichment in trace metals of each vicinal face is related to kink structures that are caused by the Ca^{2+} and CO_3^{2-} coordination in the crystal structure. Paquette and Reeder (1995) also found that the degree of supersaturation of calcite in the precipitating solution (ranging from 8 to 20 times calcite saturation) and, more important, the $\alpha\text{Ca}^{2+}:\alpha\text{CO}_3^{2-}$ of the precipitating solution (ranging from 100 to 30,000 in their experiments) influenced the shape of these hillocks, with increasing αCO_3^{2-} in the precipitating solution resulting in less differentiation between the pairs of vicinal faces. The αCO_3^{2-} increase in the solution also caused a decrease in the relative growth of a' and b' vicinal faces, thus reducing the uptake of Sr. All of the Paquette and Reeder (1995) experiments were conducted at $28 \pm 2^\circ\text{C}$, and so comment on the temperature influences of Mg uptake into the a' and b' vicinal faces cannot be made.

This microstructural analysis of trace metal incorporation in calcite has fundamental implications for ostracodal $K_D[\text{Mg}]$ in lacustrine systems in SEA lacustrine systems. In pH-buffered lacustrine systems with elevated αHCO_3^- , such as SEA lakes (Radke et al., 2003), increases in αCO_3^{2-} are expected, and as Paquette and Reeder (1995) found, elevated αCO_3^{2-} suppresses trace metal, in particular Sr, incorporation into the calcitic lattice during crystal growth. The implication for ostracodal $K_D[\text{Mg}]$ is that as αHCO_3^- increases, trace metal incorporation into ostracode calcitic valves will be suppressed, regardless of the $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$. This results in decreased $K_D[\text{Mg}]$ in HCO_3^- -enriched waters.

The biomineralization of several ostracode species was investigated by Keyser and Walter (2004); they showed that calcium mobilization from inside epidermal cells into the calcite valves changed morphology and that calcium underwent at least one chemical transformation, from calcium phosphate to calcium carbonate. The microenvironment in which these chemical and morphological transformations occur must be the result of

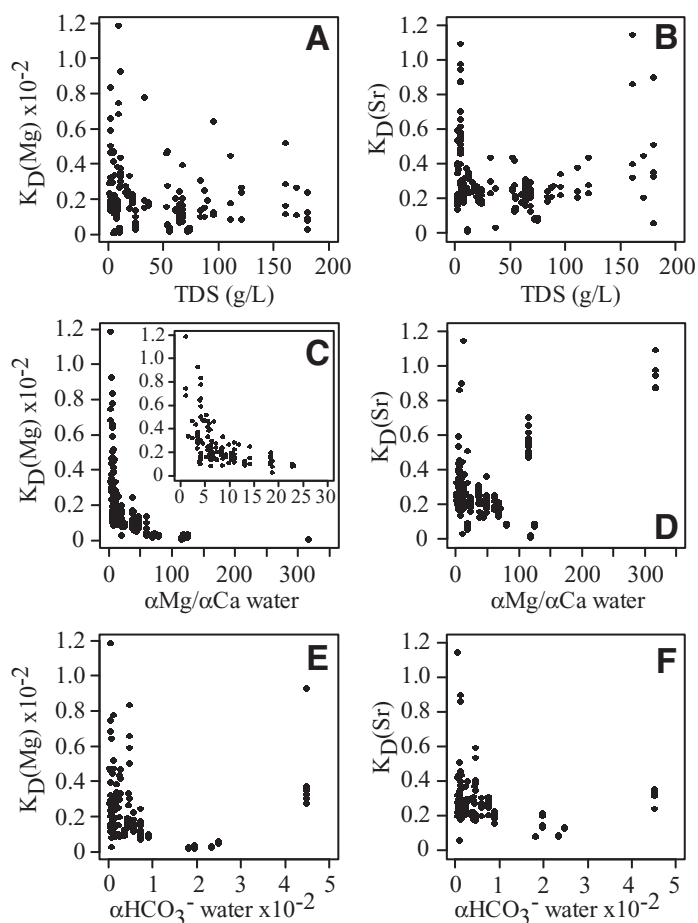


Figure 2. Plots of combined southeastern Australia and southwestern Western Australia data showing relationship between ostracode $K_D[\text{Mg}]$ (on left) and $K_D[\text{Sr}]$ (on right). A, B: Against TDS (total dissolved solids equivalent to salinity, g/L). C, D: Against $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$. (Inset in C enlarges 0–30 $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ range). E, F: Against αHCO_3^- water.

subtle chemical variations. Comprehension on how ostracodes secrete their valves and the biophysical and biochemical changes during this calcification is still in its infancy and more research is required before a holistic system-based understanding is gained.

CONCLUSION

The $K_D[\text{Mg}]$ and $K_D[\text{Sr}]$ of several Australian saline lacustrine ostracode species are shown to vary between southeast Australia and southwest Australia, both in terms of mean values and in the degree of variability. As the $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ increases above ~ 50 , the Mg uptake by ostracodes has a reduced thermodependence, and so $K_D[\text{Mg}]$ can be utilized as an indicator of $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$. When $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}} < 50$, $K_D[\text{Mg}]$ depends both on $\alpha\text{Mg}/\alpha\text{Ca}_{\text{water}}$ and temperature at the time of calcification. In low αHCO_3^- waters, the $K_D[\text{Sr}]$ is higher and more variable than in waters with high αHCO_3^- . This suggests that at low αHCO_3^- water, the $K_D[\text{Sr}]$ does not accurately reflect the $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$. At the opposite, at greater αHCO_3^- water, the $K_D[\text{Sr}]$ variability decreases, suggesting that it can be used as an accurate indicator of $\alpha\text{Sr}/\alpha\text{Ca}_{\text{water}}$. Across all salinities, the $\text{Sr}/\text{Ca}_{\text{valve}}$ is clearly a poor indicator of salinity in Australian lacustrine ostracodes.

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REFERENCES CITED

- Bath, G.E., Thorrold, S.R., Jones, C.M., Campana, S.E., McLaren, J.W., and Lam, J.W.H., 2000, Strontium and barium uptake in aragonitic otoliths of marine fish: *Geochimica et Cosmochimica Acta*, v. 64, p. 1705–1714, doi: 10.1016/S0016-7037(99)00419-6.
- Chivas, A.R., De Deckker, P., and Shelley, J.M.G., 1983, Magnesium, strontium and barium partitioning in nonmarine ostracode shells and their use in paleoenvironmental reconstructions—A preliminary study, *in* Maddocks, R.F., ed., *Applications of Ostracoda*: Houston, Texas, University of Houston Geosciences, p. 238–249.
- Chivas, A.R., De Deckker, P., and Shelley, J.M.G., 1985, Strontium content of ostracods indicates lacustrine palaeosalinity: *Nature*, v. 316, p. 251–253, doi: 10.1038/316251a0.
- Chivas, A.R., De Deckker, P., and Shelley, J.M.G., 1986a, Magnesium and strontium in non-marine ostracod shells as indicators of palaeosalinity and palaeo-temperature: *Hydrobiologia*, v. 143, p. 135–142, doi: 10.1007/BF00026656.
- Chivas, A.R., De Deckker, P., and Shelley, J.M.G., 1986b, Magnesium content of non-marine ostracod shells: A new palaeosalinometer and palaeothermometer: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 54, p. 43–61, doi: 10.1016/0031-0182(86)90117-3.
- Corrège, T., 2006, Sea surface temperature and salinity reconstruction from coral geochemical tracers: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 232, p. 408–428, doi: 10.1016/j.palaeo.2005.10.014.
- Corrège, T., and De Deckker, P., 1997, Faunal and geochemical evidence for changes in intermediate water temperature and salinity in the western Coral Sea (northeast Australia) during the late Quaternary: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 131, p. 183–205, doi: 10.1016/S0031-0182(97)00003-5.
- Cusack, M., and Freer, A., 2008, Biomineralization: Elemental and organic influence in carbonate systems: *Chemical Reviews*, v. 108, p. 4433–4454, doi: 10.1021/cr078270o.
- De Deckker, P., Chivas, A.R., Shelley, J.M.G., and Torgerson, T., 1988, Ostracod shell chemistry: A new palaeoenvironmental indicator applied to a regressive/transgressive record from the Gulf of Carpentaria, Australia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 66, p. 231–241, doi: 10.1016/0031-0182(88)90201-5.
- De Deckker, P., Chivas, A.R., and Shelley, J.M.G., 1999, Uptake of Mg and Sr in the euryhaline ostracod *Cyprideis* determined from in vitro experiments: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 148, p. 105–116, doi: 10.1016/S0031-0182(98)00178-3.
- Dwyer, G.S., Cronin, T.M., and Baker, P.A., 2002, Trace elements in marine ostracodes, *in* Holmes, J.A., and Chivas, A.R., eds., *The Ostracoda: Applications in Quaternary research: American Geophysical Union Geophysical Monograph* 131, p. 205–225, doi: 10.1029/131GM11.
- Eggins, S.M., De Deckker, P., and Marshall, J., 2003, Mg/Ca variation in planktonic foraminifera tests: Implications for reconstructing palaeo-seawater temperature and habitat migration: *Earth and Planetary Science Letters*, v. 212, p. 291–306, doi: 10.1016/S0012-821X(03)00283-8.
- Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.
- Holmes, J.A., 1998, The palaeoenvironmental significance of iron and manganese in non-marine ostracod shells: A preliminary analysis, *in* Holmes, J., and Lynch, K., eds., *The Kingston Papers, a geographical perspective on the environment, economy and society*: London, Kingston University School of Geography, p. 198–212.
- Holmes, J.A., and Chivas, A.R., 2002, Ostracod shell chemistry—Overview, *in* Holmes, J.A., and Chivas, A.R., eds., *The Ostracoda: Applications in Quaternary Research: American Geophysical Union Geophysical Monograph* 131, p. 185–204, doi: 10.1029/131GM10.
- Ito, E., and Forester, R.M., 2009, Changes in continental ostracode shell chemistry; uncertainty of cause: *Hydrobiologia*, v. 620, p. 1–15, doi: 10.1007/s10750-008-9622-7.
- Ito, E., De Deckker, P., and Eggins, S.M., 2003, Ostracodes and their shell chemistry: Implications for paleohydrologic and paleoclimatologic applications, *in* Park, L.E. and Smith, A.J., eds., *Bridging the gap: Trends in the ostracode biological and geological sciences: Palaeontological Society Papers*, v. 9, p. 119–152.
- Katz, A., Sass, E., Starinsky, A., and Holland, H.D., 1972, Strontium behaviour in the aragonite-calcite transformation: An experimental study at 40–98°C: *Geochimica et Cosmochimica Acta*, v. 36, p. 481–496, doi: 10.1016/0016-7037(72)90037-3.
- Keyser, D., and Walter, R., 2004, Calcification in ostracodes: *Revista Espanola de Micropaleontologia*, v. 36, p. 1–11.
- Lea, D.W., 2003, Elemental and isotopic proxies of marine temperatures, *in* Elderfield, H., ed., *The oceans and marine geochemistry: Treatise on Geochemistry Volume 6*: Oxford, Elsevier-Perigamon, p. 365–390.
- Paquette, J., and Reeder, R.J., 1995, Relationship between surface structure, growth mechanism, and trace element incorporation in calcite: *Geochimica et Cosmochimica Acta*, v. 59, p. 735–749, doi: 10.1016/0016-7037(95)00004-J.
- Radke, L.C., Juggins, S., Halse, S.A., De Deckker, P., and Finston, T., 2003, Chemical diversity in south-eastern Australian saline lakes II: Biotic implications: *Marine & Freshwater Research*, v. 54, p. 895–912, doi: 10.1071/MF03021.
- Ricketts, R.D., Johnson, T.C., Brown, E.T., Rasmussen, K.A., and Romanovsky, V.V., 2001, The Holocene paleolimnology of Lake Issyk-Kul, Kyrgyzstan: Trace element and stable isotope composition of ostracodes: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 176, p. 207–227, doi: 10.1016/S0031-0182(01)00339-X.
- Turpen, J.B., and Angell, R.W., 1971, Aspects of moulting and calcification in the ostracod *Heterocypris*: *Biological Bulletin*, v. 140, p. 331–338, doi: 10.2307/1540077.
- Wansard, G., 1996, Quantification of paleotemperature changes during isotopic stage 2 in the La Draga continental sequence (NE Spain) based on the Mg/Ca ratio of freshwater ostracods: *Quaternary Science Reviews*, v. 15, p. 237–245, doi: 10.1016/0277-3791(95)00044-5.
- Wansard, G., De Deckker, P., and Julia, R., 1998, Variability in ostracod partition coefficients D(Sr) and D(Mg)—Implications for lacustrine palaeoenvironmental reconstructions: *Chemical Geology*, v. 146, p. 39–54, doi: 10.1016/S0009-2541(97)00165-4.
- Wansard, G., Roca, J.R., and Mezquita, F., 1999, Experimental determination of strontium and magnesium partitioning in calcite of the freshwater ostracod *Herpetocypris intermedia*: *Archiv für Hydrobiologie*, v. 145, p. 237–253.
- Xia, J., Engstrom, D.R., and Ito, E., 1997, Geochemistry of ostracode calcite: Part 2. The effects of water chemistry and seasonal temperature variation on *Candona rawsoni*: *Geochimica et Cosmochimica Acta*, v. 61, p. 383–391, doi: 10.1016/S0016-7037(96)00354-7.

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