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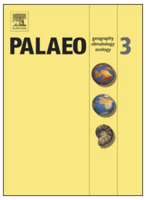

Assessment of Mg/Ca in *Saccostrea glomerata* (the Sydney rock oyster) shell as a potential temperature record

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ABSTRACT

Bivalve shell Mg/Ca records can be important potential tracers of paleo-temperature, but evidence has shown that the temperature dependence of trace metal incorporation rates can vary significantly between different species and even within the same species. This study assesses one such bivalve specimen as a potential temperature proxy for the east coast of Australia. Specimens of the Sydney rock oyster (*Saccostrea glomerata*) were cultured for approximately one year at two locations on the east coast of Australia: Moreton Bay, Queensland, a semi-enclosed bay with consistently marine conditions, and Pambula Lake, New South Wales, a tidal lake which can undergo significant variations in salinity as a result of rainfall and river discharge. Transects of the oysters' growth axis were analysed via LA-ICP-MS. Mg/Ca-temperature relationships for the oysters show a robust temperature dependence but there is also a clear discrepancy between the two sites. However, this discrepancy was not evident when the temperature dependence of Mg partition coefficients (D_{Mg}) was determined, indicating that the difference seen in the direct Mg/Ca$_{shell}$-temperature relationships can be accounted for by variation in salinity at the estuarine site at Pambula Lake. This has implications for the use of Mg/Ca as a paleo-temperature tracer within estuarine fauna as knowledge of the water chemistry is required to determine D_{Mg} values. However, *S. glomerata* Mg/Ca remains a promising paleo-temperature tracer as the direct Mg/Ca-temperature relationships can still be applied to samples from environments that experienced little variation in salinity. Combined analysis of Mg/Ca coupled with $\delta^{18}O_{shell}$ records has the potential to enable the deconvolution of the combined salinity/temperature signal in the $\delta^{18}O_{shell}$ and Mg/Ca$_{shell}$ records.

1. Introduction

In the absence of instrumental climate records that extend back further than a few hundred years, paleoclimate studies rely on various proxy records such as the geochemical signals of biogenic carbonates. These include $\delta^{18}O_{carbonate}$ and trace element ratios found in corals (e.g. Corrége, 2006), bivalves (e.g. Driscoll et al., 2014; Elliot et al., 2009; Dutton et al., 2002), gastropods (e.g. Sisma-Ventura et al., 2009), and foraminifera (e.g. Rosenthal et al., 1997; Lea et al., 1999). However, the utility of $\delta^{18}O_{carbonate}$ as a temperature tracer can be somewhat limited as it is influenced not only by precipitation temperature, but also $\delta^{18}O_{water}$. The record obtained from $\delta^{18}O_{carbonate}$ in locations where $\delta^{18}O_{water}$ is markedly variable, usually concurrent with changes in salinity, is often a combined temperature-salinity signal from which it can be difficult to isolate a temperature record.

As it is generally accepted that Mg/Ca remains constant in seawater unless salinity falls below 10 (Dodd and Crisp, 1982), Mg/Ca presents a potential temperature tracer that is comparatively independent of salinity. Trace element ratios of biogenic carbonates, most commonly Mg/Ca in biogenic calcite and Sr/Ca in aragonite, have been widely investigated as potential temperature proxies to serve as complements or alternatives to $\delta^{18}O_{carbonate}$. Mg/Ca-temperature calibration curves have been successfully developed for foraminifera (Lea et al., 1999; Elderfield and Ganssen, 2000), ostracods (e.g. Elmore et al., 2012; Ingram et al., 1998), and gastropods (e.g. Ingram et al., 1998).

Obtaining a robust temperature record from bivalve shell Mg/Ca has proved somewhat problematic, as a number of factors other than temperature have been reported to influence bivalve shell Mg/Ca, including ontogenetic and developmental factors (e.g. Freitas et al., 2005; Surge and Lohmann, 2008; Takesue et al., 2008; Freitas et al., 2009; Schöne et al., 2011), growth rate and other biological factors (e.g. Carré et al., 2006; Strasser et al., 2008; Heinemann et al., 2011) and a tendency for some elements to be incorporated into organic components of the

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shell rather than the crystal lattice (Takesue et al., 2008; Schöne et al., 2010). Variability of Mg/Ca between contemporaneous individuals and also intra-shell variability can further limit the reliability of a temperature tracer offered by shell Mg/Ca in some bivalve species (e.g. mussel *Mytilus edulis*, scallop *Pecten maximus*: Freitas et al., 2008; clam *Tridacna gigas*: Elliot et al., 2009).

Despite these complications, a number of studies have yielded (qualified) Mg/Ca-temperature equations for various bivalves (Table 1). For a number of these equations, the Mg/Ca-temperature relationship is valid only for certain periods of the bivalve's life: Surge and Lohmann (2008) found that Mg/Ca in the oyster *Crassostrea virginica* exhibited a temperature dependence only in the later period of their growth, while other studies have reported a significant relationship between Mg/Ca and temperature only in the juvenile portions of shell growth in the oyster *Crassostrea gigas* (Mouchi et al., 2013) and the mussel *M. edulis* (Vander Putten et al., 2000). Some calibration relationships are limited to certain regions of the bivalve shell (Freitas et al., 2008; Elliot et al., 2009; Freitas et al., 2012; Ullmann et al., 2013), while other modern bivalve studies have identified weak correlations between Mg/Ca and temperature but were unable to derive a quantitative calibration, such as that reported by Ullmann et al. (2013) for *C. gigas*, Elliot et al. (2009) for *T. gigas*, Freitas et al. (2006) for *P. maximus*. Indeed, the latter study found that the Mg/Ca-temperature relationship showed a positive correlation within some portions of the shell, and an inverse correlation in others. In addition to the compelling evidence for species-specific Mg/Ca-temperature relationships, marked differences can also be seen for calibrations derived for the same species by different studies: Wanamaker et al. (2008) derived a significantly different Mg/Ca-temperature relationship to that of Freitas et al. (2008) for the mussel *M. edulis*, which is different again to that observed by Vander Putten et al. (2000).

This paper examines the Mg/Ca-temperature relationship in the shell of two geographically distinct populations of the Sydney rock oyster, *Saccostrea glomerata*, to assess this species' potential as a paleotemperature tracer and to derive a robust Mg/Ca-temperature relationship that can be applied to archaeological or fossil samples. This oyster is endemic to Australia and is prevalent within Holocene-age archaeological midden sites along the Australian east coast. If a robust Mg/Ca-temperature relationship can be established for this species, it has the potential to be a valuable source of Holocene climate information, particularly as this is a regions for which few such records exist (see Reeves et al., 2013; Petherick et al., 2013).

2. Methods and materials

2.1. *Saccostrea glomerata* (Sydney rock oyster)

Saccostrea glomerata is found along the east, north and west coasts of Australia, from northern Victoria through New South Wales and Queensland and through the tropics to Shark Bay in Western Australia (Malcolm, 1971; Kailola, 1993; Nell, 2001). *Saccostrea glomerata* is almost always cemented to a hard substrate and while it prefers an estuarine intertidal habitat, can be found in up to 3 m water depth, surviving completely submerged conditions (Malcolm, 1971; Kailola, 1993).

The reported preferred temperature tolerance for *S. glomerata* is 12–25 °C. *S. glomerata* in New Zealand exhibit the greatest growth between temperatures of 17–20 °C (Dinamani, 1991), while Nell and Dunkley (1984) found optimum nutrient uptake and growth in *S. glomerata* from New South Wales, Australia occurred in the range 20–30 °C.

The oysters grow best in salinities of ~26–36 but can tolerate the range ~15–45 (Nell and Dunkley, 1984; reported as $g\,l^{-1}$) and possibly even up to ~50 (Nell and Gibbs, 1986). *Saccostrea glomerata* generally take 2.5–3 years to reach a commercial sale size, which is usually shell length (from hinge to growth edge) of 85–100 mm (Malcolm, 1971), and some cultivated oysters have reached 255 mm (Lamprell and Healy, 1998). *Saccostrea glomerata* can live for up to 10 years (Kailola, 1993). *Saccostrea glomerata* was a commonly exploited species among Australia's indigenous population and is found in Aboriginal midden sites along the east coast of Australia (e.g. Bailey, 1975; Sullivan, 1982; Ulm, 2002).

2.2. Field culturing experiments

In-situ culturing experiments were conducted at two locations on the east coast of Australia: Moreton Bay, Queensland and Pambula Lake, New South Wales (Fig. 1). These two locations approximate the geographical extremes of *S. glomerata*'s occurrence in the Western Pacific. Commercial oyster farms at each location provided the samples for the experiments, and infrastructure such as trays, bags and suitable mooring sites for the oysters.

2.2.1. Moreton Bay

Moreton Bay is located in the transitional subtropical/tropical climate zone of southeast Queensland. The bay is a wedge-shaped

Table 1

Published Mg/Ca-temperature relationships for various bivalve species.

Species	Equation	r^2	Temperature range (°C)	Environment	Comments	Citation
Crassostrea virginica	$Mg/Ca = 0.72\,T - 0.23$	0.3	19.1–31.4	Estuarine	Older (most recent) growth only	Surge and Lohmann (2008)
Mytilus edulis	$Mg/Ca = 0.70\,T - 0.63$	0.91	5–20	Estuarine (intertidal bay)	Younger growth only	Vander Putten et al. (2000)
Mytilus edulis	$Mg/Ca = 0.26_{(\pm 0.06)}T + 1.56_{(\pm 0.84)}$	0.37	10–20	Laboratory culture		Freitas et al. (2008)
Mytilus edulis	$Mg/Ca = 0.82_{(\pm 0.24)}T + 3.6_{(\pm 3.24)}$	0.82	7–20	Laboratory culture	Juvenile (<2 years) growth, low salinity	Wanamaker et al. (2008)
Mytilus edulis	$Mg/Ca = 0.75_{(\pm 0.22)}\,T + 5.44_{(\pm 0.31)}$	0.49	7–20	Laboratory culture	Juvenile (<2 years) growth	Wanamaker et al. (2008)
Pecten maxiumus	$Mg/Ca = 0.52_{(\pm 0.19)}\,T + 9.89_{(\pm 0.84)}$	0.21	10–20	Laboratory culture	Outer shell section	Freitas et al. (2008)
Pecten maxiumus	$Mg/Ca = 0.17_{(\pm 0.03)}\,T + 2.56_{(\pm 0.42)}$	0.77	10–20	Laboratory culture	Inner shell section	Freitas et al. (2012)
Mytilus trossulus	$Mg/Ca = 0.30_{(\pm 0.04)}\,T + 2.25_{(\pm 0.63)}$	0.74		Estuarine (shallow tidal inlet)		Klein et al. (1996)
Pinna nobilis	$Mg/Ca = \exp 0.022_{(\pm 0.04)}T + 17.16_{(\pm 1.95)}$	0.62	10–22.5	Marine (seagrass meadow)	Younger (<4.5 years) growth only	Freitas et al. (2005)
Crassostrea gigas	$Mg/Ca = 0.27\,T - 0.5$		4.8–23	Marine	Juvenile (<2 years) growth	Mouchi et al. (2013)
Saccostrea glomerata Moreton Bay	$Mg/Ca = 0.71_{(\pm 0.02)}T + 2.31_{(\pm 0.61)}$	0.46	11–30	Marine	Juvenile (1–2 years) growth	This study
Saccostrea glomerata Pambula Lake	$Mg/Ca\ 0.81_{(\pm 0.02)}T - 2.35_{(\pm 0.32)}$	0.52	10–26	Estuarine	Juvenile (1–2 years) growth	This study

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