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Eocene seasonality and seawater alkaline earth reconstruction using shallow-dwelling large benthic foraminifera

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ABSTRACT

Intra-test variability in Mg/Ca and other (trace) elements within large benthic foraminifera (LBF) of the family Nummulitidae have been investigated using laser-ablation inductively-coupled plasma mass spectrometry (LA-ICPMS). These foraminifera have a longevity and size facilitating seasonal proxy retrieval and a depth distribution similar to 'surface-dwelling' planktic foraminifera. Coupled with their abundance in climatically important periods such as the Paleogene, this means that this family of foraminifera are an important but under-utilised source of palaeoclimatic information. We have calibrated the relationship between Mg/Ca and temperature in modern *Operculina ammonoides* and observe a $\sim 2\%$ increase in Mg/Ca $^\circ C^{-1}$. *O. ammonoides* is the nearest living relative of the abundant Eocene genus *Nummulites*, enabling us to reconstruct mid-Eocene tropical sea surface temperature seasonality by applying our calibration to fossil *Nummulites djokdjokartae* from Java. Our results indicate a 5–6 °C annual temperature range, implying greater than modern seasonality in the mid-Eocene (Bartonian). This is consistent with seasonal surface ocean cooling facilitated by enhanced Eocene tropical cyclone-induced upper ocean mixing, as suggested by recent modelling results. Analyses of fossil *N. djokdjokartae* and *Operculina* sp. from the same stratigraphic interval demonstrate that environmental controls on proxy distribution coefficients are the same for these two genera, within error. Using previously published test–seawater alkaline earth metal distribution coefficients derived from an LBF of the same family (Raitzsch et al., 2010) and inorganic calcite, with appropriate correction systematics for secular Mg/Ca_{sw} variation (Evans and Müller, 2012), we use our fossil data to produce a more accurate foraminifera-based Mg/Ca_{sw} reconstruction and an estimate of seawater Sr/Ca. We demonstrate that mid-Eocene Mg/Ca_{sw} was $\lesssim 2$ mol mol^{-1}, which is in contrast to the model most commonly used to correct deep-time Mg/Ca data from foraminifera, but in agreement with most other Paleogene proxy and model data. This indicates that Mg/Ca_{sw} has undergone a substantial (3–4×) rise over the last ~ 40 Ma.

1. Introduction

The trace element chemistry of foraminifera tests is increasingly being used as a palaeoceanic reconstruction tool. Many potential proxies linking test chemistry to palaeoenvironmental information have been developed (see e.g. Katz et al., 2010), which are most commonly applied in the fossil record to either planktic or deep benthic foraminifera (where deep is used here to distinguish these foraminifera from the shallow-dwelling large benthic species under consideration in this study) (e.g. Tripati et al., 2011; Bohaty et al., 2012; Lear et al., 2000). The abundance of foraminifera in sediment cores, along with the widespread distribution of some species (Fraile et al., 2008) has resulted in this group of organisms becoming one of the key sources of palaeoceanic proxy information available (Pearson, 2012).

A disadvantage with the use of planktic foraminifera for palaeoceanic reconstruction is that they are relatively short lived, mineralising over days or weeks (Anderson and Faber, 1984), thus providing a short temporal record of changes in (e.g.) sea surface temperature (SST) (but see Wit et al., 2010). This may be further complicated by migration through the water column during the lifespan of some foraminifera (Eggins et al., 2003) or seasonal bias in biomineralisation (e.g. Jonkers et al., 2010). Seasonality is increasingly being recognised as a key component of climate change (Hollis et al., 2012; Denton et al., 2005; Crowley et al., 1986), although there are a limited amount of studies that have attempted to reconstruct seasonality from periods such as the Paleogene, potentially one of the most important time intervals with respect to similarity to predicted future pCO_2 (Zachos et al., 2008). Much of

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what is currently known is derived from $\delta^{18}O$ measurements in bivalves (e.g. Ivany et al., 2004; Andreasson and Schmitz, 2000; Dutton et al., 2002; Kobashi et al., 2004), which – whilst being an almost unique source of Paleogene ocean seasonality reconstruction – may suffer from biases resulting from freshwater-modified seawater $\delta^{18}O$ in near-coastal environments. Clumped isotope data may offer a solution to this problem (Keating-Bitonti et al., 2011), particularly with improved precision of such measurements.

Reconstructing seawater Mg/Ca (Mg/Ca_{sw}) is of great importance as fossil Mg/Ca data must be corrected for secular changes in this ratio when applying Mg/Ca–temperature calibrations derived from samples grown in or collected from modern seawater. The Cenozoic evolution of Mg/Ca_{sw} has been the subject of considerable debate (e.g. Coggon et al., 2011; Broecker and Yu, 2011; Lear et al., 2002), some of which is the result of uncertainties regarding the appropriate methodology for the correction of foraminiferal Mg/Ca data (summarised in Evans and Müller, 2012). It is clear that in order for the Mg/Ca palaeothermometer to produce accurate pre-Pleistocene palaeotemperatures, further reconstructions of palaeo-Mg/Ca_{sw} are required.

In order to (1) provide a method of seasonality reconstruction other than mollusc $\delta^{18}O$ and (2) produce an accurate foraminifera-derived Mg/Ca_{sw} reconstruction, we have investigated trace element heterogeneity in the tests of large benthic foraminifera (LBF). We utilise laser-ablation inductively-coupled-plasma mass spectrometry (LA-ICPMS) as a highly spatially-resolved technique capable of identifying µm-scale heterogeneity whilst simultaneously assessing sample preservation. LBF are an informal group that typically exceed 3 mm^3 in volume (Ross, 1974) and have photosymbiotic algae (Hallock, 1984), inhabiting the photic zone. We present data from LBF of the family Nummulitidae, with focus on the Eocene genus *Nummulites*, as well as its nearest living relative *Operculina*, which was also present in the Eocene. Our data are primarily derived from *Nummulites* because they are more abundant than *Operculina* and form far larger tests, implying growth over a longer time period, therefore *Nummulites* have greater potential as tools for seasonal palaeoenvironment reconstruction. By comparing Recent *O. ammonoides* and *O. complanata* from seven modern locations to fossil samples of both *Operculina* sp. and *N. djokdjokartae* from the Eocene Nanggulan Formation of Central Java, we demonstrate how these foraminifera can be used as a palaeoceanic reconstruction tool. The size, abundance and (sub)tropical distribution of LBF such as the nummulitids make them a hitherto under-utilised source of proxy information from a climatically critical region of the oceans – the low latitudes – of which our knowledge of palaeocean temperatures is currently limited.

1.1. Ecology and biology of the nummulitids

The main morphological features of the nummulitids (order: Rotaliida) referred to in the text are shown in Fig. 1. The nummulitids are defined by the presence of a marginal cord (Fig. 1), the thickened margin of the shell exposed in an equatorial section (Loeblich and Tappan, 1987). This serves as a method of communication and transport between chambers, as well as playing an important role during sexual reproduction (Röttger et al., 1984). These foraminifera initially construct their chambers with walls consisting of two layers of calcite formed on either side of a primary organic membrane (Reiss, 1958). The test is hyaline, giving well-preserved calcite a glassy appearance.

LBF have a complex reproductive cycle resulting in morphologically distinct generations. Those with a large proloculus and a small number of chambers are known as the macrospheric generation, or A-forms. These reproduce sexually to form a microspheric generation (B-form) with a small proloculus and a large number of chambers (Dettmering et al., 1998; Kuile and Erez, 1991). This generation undergoes multiple fission, producing A-forms. Through this reproductive cycle at least two morphologically distinct generations of the same species are produced.

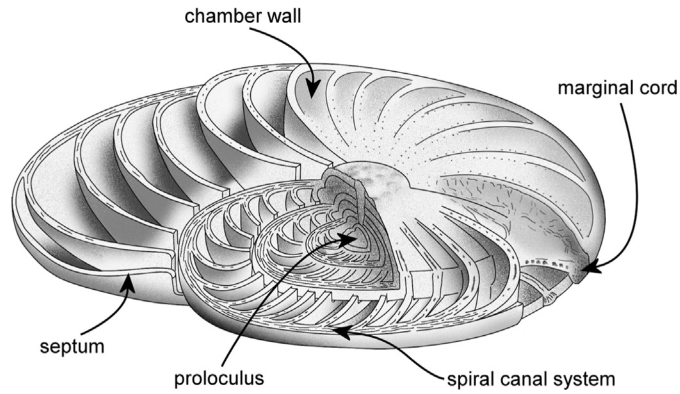

Fig. 1. Cutaway diagram of *O. ammonoides* with features referred to in the text labelled. Re-drawn from Carpenter et al. (1862). Although there are morphological differences between Recent *O. ammonoides* and Eocene *N. djokdjokartae*, all features labelled are present in both genera.

O. ammonoides are epifaunal, prefer sandy substrates and have a peak abundance range of 10–35 m water depth (Renema, 2008, 2006; Renema and Troelstra, 2001) but may live as deep as 130 m in the northernmost Red Sea (Reiss and Hottinger, 1984). This depth range may be related to the less turbid waters of the Gulf of Eilat; the nummulitids are sensitive to high light intensity and live at shallower depths if suspended sediment reduces the extent of the photic zone (Reiss and Hottinger, 1984). *O. complanata* prefers lower light intensities and occurs slightly deeper than *O. ammonoides* (Renema, 2003). Although temperature at the peak abundance depth of *O. ammonoides* may be 1–2 °C below SST, planktic foraminifera such as *Globigerinoides ruber* that are routinely considered to be surface dwelling inhabit a similar range (Anand et al., 2003). Hence, results derived from these LBF can be considered comparable to surface-dwelling planktic foraminifera, with respect to the extent to which these results relate to surface ocean conditions. *O. ammonoides* are limited to areas with minimum SST $> 18\,^{\circ}C$ and are currently found in the Indian and west Pacific Oceans (Langer and Hottinger, 2000).

1.2. Previous LBF proxy development and application

Given the abundance of LBF in geologically and palaeoclimatologically important periods such as the Paleogene it is surprising that there has been relatively little work investigating their use as palaeoenvironmental archives. Wefer and Berger (1980) investigated intra-test stable isotope variability in the Recent LBF *Marginopora vertebralis* and *Cyclorbiculina compressa*. $\delta^{18}O$ microsampled from these foraminifera showed seasonal variation matching instrumental records in both species, demonstrating that these organisms record seasonality along their test growth axis. Recent *O. ammonoides* from the Red Sea precipitate calcite slightly lighter than expected for inorganic calcite (Fermont et al., 1983), although using the *Cibicidoides* $\delta^{18}O$–temperature calibration of Lynch-Stieglitz et al. (1999) and the local $\delta^{18}O_{sw}$ value (1.9‰) yields mean reconstructed temperature virtually identical to measured sea surface temperature (SST). Brasier and Green (1993) and Purton and Brasier (1999) were the first to apply mean $\delta^{18}O$ and stable isotope heterogeneity data from fossil LBF to reconstruct palaeoseasonality and temperature respectively. This work, based on well-preserved Eocene *Nummulites* revealed what the authors interpreted to be seasonal cycles, demonstrating the potential of these organisms for palaeoseasonality reconstruction.