

Revisiting carbonate chemistry controls on planktic foraminifera Mg/Ca: implications for sea surface temperature and hydrology shifts over the Paleocene–Eocene Thermal Maximum and Eocene–Oligocene Transition

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Abstract

Much of our knowledge of past ocean temperatures comes from the foraminifera Mg/Ca palaeothermometer. Several non-thermal controls on foraminifera Mg incorporation have been identified, of which vital-effects, salinity and secular variation in seawater Mg/Ca are the most commonly considered. Ocean carbonate chemistry is also known to influence Mg/Ca, yet this is rarely considered as a source of uncertainty either because (1) precise pH and $[\text{CO}_3^{2-}]$ reconstructions are sparse, or (2) it is not clear from existing culture studies how a correction should be applied. We present new culture data of the relationship between carbonate chemistry for the surface-dwelling planktic species *Globigerinoides ruber*, and compare our results to data compiled from existing studies. We find a coherent relationship between Mg/Ca and the carbonate system and argue that pH rather than $[\text{CO}_3^{2-}]$ is likely to be the dominant control. Applying these new calibrations to datasets for the Paleocene–Eocene Thermal Maximum (PETM) and Eocene–Oligocene Transition (EOT) enable us to produce a more accurate picture of surface hydrology change for the former, and a reassessment of the amount of subtropical precursor cooling for the latter. We show that properly corrected Mg/Ca and $\delta^{18}\text{O}$ datasets for the PETM imply no salinity change, and that the amount of precursor cooling over the EOT has been previously underestimated by $\sim 2^\circ\text{C}$ based on Mg/Ca. Finally, we present new laser-ablation data of EOT-age *Turborotalia ampliapertura* from St Stephens Quarry (Alabama), for which a solution ICPMS Mg/Ca record is available (Wade et al., 2012). We show that the two datasets are in excellent agreement, demonstrating that fossil solution and laser-ablation data may be directly comparable. Together with an advancing understanding of the effect of $\text{Mg}/\text{Ca}_{\text{sw}}$, the coherent picture of the relationship between Mg/Ca and pH that we outline here represents a step towards producing accurate and quantitative palaeotemperatures using this proxy.

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1 Introduction

The relationship between foraminifera Mg/Ca and temperature has been widely applied as a method of reconstructing the thermal evolution of the oceans across a range of timescales (e.g. Mashiotta et al., 1999; Lear et al., 2000; Sosdian and Rosenthal, 2009; Wade et al., 2012). Whilst a substantial portion of our understanding of the response of ocean temperature, hydrology and circulation to external forcing is derived from this proxy, several non-thermal controls, aside from the well-known vital effects, have been identified which complicate the translation of measured Mg/Ca ratios to temperature. Principal amongst these are dissolution (Regenberg et al., 2014), salinity (Kisakürek et al., 2008; Hönisch et al., 2013), and deeper in geological time, bias derived from secular variation in seawater Mg/Ca (Evans and Müller, 2012; Evans et al., 2015a). Finally, the effect of seawater carbonate chemistry on Mg incorporation has been investigated by several culture studies (Lea et al., 1999; Russell et al., 2004; Kisakürek et al., 2008). However, the potential effect of differential palaeo-carbonate chemistry on Mg/Ca-derived reconstructions is rarely noted for planktic foraminifera, although a carbonate ion correction is routinely applied to some benthic foraminifera species (Sosdian and Rosenthal, 2009; Yu and Broecker, 2010). All of these studies indicate that the relationship between pH or $[\text{CO}_3^{2-}]$ and Mg/Ca is large, on the order of a 30–60% increase in Mg/Ca for a 0.4 unit pH decrease from 8.0 (total scale). This implies that absolute Mg/Ca-derived temperatures may be systematically biased when ocean pH or $[\text{CO}_3^{2-}]$ was significantly different to modern, and relative Mg/Ca-derived temperature shifts over climatic events associated with a large perturbation of the carbonate system may be inaccurate.

Here we focus on the implications of variable carbonate chemistry for Mg/Ca-derived sea surface temperature (SST) shifts across two key intervals of geologically rapid climatic change, the Paleocene–Eocene Thermal Maximum (PETM) and Eocene–Oligocene Transition (EOT). Both of these events are associated with significant (0.1–0.3 unit) pH shifts (Pearson et al., 2009; Penman et al., 2014) and therefore a re-

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relationship between foraminifera Mg/Ca and carbonate system parameters warrants a re-examination of previously published records.

The PETM is characterised by a massive release of ^{13}C -depleted carbon over a geologically brief period of time (Kennett and Stott, 1991). The event is associated with a surface warming of several $^{\circ}\text{C}$ in most locations that this has been reconstructed at, using TEX_{86} or planktic foraminifera Mg/Ca and $\delta^{18}\text{O}$ (e.g. Sluijs et al., 2007; Zachos et al., 2003). Because there is evidence that the PETM was also associated with a shift in the terrestrial and oceanic hydrological cycle (Schmitz and Pujalte, 2007; John et al., 2008; D'haenens et al., 2012), $\delta^{18}\text{O}$ is frequently coupled with an independent temperature proxy in order to reconstruct surface ocean salinity change (Zachos et al., 2003; Tripathi and Elderfield, 2004). Both these, and the results of coupled climate models suggest that the hydrological response was complex and spatially variable (Sluijs et al., 2011; Winguth et al., 2010), indicating more saline surface waters in the (sub)tropical Pacific, whilst the subtropical Atlantic and coastal-proximal sites may have seen the effects of increased freshwater flux to the surface ocean. These proxy reconstructions may be highly sensitive to pH on $\delta^{18}\text{O}$ (Uchikawa and Zeebe, 2010), and also require revision in light of our analysis of the relationship between carbonate chemistry and Mg/Ca. Our data and reanalysis of existing records are timely given the recent publication of a high resolution $\delta^{11}\text{B}$ record across the PETM (Penman et al., 2014).

The EOT is marked by a stepwise transition to a climate state characterised by a continental-scale ice sheet on Antarctica, as evidenced by $\delta^{18}\text{O}$ measurements of benthic foraminifera (Zachos et al., 1996; Katz et al., 2008; Coxall et al., 2005). Sequence stratigraphic studies and Mg/Ca-derived deep ocean temperatures indicate that approximately 50% of this shift can be attributed to temperature (Miller et al., 2008; Lear et al., 2008). A $\delta^{11}\text{B}$ -pH record is now available (Pearson et al., 2009), which means that both planktic foraminiferal $\delta^{18}\text{O}$ and Mg/Ca may be corrected for the effects of a significant (~ 0.15 unit), permanent shift in the ocean carbonate system associated with CO_2 drawdown. There are relatively few high-resolution SST records across the transition. In the subtropics, the St Stephens Quarry (SSQ, Alabama) *Tur-*

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borotalia ampliapertura Mg/Ca record shows a large precursor cooling event beginning ~ 250 ka before the Eocene–Oligocene boundary (Wade et al., 2012). In the Southern Hemisphere, a similar albeit smaller event has been reconstructed from Tanzania Drilling Project samples of the same species (Lear et al., 2008). Finally, several sites in the Southern Ocean show Mg/Ca cooling that occurs prior to the largest benthic foraminifera $\delta^{18}\text{O}$ shift, “Oi-1” (Bohaty et al., 2012). Whilst this indicates a spatially coherent picture of surface ocean cooling, a large portion of our current knowledge is derived from Mg/Ca analyses of planktic foraminifera, although biomarker-derived proxies have also been utilised (Liu et al., 2009). Therefore, improving the accuracy of these reconstructions is of critical importance to our understanding of this major climatic transition.

As well as examining the implications of this pH change on published Mg/Ca-derived subtropical sea surface temperatures across the EOT, we also present new laser-ablation ICPMS data of *Turborotalia ampliapertura* from SSQ, for which a solution ICPMS Mg/Ca record is already available (Wade et al., 2012). This provides a methodological comparison for deep-time fossil samples: laser-ablation is spatially resolved (inter- and intra-chamber) and allows the exclusion of data from poorly preserved areas of the test, whilst samples crushed for solution analysis may be easier to clean.

In order to form the basis of more accurate Mg/Ca-derived absolute and relative temperature shifts throughout the Cenozoic, we present a compilation of new and previously published data of the relationship between Mg/Ca, pH and $[\text{CO}_3^{2-}]$ for planktic foraminifera. Whilst we use the PETM and EOT as examples of climatic events for which ignoring this effect may lead to substantial bias, as high-resolution pH reconstructions are available for both, our findings are applicable to any time period with a non-modern and/or temporally variable surface ocean carbonate chemistry.

2 Materials and methods

We present new culture data of the relationship between Mg/Ca and carbonate system parameters for *Globigerinoides ruber*, and a reanalysis and compilation of literature data for this species, *Globigerina bulloides* and *Orbulina universa*. We utilise data from culture experiments of *Globigerinoides ruber* grown at the Inter-University Institute for Marine Science, Eilat, between January 2010 and November 2013. The primary purpose of these experiments was to determine the pH-sensitivity of $\delta^{11}\text{B}$ in *G. ruber* for different $[\text{B}]_{\text{sw}}$ (with some of these cultures described in Henehan et al., 2013), and to examine the relationship between $(\text{Mg}/\text{Ca}_{\text{sw}})$ and shell Mg/Ca (Evans et al., 2015b). Because seawater Mg/Ca ($\text{Mg}/\text{Ca}_{\text{sw}}$) was varied in the cultures of Evans et al. (2015b), this enables the consistency of the relationship between carbonate chemistry and foraminifera Mg/Ca ($\text{Mg}/\text{Ca}_{\text{test}}$) to be examined at below-modern $\text{Mg}/\text{Ca}_{\text{sw}}$.

For both new and previously published data, Mg/Ca is normalised to the ratio that would be expected at 26°C and a salinity of 35‰, specific to each species. In order to account for different temperatures, salinities and in one case $\text{Mg}/\text{Ca}_{\text{sw}}$ between the cultures, all data were normalised to these conditions where they differed and/or where $\text{Mg}/\text{Ca}_{\text{sw}}$ was not the same as in the modern ocean. For *G. ruber* this was achieved using the Mg/Ca-temperature calibration of Kisakürek et al. (2008), the Mg/Ca-salinity relationship of Hönisch et al. (2013) and the seawater-test Mg/Ca calibration of Evans et al. (2015b). Between the three sets of *G. ruber* cultures, temperature varied between 26–27°C and salinity varied between 35.0–37.2‰. For *G. bulloides* and *O. universa*, data were normalised to 26°C assuming both species are characterised by Mg/Ca-temperature relationships with an exponential coefficient of 0.09 in the modern ocean (Anand et al., 2003). Mg/Ca was then normalised to that of the culture(s) with modern seawater pH (~ 8.02 total scale) within the same study. No salinity correction was necessary as this was consistent within the studies of Russell et al. (2004) and Lea et al. (1999) and would therefore cancel. Where measurements were not available, DIC and

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[CO₃²⁻] were calculated using co2sys (Lewis and Wallace, 2006), based on the same constants as Raitzsch et al. (2010).

2.1 Laboratory culture calibration

Whilst a more detailed description of culturing methods is provided elsewhere (Henehan et al., 2013; Evans et al., 2015b), a brief summary is given here. Foraminifera were towed from the Gulf of Eilat, and cultured in individual 120 mL airtight flasks. Individuals were fed a juvenile brine shrimp every 1–2 days until gametogenesis took place or calcification ceased, after which they were rinsed in deionised water, dried and stored for analysis.

Within experiments intended for boron isotope measurement, the pH of flask solutions was measured at the beginning of each experiment, and then every 2–3 days using an electrode calibrated against NBS buffers. At the end of experiments, individual flask pH was measured and a composite sample of all flasks combined, measured and then poisoned for Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA) analysis at the UKOARP, Southampton (see Henehan et al., 2013). For experiments designed around varying Mg/Ca_{sw} (Evans et al., 2015b), pH was measured at the start of culture. Based on repeat measurements of the reservoir seawater used to fill the individual culture flasks, we apply a conservative pH uncertainty of ±0.1. For all culture experiments, pH electrode measurements were corrected to total scale pH via calibration against pHs derived from analysis of multiple DIC and TA water samples.

2.1.1 Laser-ablation analysis

The cultures outlined in Evans et al. (2015b) were analysed using the 193 nm RES-Olution M50 laser-ablation system at Royal Holloway (Müller et al., 2009), as described previously (Evans et al., 2015a). Briefly, foraminifera were cleaned in 10% NaOCl, rinsed in deionised water and mounted on carbon tape. Individual chambers were identified as those precipitated in culture if they were characterised by elevated

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$^{135}\text{Ba}/^{138}\text{Ba}$, as the seawater used in these experiments was spiked with 74 nM ^{135}Ba . NIST610 was used as a calibration standard for Mg, based on the NIST Mg value of Pearce et al. (1997) which results in Mg/Ca accuracy $\sim 7\%$ better than the value of Jochum et al. (2012) on our system. Data reduction followed established procedures (Longerich et al., 1996) using in-house Matlab data reduction software. ^{43}Ca was used as an internal standard. Long-term Mg/Ca accuracy and precision is better than 5% (2SD) as assessed by standardising the MPI-DING komatiite glass GOR132 (Jochum et al., 2006) to NIST610.

2.1.2 Solution ICPMS

Prior to analysis, foraminifera were cleaned as described in Henehan et al. (2013). Foraminiferal culture samples of 1–3 mg (to permit boron isotope analysis on the same samples where possible) were lightly crushed between two clean glass slides, ultrasonicated and rinsed repeatedly with Milli-Q ultrapure water (18.2 M Ω). Samples were subject to intensified oxidative cleaning (3 \times 20–30 min treatments of 250–400 μL 1% H_2O_2 in 0.1 M NH_4OH at 80 $^\circ\text{C}$) to remove organic material, followed by a brief weak acid leach in 0.0005 M HNO_3 to remove any readsorbed contaminants. Finally, 200 μL of Milli-Q was added to each sample (to slow subsequent dissolution and reduce the likelihood of leaching of B off any remnant contaminants) and 0.5 M HNO_3 (normally < 300 μL) added incrementally until the sample was fully dissolved. Samples were centrifuged for > 5 min at 1400 rpm, and the supernatant removed to a clean vial, leaving the last $\sim 20 \mu\text{L}$ to be discarded.

Solution ICPMS measurements of Mg/Ca were performed on a Thermo Element ICP-MS at the University of Southampton and the Bristol Isotope Group. Analysis of common consistency standards ensures no bias exists between these two laboratories. Tuning is performed on a 0.1 ppb multielement tune solution to optimize sensitivity while minimising the presence of oxides (the ratio of m/z 248/232 was maintained below 7%). During each analytical session, in-house consistency standards (Mg/Ca

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ratios of 1.277, 3.289 and 7.573 mmol mol⁻¹ respectively) were analysed at a range of concentrations (typically 0.5, 1, and 2 mM Ca) to monitor accuracy and precision. Reproducibility of element ratio measurements is optimised (following Yu et al., 2005) by matrix-matching samples and their bracketing standards (the in-house gravimetric standard BSGS). This is achieved by analysing for [Ca] in a dilute aliquot of each sample (typically 20 in 200 µL 0.5 M HNO₃) prior to full elemental determination. Samples are then diluted with 0.5 M HNO₃ to match standard [Ca] and analysed for the full trace metal suite. Long-term reproducibility of Mg/Ca ratio measurements is better than 3% (2SD), based on repeat measurements of in-house consistency standards.

Because foraminifera did not precipitate calcite exclusively in culture, Mg/Ca ratios were obtained via mass-balance calculations. To determine this, initial pre-culture mass was estimated from starting diameter using the calculated size-mass relationship from Henahan et al. (2013).

2.2 Fossil samples: St Stephen's Quarry

St Stephens Quarry (Alabama) is a shallow water site characterised by a palaeodepth of 50–100 m (Miller et al., 2008) and exceptional foraminifera preservation (Wade et al., 2012). In order to compare laser-ablation-derived trace element data with the solution ICPMS Mg/Ca record of Wade et al. (2012), the planktic foraminifera *Turborotalia ampliapertura* was sampled from selected intervals across the Eocene–Oligocene Transition. The laser-ablation analytical procedure differed from above only in that foraminifera were cleaned by ultrasonication for one minute in acetone, one minute in methanol and 4 min in deionised water to maximise removal of clay particles without damaging the foraminifera. Every chamber available for analysis was targeted and mean specimen values were calculated by taking the average of all measurements for that individual. Because laser-ablation depth profiling is a highly spatially-resolved technique, poorly preserved areas of the test or those associated with clay mineral contamination could be excluded before the calculation of these means. We use the qual-

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itative coherence of Mg/Ca and elements indicative of diagenetic overgrowths (e.g. the REE which are present at very low concentrations in primary foraminifera calcite Palmer, 1985). A sample-specific Al/Ca cut-off was used to exclude foraminifera that presumably contained clay minerals which were not removed during ultrasonication.

5 This was either 2 or 4 mmol mol⁻¹, based on the point at which elevated Al/Ca resulted in elevated Mg/Ca.

3 Results

3.1 Carbonate chemistry control on foraminifera Mg/Ca

New and published Mg/Ca-carbonate chemistry data are shown in Table 1, and our *G. ruber* culture data is shown in the context of a previous study examining the relationship between pH and Mg/Ca in this species (Kisakürek et al., 2008), as well as data compiled for *Globigerina bulloides* and *Orbulina universa* (Lea et al., 1999; Russell et al., 2004), in Fig. 1. Because it has been argued that there is a limited control on foraminifera Mg/Ca at high pH and/or [CO₃²⁻] (Russell et al., 2004), and there is no relationship between pH and Mg/Ca below pH 7.8 for *G. ruber*, we fit regressions that capture the nonlinear aspects of the data. In pH space, *G. ruber* is characterised by a steeper slope between pH 7.8 and 8.1 (Fig. 1a), and we use this as justification for fitting logistic functions to the data. pH and [CO₃²⁻] covaried in both our cultures and those previously published. Therefore it is not possible to identify which is the controlling factor based on these data. For this reason, normalised Mg/Ca is also shown in [CO₃²⁻] space in Fig. 1b. We fit power regressions to these data in order to capture the decreasing sensitivity of Mg/Ca to pH or [CO₃²⁻] at high values.

There are significant differences between the species-specific regressions. These may represent real differences in the varying ability of the different foraminifera to exclude Mg from the site of biomineralisation as seawater carbonate chemistry changes, or it may represent analytical and experimental noise given the different culturing meth-

ods, locations, and necessary corrections we describe above. Whilst these calibrations should be used where these species have been utilised in the fossil record, in order to apply these relationships to reconstructions based on extinct species in the Paleogene we combine all the data in order to derive a broad picture of the likely response of foraminifera Mg/Ca to carbonate system perturbations (Fig. 1c and d). The change in slope in the relationship between Mg/Ca and pH, with two inflection points, is also manifest in the combined data and is described by the logistic function:

$$\text{Mg/Ca} = \frac{0.66}{1 + \exp(6.9 \times (\text{pH} - 8.0)) + 0.76} \quad (1)$$

$R^2 = 0.74$, $n = 27$. One outlier (the *G. bulloides* datapoint at pH 7.6) has been excluded from all regressions. Whilst a logistic function is consistent with the empirical insensitivity of Mg/Ca to pH or $[\text{CO}_3^{2-}]$ at higher values, it is not possible to statistically exclude a simpler relationship. Therefore, we also provide a linear regression through the data:

$$\text{Mg/Ca} = -0.70 \times \text{pH} + 6.7 \quad (2)$$

$R^2 = 0.71$. Finally, because it is not possible to distinguish between a $[\text{CO}_3^{2-}]$ and pH control based on these datasets, we also provide a combined power regression between Mg/Ca and $[\text{CO}_3^{2-}]$:

$$\text{Mg/Ca} = 8.1 \times [\text{CO}_3^{2-}]^{-0.068} - 4.6 \quad (3)$$

$R^2 = 0.61$. The application of these calibrations to fossil samples implicitly assumes that they describe some fundamental characteristic of the ability of the biological processes within foraminifera that exclude Mg, i.e. that the location of typical modern surface pH midway between the two inflection points of the logistic regression is coincidental and does not represent an evolutionary adaptation to modern carbonate chemistry. This is important as, if a logistic function is indeed appropriate, perturbations to the carbonate system that do not shift pH outside of the range 8.2–8.6 or 7.7–7.4 are unlikely

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to be associated with a large pH-derived shift in $\text{Mg}/\text{Ca}_{\text{test}}$. There is no relationship between foraminifera Mg/Ca and DIC (Fig. 2), and we eliminate secular changes in DIC as a potential control on foraminifera Mg/Ca through time.

Because a proxy that relates directly to pH is available ($\delta^{11}\text{B}$), whereas $[\text{CO}_3^{2-}]$ cannot be reconstructed without another known carbonate system parameter (e.g. alkalinity, DIC), we base the implications for palaeotemperature reconstruction on the relationship between Mg/Ca and pH. Whilst we cannot eliminate $[\text{CO}_3^{2-}]$ as the primary control, we argue that pH is the most likely driver of carbonate chemistry related Mg/Ca shifts in Sect. 4.1. If this is incorrect, and changing $[\text{CO}_3^{2-}]$ is found to exert the dominant control on Mg/Ca , then our results may require minor revision.

3.2 St Stephens Quarry laser-ablation data

Laser-ablation data of *T. ampliapertura* from St Stephens Quarry are characterised by excellent foraminifera preservation. Mn/Ca ratios are typically $< 0.2 \text{ mmol mol}^{-1}$, suggesting little or no bias from diagenetic overgrowths. Inter-chamber profiles (Fig. 3a) show localised areas with elevated Al/Ca which likely result from remnant clay particles. Four intervals were sampled for which solution ICPMS Mg/Ca data have already been published (Wade et al., 2012), shown in Fig. 3b. Mg/Ca from both techniques are within error of each other for all intervals. Moreover, relative inter-sample differences in Mg/Ca are indistinguishable between the laser-ablation and solution Mg/Ca data. Whilst mean laser-ablation measurements (which represent the average of 10–30 individual chamber profiles) are offset to values $\sim 10\%$ higher, which would result in a 1°C temperature bias, this error is small compared to uncertainties derived from the complications we list below (see Sect. 4.4).

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4 Discussion

4.1 A mechanistic understanding of Mg/Ca variation with carbonate chemistry

Foraminifera are known to elevate the pH of vacuolised seawater by up to ~ 1 unit (Bentov et al., 2009; de Nooijer et al., 2009), and seawater vacuoles have been suggested to play a fundamental role in calcification (Erez, 2003; Bentov and Erez, 2006). This implies that the $[\text{CO}_3^{2-}]$ of the calcifying fluid is significantly higher than that of the vacuolised seawater, especially given the carbon concentrating mechanism proposed by ter Kuile and Erez (1987) and modified by Bentov et al. (2009). If Mg is pumped out of seawater vacuoles by the vacuole-cytosol concentration gradient and membrane potential, as suggested by Bentov and Erez (2006), then the efficiency of Mg removal may be sensitive to pH. There are several reasons that this could be the case. When seawater pH is lower, then the foraminifer needs to work harder in order to elevate vacuolar pH. If this process is fundamentally linked to the ability of these organisms to remove Mg, whereby a lower pH makes it more difficult to precipitate calcite with low Mg/Ca, then a decreased pH would result in calcite with a higher Mg concentration. This may be because calcification proceeds through an intermediate mineral such as amorphous calcium carbonate (e.g. Politi et al., 2004), for which there may be a relationship between Mg and pH that is different to calcite (Burton and Walter, 1991). Alternatively, pH has been shown to significantly affect membrane potential in algae (Spanswick, 1972). If foraminifera use this gradient to pump Mg out of vacuolised seawater at some point in the calcification process, the Mg driving force would therefore also be sensitive to seawater pH.

It is more difficult to imagine a mechanistic control of seawater $[\text{CO}_3^{2-}]$ on $\text{Mg}/\text{Ca}_{\text{test}}$, because foraminifera probably source a portion of the DIC required for calcification from metabolic CO_2 (ter Kuile et al., 1989; Bentov et al., 2009). Whilst lower pH or $[\text{CO}_3^{2-}]$ is known to negatively affect calcification rates in several marine organisms (Ries et al., 2009) including *G. ruber* (Kisakürek et al., 2008; Henehan et al., 2013), in foraminifera it is more likely as a result of the reduced efficiency of the carbon concentrating mech-

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anism when vacuole pH is lower, and not because fewer $[\text{CO}_3^{2-}]$ ions are present in the endocytosed seawater (the two are related but it is the pH of seawater that is the fundamental control).

An alternative biomineralisation model has been proposed, wherein ions predominantly arrive at the site of calcification through channels (the transmembrane transport model), with a small proportion arriving as a result of seawater leakage from vacuoles (Nehrke et al., 2013). However, there is no clear reason that a lower pH of the foraminifer microenvironment would result in greater seawater leakage and therefore a higher $\text{Mg}/\text{Ca}_{\text{test}}$, and this model may not be able to explain the observed relationship between seawater carbonate chemistry and Mg incorporation.

4.2 Implications for reconstructing relative temperature shifts

Both transient and more permanent temperature shifts are often associated with a change in ocean pH, as has been demonstrated for both the PETM (Penman et al., 2014) and the EOT (Pearson et al., 2009) based on $\delta^{11}\text{B}$ measurements of planktic foraminifera. It therefore follows that some portion of the observed foraminifera Mg/Ca shift over such events is not due to temperature, but changes in the pH of seawater. Figure 4 shows the extent to which relative temperature shifts would be overestimated as a result of assuming that temperature is the only dominant control on foraminifera Mg incorporation. The degree to which the associated temperature change may have been overestimated is dependent on the magnitude of the pH shift and the type of regression used to describe $\text{Mg}/\text{Ca}_{\text{test}}$ change with pH. Using a logistic relationship, Mg/Ca is most sensitive to pH change between 7.9 to 8.4, as the regression slope becomes less steep outside of this range, which is not the case for a linear Mg/Ca -pH relationship.

Correcting PETM records for pH change is therefore sensitive to the type of regression used, based on the pre-excursion pH reconstructions of Panchuk et al. (2008) and Zeebe et al. (2009) which are ≤ 7.8 . If a linear fit is more appropriate, and assuming

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no other bias on deep-time Mg/Ca-derived relative temperature shifts, then a 0.3 unit pH drop would cause an apparent change in foraminifera Mg/Ca equivalent to a 1.6–1.8 °C temperature shift, implying that a reconstruction of relative temperature change would be overestimated by this amount if the effect of pH is not accounted for. If the logistic regression is applied to the data then the contribution of pH would cause the temperature shift to be overestimated by < 1 °C.

For the EOT, the Mg/Ca shift associated with the pH reconstructions of Pearson et al. (2009) is less uncertain. This is because the maximum pH over this interval was probably higher than the background pH during the time of the early Eocene hyperthermals, and therefore there is a smaller difference between the pH-derived Mg shift between a logistic and linear regression through the culture data (dashed lines in Fig. 4). If pH is unaccounted for in Mg/Ca-derived temperature reconstructions over the EOT (and again, assuming there are no other biases on Mg/Ca), then the relative temperature shift would be overestimated by 0.8–1.5 °C. This relative temperature bias is insensitive to the assumption of $\delta^{11}\text{B}_{\text{sw}}$ (Pearson et al., 2009 report pH reconstructions based on $\delta^{11}\text{B}_{\text{sw}} = 38 \pm 1\text{‰}$), as the pH-induced temperature bias is reasonably insensitive to both pH and the choice of Mg/Ca-pH regression over the seawater pH range 7.75–7.95 for a pH change of this magnitude.

Whilst it is beyond the scope of this paper to discuss the implications across all climatic events with an associated shift in carbonate chemistry, aside from the intervals discussed here, this finding has particular relevance to glacial-interglacial sea surface temperature reconstructions based on foraminifera Mg/Ca, which are typically viewed as being relatively robust as no Mg/Ca_{sw} correction is necessary during the Pleistocene. Whilst glacial-interglacial surface ocean pH shifts were spatially variable (e.g. Foster et al., 2008; Martínez-Botí et al., 2015), a 0.1–0.15 unit change is typical, between ~ 8.1–8.25 which may result in an overestimation of glacial-interglacial SST change on the order of 1–1.5 °C.

The relationship between pH and Mg/Ca means that relative temperature shifts in the past may have been overestimated. However, a further consideration is the re-

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cent finding that the sensitivity of the relationship between Mg/Ca and temperature is not constant at below-modern Mg/Ca_{sw} (Evans et al., 2015b). Figure 5 shows calibrated and modelled variation in the exponential coefficient (A) of a *G. ruber* Mg/Ca-temperature calibration with Mg/Ca_{sw}. The relationship between Mg/Ca and temperature is assumed to take the form $\text{Mg/Ca} = B \exp^{AT}$, where B and A vary according to an unknown function with respect to Mg/Ca_{sw}. At present, only the sensitivity in the modern ocean (e.g. Anand et al., 2003; Kisakürek et al., 2008) and at Mg/Ca_{sw} = 3.4 mol mol⁻¹ (Evans et al., 2015b) is known, indicating a reduction in sensitivity from 9 to 7.4 % °C⁻¹. Further calibrations are required to constrain this sensitivity at Paleogene Mg/Ca_{sw} ratios, which were reasonably invariant between 2.0–2.5 mol mol⁻¹ (Dickson, 2004; Coggon et al., 2010; Evans et al., 2013). Seven different model curves between the exponential coefficient (A) and Mg/Ca_{sw} are shown in Fig. 5. These were derived by fitting both the observed sensitivity change as well as the calibrated nonlinear relationship between seawater-test Mg/Ca reported by Evans et al. (2015b), for a variety of assumptions regarding the shape that this relationship should take (linear, power, exponential, quadratic). These curves are better constrained than they appear from the two datapoints available, as only specific models are capable of also capturing the upwards-convex seawater-test Mg/Ca relationship for *G. ruber*, which is also the case for other foraminifera (Evans et al., 2015a; Raitzsch et al., 2010). For example, a linear regression through the two datapoints produces a seawater-test Mg/Ca curve that is convex down, the opposite of that for all species studied so far (see Evans and Müller, 2012), and can be immediately discounted. Nonetheless, the shift in sensitivity of Mg/Ca to temperature is not yet precisely known for the Paleogene, and may lie anywhere in the range 5.0–7.5 % °C⁻¹ based on the data currently available.

The effect of the control exerted on Mg/Ca by pH and the shift in sensitivity with Mg/Ca_{sw} act in opposite directions on reconstructed relative temperature shifts using foraminifera Mg/Ca, and these effects may – to some extent – cancel each other in the Paleogene when Mg/Ca_{sw} was ~ 50 % of modern. However, it should not be as-

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sumed that the two exactly balance, and at the very least both of these factors should be propagated into error estimates. This may be the case to a lesser extent for events that occurred within the last ~ 20 Ma, when seawater chemistry was closer to that of today and therefore the effect of pH dominates the correction applied. Finally, whilst both factors should be considered when reconstructing relative temperature shifts, the relationship between pH and foraminifera Mg/Ca is such that the reporting of absolute temperatures will be highly sensitive to differential carbonate chemistry throughout the Paleogene, as pH was probably broadly lower throughout this Period (Tyrrell and Zeebe, 2004). Absolute Mg/Ca-derived temperatures should not be reported without an estimate of both the degree of nonlinearity of the seawater-test Mg/Ca relationship and the seawater pH for the interval of interest.

We now apply these findings to the PETM and the EOT in detail, in order to better constrain SST and hydrological shifts over the former, and to produce the first fully-corrected (for Mg/Ca_{sw} and pH) absolute Mg/Ca-derived temperatures across the EOT.

4.3 Implications for SST and hydrological shifts over the PETM

Coupled Mg/Ca- $\delta^{18}\text{O}$ measurements of foraminifera have been used not only to reconstruct SST change associated with the event, but also hydrological change. Based on this technique, Zachos et al. (2003) reconstruct a 1.0–2.6‰ positive salinity shift at ODP Site 1209, implying higher evaporation during the PETM. Similarly, this technique has been applied to ODP Site 865 (equatorial Pacific) and DSDP 527 (subtropical South Atlantic) (Tripathi and Elderfield, 2004), with a more complex picture of hydrological change emerging. Uncorrected for pH, these data also imply enhanced evaporation in the Pacific (i.e. Mg/Ca shows a larger temperature shift than $\delta^{18}\text{O}$), whereas the Atlantic site shows a shift towards more negative $\delta^{18}\text{O}_{\text{sw}}$ during the PETM. Finally, Zachos et al. (2006) reconstruct an negative $\delta^{18}\text{O}_{\text{sw}}$ shift at the coastal proximal Wilson Lake (US Gulf Coast), which may be related to increased freshwater runoff, given that the PETM is known to be associated with seasonally increased precipitation (Schmitz

and Pujalte, 2007). All of these datasets require revision in light of the control that both pH and Mg/Ca_{sw} exert on the reconstruction of relative temperature shifts. As an example, this is shown for ODP Site 1209 in Fig. 6.

The ~ 0.3 unit pH shift over the PETM (Penman et al., 2014) would result in a 15–20 % increase in foraminifera Mg/Ca using the pre-excursion pH scenario of 7.8. If this was the only previously unaccounted for source of error, this would result in a reduction of the reconstructed SST shift from 4.5 to 3 °C (Fig. 6). However, the potential shift in Mg/Ca-temperature sensitivity, or rather the large uncertainty in how this may have varied in the past means that the maximum SST excursion may lie anywhere between 3–6 °C. This full range of error includes the pH correction that we outline and assumes that the exponential constant of a Mg/Ca-temperature calibration may lie anywhere between the modern value (0.09) and the lowest modelled value shown in Fig. 5 (0.05). Until this is further constrained, it should be considered as a source of error for relative temperature shifts. It is not possible to assess at present whether reported temperature shifts are overestimates or underestimates, or fortuitously accurate.

The potential effect of seawater pH on foraminifera $\delta^{18}\text{O}$ has been previously recognised (Spero et al., 1997; Uchikawa and Zeebe, 2010) and has a mechanistic basis in oxygen isotope fractionation between carbonate species (Zeebe, 1999), i.e. this fractionation is also most appropriately causally ascribed to pH rather than $[\text{CO}_3^{2-}]$. *Orbulina universa* and *Globigerina bulloides* are characterised by cultured pH- $\delta^{18}\text{O}$ slopes of -0.89 and -2.51 per pH unit respectively, which means that a 0.3 unit pH shift over the PETM would result in overestimating the combined temperature and $\delta^{18}\text{O}_{\text{sw}}$ component of the foraminifera $\delta^{18}\text{O}$ shift by 0.27–0.75 ‰. This large interspecies difference is a further large source of uncertainty given that extinct species may be characterised by different slopes. Figure 6C shows a range of $\delta^{18}\text{O}_{\text{sw}}$ shifts over the PETM based on different assumptions regarding the control that Mg/Ca_{sw} and the relationship between pH, Mg/Ca and $\delta^{18}\text{O}$ exert on this record. The blue line shows $\Delta\delta^{18}\text{O}_{\text{sw}}$ ($\delta^{18}\text{O}_{\text{sw}}$ relative to the pre-CIE baseline) fully corrected for all of the effects described above, using our logistic Mg/Ca-pH relationship (Fig. 1), a reduced Mg/Ca-temperature sensitivity

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of $7.5\% \text{ } ^\circ\text{C}^{-1}$ for the Paleogene (Fig. 5) and the $\text{pH}-\delta^{18}\text{O}$ relationship for *G. bulloides* (Spero et al., 1997). This fully corrected record is characterised by $\Delta\delta^{18}\text{O}_{\text{sw}}$ within $\pm 0.25\%$ of zero, essentially implying little surface hydrology change at this site over the PETM.

5 Aside from those mentioned above, both $\delta^{18}\text{O}$ and Mg/Ca data are also available for DSDP Site 401 in the Bay of Biscay (Bornemann et al., 2014) and DSDP Site 277 in the southwest Pacific (Hollis et al., 2015). Finally, $\delta^{18}\text{O}$ and TEX_{86} data are available for Bass River (Sluijs et al., 2007; John et al., 2008), ~ 50 km to the East of Wilson Lake. Compiling the data for these sites and applying the corrections that we detail
10 above (Fig. 7) enables a more accurate picture of sea surface temperature and hydrological shift over the PETM to be constructed. This figure shows peak PETM SST and $\Delta\delta^{18}\text{O}_{\text{sw}}$ relative to the pre-CIE baseline, with error bars that incorporate the full range of uncertainties that we discuss above. Temperature shows a broad relationship with palaeolatitude, with $< 2^\circ\text{C}$ warming in the (sub)tropics and $2\text{--}7^\circ\text{C}$ at higher latitudes. The Mg/Ca data from DSDP Site 401 do not conform to this (Bornemann et al.,
15 2014), which show only a 0.3 mmol mol^{-1} raw Mg/Ca shift and therefore a corrected temperature shift of $0.2 \pm 0.1^\circ\text{C}$. In contrast, the *Morozovella* $\delta^{18}\text{O}$ excursion at this site would imply a SST change of $5\text{--}7^\circ\text{C}$ if interpreted purely in terms of temperature. Conversely, the oxygen isotope data may simply reflect freshwater flux, given that
20 there is also evidence for an abrupt shift in hydrological regime from the style of clay deposition (Bornemann et al., 2014), although modelling results predict a substantial surface ocean warming in the northeast Atlantic (Jones et al., 2013). It is possible that the small Mg/Ca shift at DSDP Site 401 is a result of poor foraminifera preservation, however the raw ratios are not abnormal for this time interval, and the high clay content and relatively shallow palaeo-water depth of $1.5\text{--}2$ km (D'haenens et al., 2012) means that differential preservation across the PETM is potentially unlikely. Irrespective, the broad relationship between the magnitude of the SST excursion and latitude is consistent with enhanced high latitude warming compared to the tropics and a reduction in latitudinal temperature gradients with global warming (Bijl et al., 2009).

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Compiled $\Delta\delta^{18}\text{O}_{\text{sw}}$ shifts over the PETM (Fig. 7b) are all within error of zero, with the exception of the northeast Atlantic (which is a result of the small Mg/Ca shift discussed above) and Wilson Lake. The difference between reconstructed hydrology at Wilson Lake and Bass River is not a GDGT calibration artefact, as Wilson Lake shows a larger raw TEX_{86} shift across the PETM (Sluijs et al., 2007). It is more likely that $\delta^{18}\text{O}$ at Wilson Lake is affected to a greater extent from terrestrial freshwater input as it was located closer to the palaeoshoreline, whilst Bass River essentially shows no shift in surface hydrology. Although some sites are likely influenced by near-coastal processes, applying these corrections overall implies a slight freshening of surface waters during the peak CIE. In distal sites, this can only result from a change in hydrology towards relatively more precipitation. Although the detail of hydrological change across the full PETM interval is evidently more temporally complex, particularly when differences between surface and thermocline water are considered (e.g. Tripathi and Elderfield, 2004), this is in contrast to the prevailing hypothesis which is that the PETM broadly resulted in saltier surface waters in the Pacific (sub)tropics (Zachos et al., 2003; Tripathi and Elderfield, 2004) and suggests most areas were characterised by a salinity decrease. A salinity increase associated with the peak-CIE PETM interval is only possible if the pH- $\delta^{18}\text{O}$ slope of *Morozovella* and *Acarinina* was substantially lower than that of the extant species for which this relationship has been calibrated (Spero et al., 1997) and/or (1) if the reduction in the exponential coefficient of the Mg/Ca-temperature calibration was greater than shown in Fig. 5, and/or (2) the pH-Mg/Ca relationship was steeper for these extinct species than shown in Fig. 1. Whilst some of these issues will be challenging to address, we highlight that all of these factors should be considered as sources of error, and applying corrections for both pH and $\text{Mg}/\text{Ca}_{\text{sw}}$ gives a current best estimate of no surface hydrological change to a slight freshening at any site distal from the coast, with the possible exception of ODP Site 1209. Further calibration of the pH- $\delta^{18}\text{O}$ relationship in both symbiont bearing and asymbiotic foraminifera would enable the likely inter-species variability of this relationship for extinct foraminifer with more confidence. Finally, the relatively large negative $\Delta\delta^{18}\text{O}_{\text{sw}}$ shift that we recon-

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struct for the equatorial Pacific (ODP Site 865, Fig. 7) is in part because we use the new spatially-resolved $\delta^{18}\text{O}$ data of Kozdon et al. (2013), which are characterised by a larger negative shift in raw $\delta^{18}\text{O}$ than the multiple whole-shell analyses of Tripathi and Elderfield (2004). If other sites are similarly diagenetically compromised then it is possible that these underestimate the degree of freshening during the peak CIE interval.

We do not apply a salinity correction to the Mg/Ca data as most sites are within error of no salinity change and because such a correction requires some assumption regarding the salinity– $\delta^{18}\text{O}_{\text{sw}}$ relationship at the time. However, if robust evidence for salinity change is shown then this additional factor should be accounted for. Using the Mg/Ca-salinity slopes of Hönisch et al. (2013), a PETM salinity change of 1‰ would impact ΔT reconstructions by 0.15–0.5°C.

4.4 Towards accurate absolute Mg/Ca-derived temperatures: the EOT as an example

Mg/Ca-derived reconstructions of the thermal evolution of the surface ocean across the Eocene–Oligocene climate transition is known from only a handful of sites: the Tanzania Drilling Project (Lear et al., 2008), St Stephens Quarry Alabama (Wade et al., 2012), and four locations in the Southern Ocean (Bohaty et al., 2012). Planktic foraminifera boron isotope measurements indicate that the transition was associated with a 0.1–0.15 unit pH shift, from a pre-event pH of 7.8–8.0 (Pearson et al., 2009). As for the PETM, the Mg/Ca shift over the EOT resulting from this pH change is counteracted to some extent by the reduced sensitivity of the relationship between Mg/Ca-temperature, as $\text{Mg}/\text{Ca}_{\text{sw}}$ reconstructions based on three independent proxies within a few million years of the transition are 2.0–2.4 mol mol⁻¹ (Horita et al., 2002; Coggon et al., 2010; Evans et al., 2013). However, the pH change over this interval is characterised by a reversal to more acidic conditions between 33.6–33.4 Ma (Pearson et al., 2009), which means that this will impact relative temperature reconstructions across the EOT irrespective of the reduced sensitivity in Mg/Ca-temperature. As the

pH record is far lower resolution than the Mg/Ca data, it is possible that there are unavoidable inaccuracies derived from linearly interpolating between datapoints.

In order to reconstruct absolute temperature (as well as relative shifts) from Mg/Ca before the Pleistocene, two additional pieces of information are required: (1) a Mg/Ca_{sw} reconstruction for the time interval of interest, in order to update the coefficients of the Mg/Ca-temperature calibration, and (2) a pH record for the time of interest in order to adjust the Mg/Ca data according to Eqs. (1) or (2). As before, this assumes that the pH-Mg/Ca relationship that we present is broadly characteristic of all foraminifera, and that the *G. ruber* calibrations of the nonlinearity of the Mg/Ca_{test}-Mg/Ca_{sw}-temperature surface of Evans et al. (2015b) are applicable to other species. Whilst not all foraminifera are characterised by the same pre-exponential Mg/Ca-temperature coefficient in the modern ocean (e.g. Anand et al., 2003), this may be difficult to assess for extinct species. The curvature of a seawater-test Mg/Ca calibration and the reduced sensitivity of the relationship between Mg/Ca and temperature, although now known for *G. ruber* (Evans et al., 2015b), should be calibrated in other extant foraminifera in order to see how ubiquitously these equations may be applied in deep-time. Nonetheless, now that the necessary calibrations are available for at least one species it is possible to reconstruct appropriately corrected absolute Mg/Ca temperatures for the Paleogene for the first time, with the caveat that doing so assumes that these calibrations are applicable to the extinct species on which the existing records are based. This is shown in Fig. 8 for St Stephens Quarry (see Wade et al., 2012). Realistic Mg/Ca errors for this time are $\pm 4^\circ\text{C}$, of which 2°C is derived from the uncertainty in Mg/Ca_{sw} ($\pm 0.4 \text{ mol mol}^{-1}$), 1.5°C results from a 1‰ uncertainty in $\delta^{11}\text{B}_{\text{sw}}$ at this temperature, and $\sim 0.5^\circ\text{C}$ from the uncertainty in extrapolating the seawater-shell Mg/Ca calibrations to Paleogene Mg/Ca_{sw} (Fig. 5). Within the assumptions stated above (i.e. that these calibrations are applicable to extinct foraminifera), reducing uncertainty in Mg/Ca_{sw} reconstructions is clearly a priority in order to improve the precision of absolute Mg/Ca-derived ocean temperatures before the Pleistocene.

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Although the absolute temperatures shown in Fig. 8 could shift in either direction by $\sim 4^\circ\text{C}$ as a result of these uncertainties, the Mg/Ca record from SSQ remains in good agreement with TEX_{86} from the same site; the two proxies do not deviate by more than 2°C where (approximately) coeval samples have been measured. TEX_{86} temperatures are associated with an error of a similar magnitude to Mg/Ca (Tierney and Tingley, 2014). Therefore it would be coincidental if not impossible if both proxies were offset from the true value by approximately the same amount and in the same direction. However, because the effect of pH and temperature act in the opposite direction on $\text{Mg/Ca}_{\text{test}}$, it is possible to arrive at the “right” values by any combination of incorrect assumptions regarding pH and seawater chemistry. For this reason, apparent proxy agreement with Mg/Ca should be viewed with caution (including agreement in relative temperature shifts), unless both a precise Mg/Ca_{sw} and pH value are available.

At St Stephens Quarry (Fig. 8b), the magnitude of the precursor cooling described by Wade et al. (2012) is sensitive to the corrections that we detail. Because it was not known otherwise at the time, the published 3.9°C temperature shift used 0.09 as the exponential coefficient (A) of a Mg/Ca-temperature calibration and is uncorrected for pH change. Correcting for the difference in modern-EOT Mg/Ca-temperature sensitivity, shown by the orange dashed line on Fig. 8b, results in temperatures far too high and a precursor cooling of 6.3°C . Finally, applying a pH correction brings the absolute temperatures back in good agreement with those derived from TEX_{86} and results in a slightly smaller precursor cooling of 5.9°C (albeit higher than that originally reported), as 0.4°C of apparent cooling can be ascribed to the ~ 0.05 pH change over this 200 ka interval. This further highlights how these factors may have a significant effect on both absolute and relative Mg/Ca temperature shifts. Given the stability of tropical SST at one site throughout the Eocene (Pearson et al., 2007), this event may represent unprecedented subtropical cooling compared to the earlier Paleogene. The corrected records that we present highlight that global cooling markedly greater than previously thought is likely to have occurred several 100 ka prior to the onset of major Antarctic glaciation, given that it is observed at several widely distributed sites. A sub-

tropical SST shift of almost 6 °C is greater than the change reconstructed for most of the subtropics between present day and the Last Glacial Maximum (LGM), although it is interesting to note that the US Gulf Coast LGM-Recent temperature difference is of this magnitude (Waelbroeck et al., 2009), which may imply that this region was similarly sensitive to global climate change in the Paleogene.

The excellent agreement between the published solution data and our new laser-ablation analyses (Figs. 3b and 8b) not only demonstrates that the SSQ Mg/Ca data of Wade et al. (2012) are robust, but also provides good evidence that laser-ablation and solution ICPMS results are directly comparable. It is not possible to assess whether the laser-ablation data we present here are more accurate than the solution analyses, as the two are within error of each other (Fig. 3). It is possible that the laser-ablation data are offset to higher Mg/Ca because it is more challenging to remove clay minerals from whole specimens, although given that we exclude all areas of the test with elevated Al/Ca this may be unlikely. The offset could have its roots in the necessity to standardise laser-ablation data to glasses in the absence of a homogeneous carbonate material (e.g. Hathorne et al., 2008). However, we note that inter-laboratory comparison studies of solution data are themselves not always within 10% agreement (Rosenthal et al., 2004); these data do not necessarily highlight an issue with standardising carbonate Mg using the NIST glasses. Given the recent proliferation of Paleogene laser-ablation derived trace element data (e.g. Creech et al., 2010; Evans et al., 2013; Hollis et al., 2015), the consistency that we observe between datasets (Fig. 3b) is encouraging and suggests that such datasets are likely to be directly comparable.

5 Conclusions

Using a combination of new and compiled data on the relationship between foraminifera Mg/Ca and seawater carbonate chemistry, we show that pH exerts a large control on Mg incorporation into planktic foraminiferal calcite. Using these data, we present new calibrations of how differential modern and ancient pH may be corrected for. This cor-

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rection is on the order of 10% per 0.1 unit pH shift and has the implication that both absolute and relative Mg/Ca-derived temperature changes are likely to be inaccurate and imprecise if secular variation in carbonate chemistry is unaccounted for. We apply these findings to the Paleocene–Eocene Thermal Maximum (PETM) and Eocene–Oligocene Transition (EOT). Over the PETM, the ~ 0.3 unit pH shift (Penman et al., 2014) may be counteracted to an extent by the recent finding that the sensitivity of the relationship between Mg/Ca and temperature was likely lower in the Paleogene (Evans et al., 2015b), although the uncertainty in relative temperature and hydrology change is substantially greater than previously thought. However, coupled with the effect that pH exerts on foraminifera $\delta^{18}\text{O}$ (Spero et al., 1997), we show that at most sites peak PETM sea surface hydrology was likely characterised by a shift to less saline conditions relative to the pre-onset baseline. In contrast, the broadly unidirectional pH shift over the EOT means that relative temperature shifts have been previously underestimated, as the reduced sensitivity of this thermometer at this time dominates the correction. We report the first fully-corrected absolute Mg/Ca temperatures for the Paleogene that take into account palaeo-Mg/Ca_{sw}, the differential modern-deep time Mg/Ca-temperature sensitivity, and pH.

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**Table 1.** New and compiled foraminifera culture data of the relationship between shell Mg/Ca and seawater carbonate chemistry.

Exp.	ref. ¹	pH (total scale)	[CO ₃ ²⁻] (μM)	DIC (μM)	T (°C)	salinity (‰)	Mg/Ca (mmol mol ⁻¹)	norm. Mg/Ca ²
<i>Globigerinoides ruber</i>								
DE3-5-26	1	7.90 ± 0.1	134	2089	26.3	37	6.37 ± 0.25	1.23
DE3-3-26	1	7.98 ± 0.1	162	2137	26.3	37	4.38 ± 0.25	1.34
C1	2	8.18 ± 0.01	297	1957	26.0	37	4.99 ± 0.15	0.99
C2	2	7.90 ± 0.01	164	1954	26.0	37	6.92 ± 0.21	1.38
C3	2	7.56 ± 0.01	79	1942	26.0	37	7.05 ± 0.21	1.40
MH13-1	–	7.62 ± 0.02	94	2175	26.0	37	7.99 ± 0.24	1.59
MH13-2	–	7.93 ± 0.01	175	2092	26.0	37	5.21 ± 0.16	1.04
MH13-3	–	8.48 ± 0.00	526	2026	26.0	37	3.56 ± 0.11	0.71
<i>Globigerina bulloides</i>								
BH1	3	8.17 ± 0.02	185	1996	22	33.6	4.23 ± 0.13	1.06
BH2	3	8.2 ± 0.02	197	1992	22	33.8	3.82 ± 0.11	0.96
BH3	3	7.74 ± 0.02	71	1974	22	33.7	7.75 ± 0.23	1.95
BH4	3	8.65 ± 0.02	469	1980	22	33.7	2.69 ± 0.08	0.68
–	4	7.6	51	1987	22	33	6.33 ± 0.13	1.33
–	4	8.5	282	1591	22	33	3.67 ± 0.07	0.77
<i>Orbulina universa</i>								
–	4	7.8	78	1927	22	33	10.12 ± 0.20	1.14
–	4	8.6	325	1523	22	33	6.15 ± 0.12	0.69
BH3	3	7.74 ± 0.03	72	1523	22	33.7	9.41 ± 0.9	1.36
BH6	3	7.93 ± 0.01	110	1974	22	33.7	7.92 ± 1.49	1.15
AR1	3	8.24 ± 0.02	213	1981	22	33.9	6.82 ± 0.27	0.99
AR3	3	8.41 ± 0.02	300	1977	22	33.8	6.68 ± 0.33	0.97
AR4	3	8.56 ± 0.01	399	1988	22	33.6	6.42 ± 0.46	0.93
AR5	3	8.66 ± 0.01	482	2004	22	33.6	6.49 ± 0.34	0.94
AR6	3	8.22 ± 0.01	170	2030	15	33.8	3.53 ± 0.11	0.96
AR27	3	8.17 ± 0.03	167	2029	18	33.7	5.02 ± 0.33	1.04
AR10	3	8.21 ± 0.01	217	1962	25	34.0	9.6 ± 0.39	1.06

¹ 1: Evans et al. (2015b), 2: Henehan et al. (2013), 3: Russell et al. (2004), 4: Lea et al. (1999).² Normalised (ratioed) to Mg/Ca in mmol mol⁻¹ expected at 26 °C, 35 ‰, modern Mg/Ca_{sw} for a given species.

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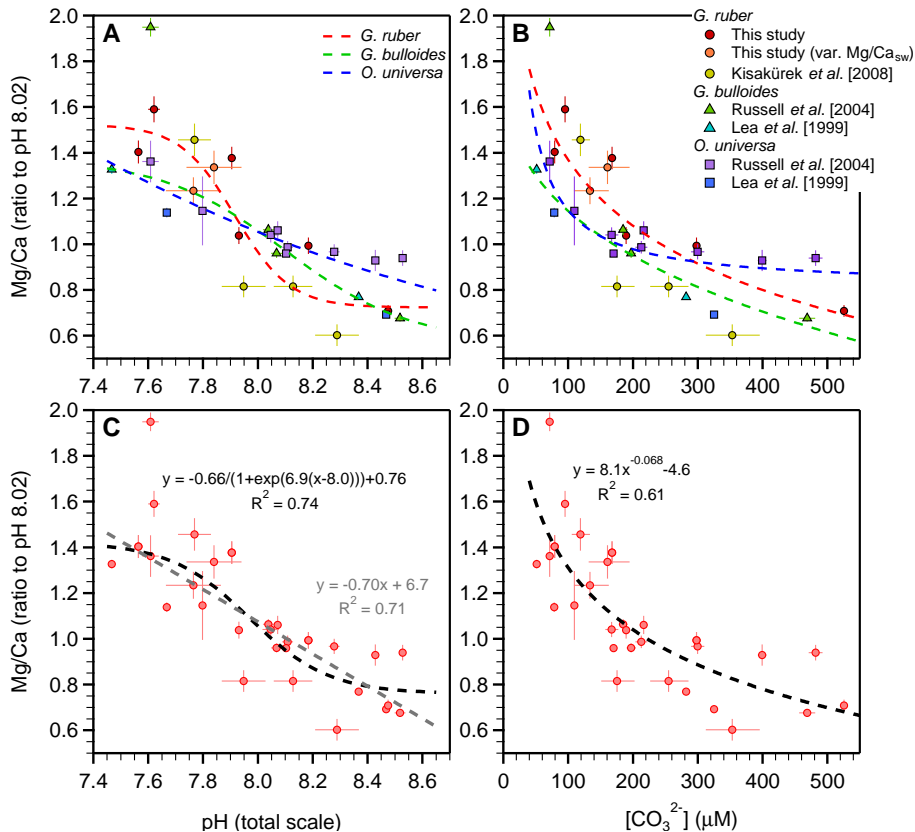


Figure 1. New and compiled planktic foraminifera Mg/Ca-carbonate chemistry data. Mg/Ca is shown as a ratio to that at pH 8.02 (~ 8.15 on the NBS scale) for each species. **(a)** Species-specific Mg/Ca variation with pH. **(b)** Mg/Ca variation with $[\text{CO}_3^{2-}]$. **(c, d)** show the same datasets with regressions calculated from all data combined. Both logistic and linear relationships are shown between Mg/Ca and pH.

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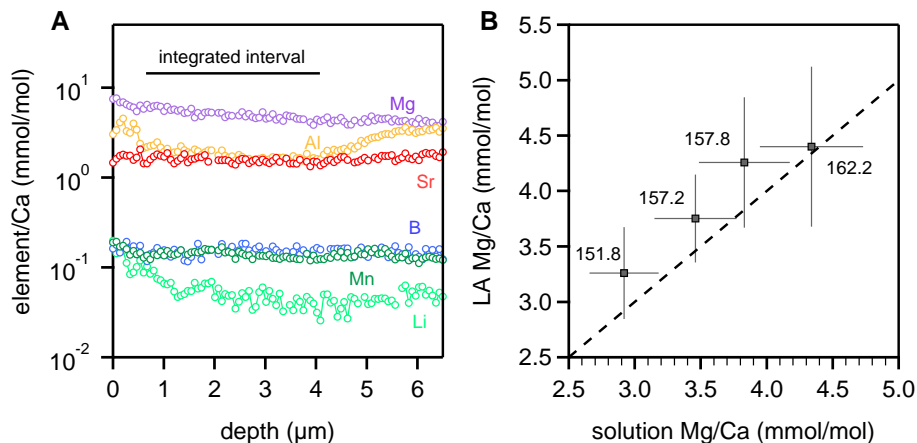


Figure 3. (a) An example laser ablation profile through a *Turborotalia ampliapertura* chamber. Sub- μm variations in element/Ca ratios are identifiable, enabling poorly preserved or contaminated areas of the test to be excluded from the calculation of mean values. Here, the inner and outer surfaces of the are characterised by elevated Al/Ca, implying incomplete clay particle removal. (b) A comparison of laser-ablation and solution ICPMS Mg/Ca data from the same intervals at St Stephens Quarry. Solution data from Wade et al. (2012). Labels show the depth intervals of these samples.

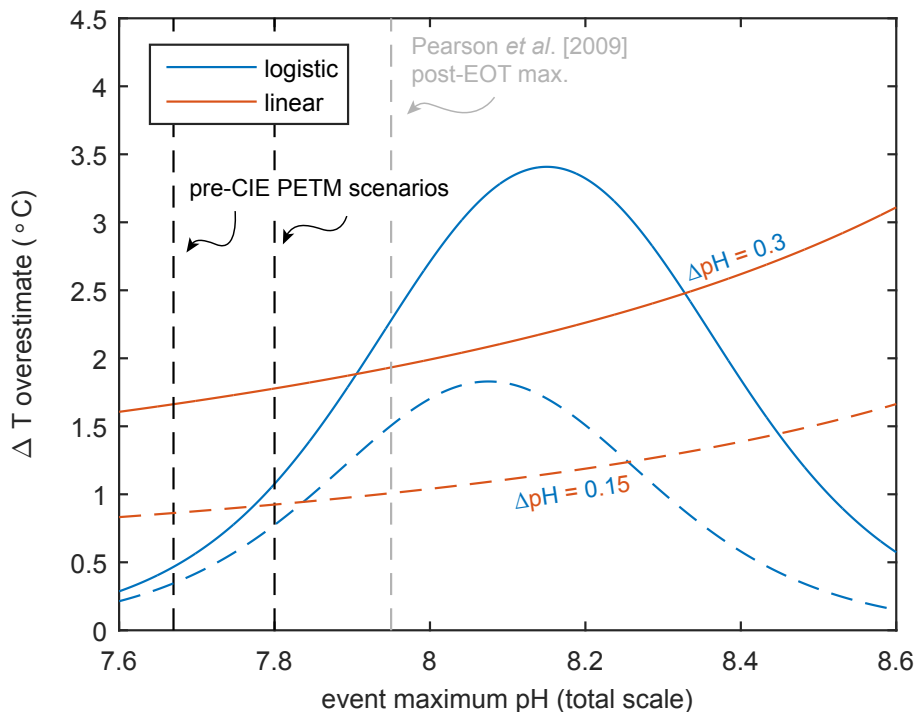


Figure 4. Temperature overestimate across climatic events if it is assumed that pH change exerts no control on foraminifera Mg/Ca. Temperature overestimates based on both a logistic and linear relationship between Mg/Ca and pH are shown, for a 0.3 unit pH shift (solid lines) and a 0.15 unit pH shift (dashed lines). pH scenarios for both the PETM (Panchuk et al., 2008; Zeebe et al., 2009) and the EOT (Pearson et al., 2009) are overlain.

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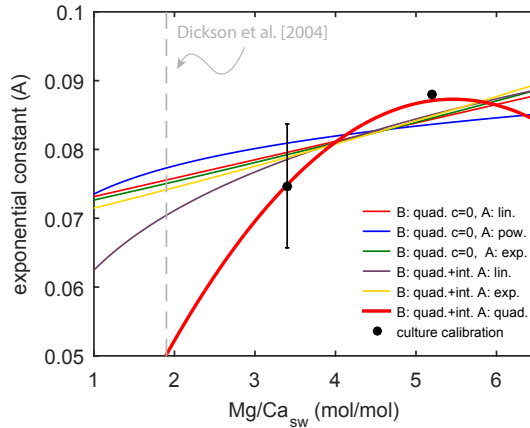


Figure 5. Variation in the sensitivity of the *G. ruber* Mg/Ca thermometer with seawater Mg/Ca, for a range of assumptions regarding the relationship between Mg/Ca_{sw} and the coefficients of a Mg/Ca-temperature calibration of the form $Mg/Ca = B \exp^{AT}$. Datapoints are based on the cultures of Kisakürek et al. (2008) (modern seawater) and Evans et al. (2015b) (Mg/Ca_{sw} = 3.4 mol mol⁻¹). Model lines are derived from least-squares modelling of these datasets as well as the seawater-shell Mg/Ca calibration of Evans et al. (2015b). A range of model curves are shown based on different assumptions of the form the regression between the exponential coefficient of a Mg/Ca-temperature calibration and Mg/Ca_{sw} should take, shown in the legend. For example the bold red line assumes that both coefficients of a Mg/Ca-temperature equation vary quadratically with Mg/Ca_{sw}, the blue line assumes that the pre-exponential coefficient varies quadratically whilst the exponential coefficient varies with a power function with respect to Mg/Ca_{sw}. “quad. c=0” are quadratic equations forced through the origin, whilst “quad.+int.” are quadratic regressions with a y intercept. An estimate of early Eocene Mg/Ca_{sw} (Dickson, 2004) is shown for comparison. These models suggest the exponential coefficient of a Mg/Ca-temperature calibration may be reduced from 0.09 to 0.05–0.075 at this time.

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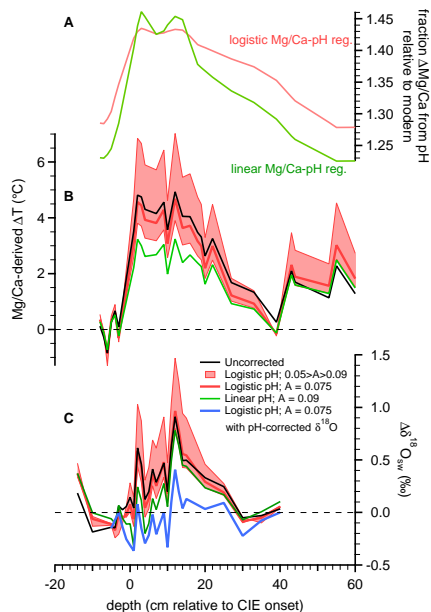


Figure 6. (a) The fraction shift in Mg/Ca over the PETM based on the calibrations between Mg/Ca and pH shown in Fig. 1, and the pH reconstructions of Penman et al. (2014) (assuming initial pH = 7.8). All data are shown relative to Mg/Ca at modern pH and display the relative change as a result of pH only. (b) ODP Site 1209 *Morozovella* Mg/Ca-derived temperature shift across the PETM. The data are shown as originally reported, and with various corrections for both pH and Mg/Ca_{sw}, relative to the pre-carbon isotope excursion (CIE) baseline. (c) δ¹⁸O_{sw} shift from coupled Mg/Ca-δ¹⁸O data, based on the range of transient temperature shifts shown in panel (b). Our preferred record (blue line), corrected for the pH effect on both foraminifera Mg/Ca and δ¹⁸O, and accounting for the likely higher sensitivity of Mg/Ca to temperature in PETM seawater, implies little change in subtropical Pacific surface hydrology over the event. Data from Penman et al. (2014) and Zachos et al. (2003). These corrections reconcile a large sea surface temperature shift with a stable open ocean hydrology at this site, see text for details.

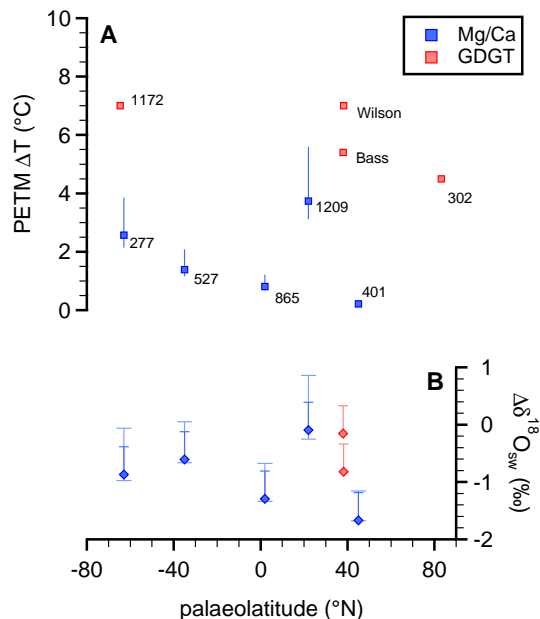


Figure 7. Compiled sea surface temperature and $\delta^{18}\text{O}_{\text{sw}}$ peak PETM shifts relative to pre-CIE values. Labels refer to IODP/DSDP site numbers or locality names. **(a)** GDGT and Mg/Ca-derived warming as a function of latitude. Mg/Ca estimates are adjusted for both pH and the sensitivity of the Mg/Ca-temperature relationship in PETM seawater (see text for details), and are the average of estimates derived from the two surface-dwelling foraminifera genera *Morozovella* and *Acarinina*. **(b)** $\Delta\delta^{18}\text{O}_{\text{sw}}$ reconstructions based on foraminifera $\delta^{18}\text{O}$ coupled with either Mg/Ca or GDGT-derived sea surface temperature shifts. $\delta^{18}\text{O}$ was adjusted for pH following Uchikawa and Zeebe (2010). Inner error bars are the uncertainty relating to the $\delta^{18}\text{O}$ -pH slope, outer error bars also include the uncertainty relating to the pH and sensitivity corrections applied to the Mg/Ca data. Data not specifically discussed in the main text are from Sluijs et al. (2006) and Sluijs et al. (2011). ODP Site 865 $\delta^{18}\text{O}$ data are the SIMS analyses of Kozdon et al. (2013).

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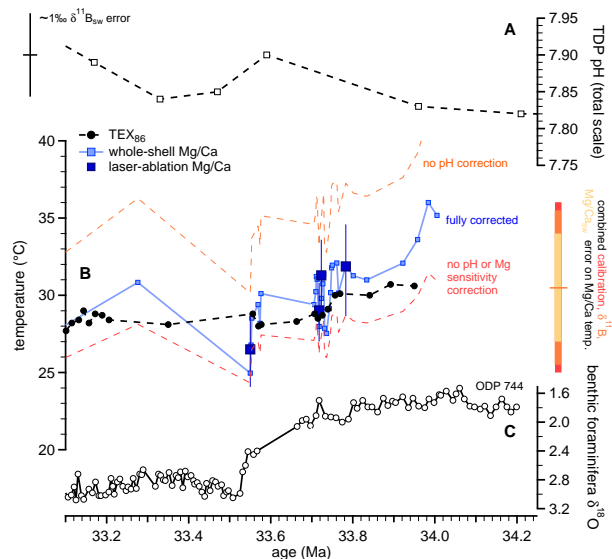


Figure 8. (a) EOT pH reconstruction from Pearson et al. (2009) based on Tanzania Drilling Project samples. The error bar is derived from an uncertainty in $\delta^{11}\text{B}_{\text{sw}}$ of $\pm 1\%$. (b) Subtropical sea surface temperature from Mg/Ca and TEX₈₆. These absolute Mg/Ca temperatures are the first to be fully corrected for both the pH effect on Mg incorporation and the nonlinear relationship between seawater-shell Mg/Ca. St Stephens Quarry Mg/Ca data from both solution ICPMS Wade et al. (2012) and laser ablation (this study) are shown. The combined Mg/Ca error estimate is that due to uncertainty in the Mg/Ca_{sw} ratio ($\pm 0.5 \text{ mol mol}^{-1}$), $\delta^{11}\text{B}_{\text{sw}}$ and the uncertainty in the calibration of Evans et al. (2015b). The corrected Mg/Ca data imply 6°C of precursor cooling at $\sim 33.9 \text{ Ma}$. (c) ODP Site 744 benthic foraminifera $\delta^{18}\text{O}$ (Zachos et al., 1996). Note that the inter-sample Mg/Ca and $\delta^{11}\text{B}_{\text{sw}}$ error (i.e. the relative differences) is far smaller than shown.