A novel approach to dissolution correction of Mg/Ca–based paleothermometry in the tropical Pacific

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[1] Mg/Ca in planktonic foraminifers carries two main signals: calcification temperature and postdepositional test dissolution. Shell dissolution thus distorts water temperature reconstructions made with Mg/Ca in foraminifers. This problem could be resolved by quantifying the impact of carbonate dissolution on Mg/Ca with an independent, temperature-insensitive deep-sea calcite dissolution proxy, such as the Globorotalia menardii fragmentation index (MFI). To test the validity of this approach, we measured Mg/Ca in the tests of several planktonic foraminifers and MFI in core tops collected over a wide geographic region of the tropical Pacific and covering a wide range of deep-sea calcite dissolution and seawater temperature. We confirm that Mg/Ca from different species have different susceptibility to temperature and dissolution. Mg/Ca in surface-dwelling Globigerina bulloides is controlled by calcification temperature and is largely unaffected by carbonate dissolution estimated from MFI. In contrast, Mg/Ca in deeper dwelling G. menardii is minimally sensitive to temperature and dominantly affected by dissolution. Mg/Ca in Neogloboquadrina dutertrei and Pulleniatina obliquiloculata are significantly affected by both temperature and dissolution, and MFI can be effectively used to correct temperature estimates from these species for calcite dissolution. Additional variables besides temperature and dissolution appear to control Mg/Ca in Globorotalia tumida, and their identification is a prerequisite for interpreting elemental shell composition in this species. Combining down-core measurements of Mg/Ca in multiple foraminifer species with MFI provides a powerful tool for reconstructing past changes in the upper water column temperature structure in the tropical Pacific.


1. Introduction

[2] Mg/Ca in planktonic foraminifers is widely used as a proxy for seawater temperature but it carries a double signal: (1) one for temperature in foraminifer habitat waters [Nürnberg, 1995; Nürnberg et al., 1996; Rosenthal et al., 1997; Mashiotha et al., 1999; Lea et al., 1999; Elderfield and Ganssen, 2000; Lea et al., 2000; Rosenthal and Lohmann, 2002; Dekens et al., 2002; Lear et al., 2002; Anand et al., 2003] and (2) one for postdepositional dissolution of foraminifer shells [Brown and Elderfield, 1996; Rosenthal et al., 2000; Dekens et al., 2002; Rosenthal and Lohmann, 2002; de Villiers, 2003; Mekik and François, 2006, Regenberg et al., 2006; Fehrenbacher et al., 2006]. This is problematic because the dissolution signal distorts seawater temperature estimates made with Mg/Ca from foraminifer shells. In an attempt to resolve this problem, we explore the possibility of quantifying the contribution of dissolution to Mg/Ca recorded in foraminifer shells by combining Mg/Ca measurements with an independent and temperature-insensitive deep sea calcite preservation proxy that can be easily measured in down core sediment samples.

[3] Our research objectives in this study are (1) to confirm and further quantify the influence of calcite dissolution on Mg/Ca in tests of planktonic foraminifers living at different depths in the water column and (2) to establish whether temperature estimates made with Mg/Ca can be corrected for dissolution using the recently developed Globorotalia menardii fragmentation index (MFI) [Mekik et al., 2002] as an independent calcite dissolution proxy.

2. Background

2.1. Mg/Ca in Planktonic Foraminifers

[4] The seminal works of several researchers have demonstrated the potential of Mg/Ca in planktonic foraminifers as a reliable seawater temperature proxy [e.g., Nürnberg, 1995; Nürnberg et al., 1996; Rosenthal et al., 1997; Hastings et al., 1998; Rosenthal et al., 2000; Elderfield and Ganssen, 2000; Lea et al., 1999, 2000; Anand et al., 2003] (the work of Lea et al. [1999] and Anand et al. [2003] was with sediment traps), but postdepositional calcite dissolution was quickly identified as a possible complicating factor [e.g., Brown and Elderfield, 1996; Rosenthal et al., 2000; Rosenthal and Lohmann, 2002; Dekens et al., 2002; de Villiers 2003; Fehrenbacher et al., 2006; Regenberg et al., 2006; Mekik and François, 2006].

[6] Dekens et al. [2002] illustrated the dissolution effects on Mg/Ca from Globigerinoides ruber, Globigerinoides sacculifer and Neogloboquadrina dutertrei and derived multiple equations which correct Mg/Ca–based temperature estimates for $\Delta$CO$_3^-$ (which is [CO$_3^-$]) of in situ waters minus the [CO$_3^-$] at saturation) in core tops with wide geographic distribution. Furthermore, Dekens et al. [2002] described the two surface dwellers, G. ruber and G. sacculifer, as having a smaller dissolution signal than the thermocline dweller, N. dutertrei. While Fehrenbacher et al.’s [2006] work seems to confirm this, Regenberg et al. [2006] found significant decrease in Mg/Ca in G. ruber and G. sacculifer with increasing carbonate ion undersaturation in core tops from the Caribbean.

[7] de Villiers [2003] used Mg/Ca in G. ruber and G. sacculifer to illustrate the effect of dissolution in down core work on the OJP by comparing the trends in Mg/Ca with Le and Shackleton’s [1992] fragmentation index data and G. sacculifer shell weight. However, neither dissolution proxy used in this study (fragmentation percent and shell weight) quantifies percent calcite dissolved. Instead they show relative dissolution variability in down core work.

[8] Instead of using an independent estimator of calcite dissolution, Fehrenbacher et al. [2006] used cores taken along a depth transect on the Ceara Rise and applied Dekens et al.’s [2002] equations down core. Assuming that $\Delta$CO$_3^-$ is the sole driver of dissolution in their samples and that the shallowest core experienced minimal or no dissolution, they reconstructed deep sea carbonate chemistry between the modern and the Last Glacial Maximum.

[9] Our present contribution to this growing body of knowledge on both temperature and dissolution effects on foraminifer Mg/Ca is in testing whether MFI can be used to independently quantify the decrease in Mg/Ca induced by calcite dissolution when making temperature estimates. MFI quantifies the percent of calcite dissolved in individual samples, not just the relative change in preservation, and takes into account dissolution resulting from undersaturation in the water column and metabolic CO$_3^-$ generation in sediment. The method is also not restricted to depth transects and can be applied to individual cores.

2.2. Tracing Deep Sea Calcite Dissolution

[10] Most deep sea calcite dissolution proxies, whether solely based on foraminifer shell weight/fragmentation or chemistry, are calibrated against CO$_3^-$ saturation of bottom waters [e.g., Broecker and Clark, 1999, 2001a, 2001b, 2003; Dekens et al., 2002; Marchitto et al., 2005; Regenberg et al., 2006; Fehrenbacher et al., 2006]. However, the organic carbon flux reaching the seabed is also an important contributor to calcite dissolution in sediments, which results from the regeneration of metabolic CO$_2$ in pore waters [Emerson and Bender, 1981]. More precisely it is the ratio of organic carbon to calcite fluxes reaching the seabed (rain ratio) that drives dissolution in addition to $\Delta$CO$_3^-$ [Archer and Maier-Reimer, 1994; Mekik et al., 2002, 2007]. It is thus imperative to take organic carbon fluxes into account when quantifying calcite dissolution, particularly in regions with large spatial variations in carbon flux.

[11] We choose the G. menardii fragmentation index (MFI) [Mekik et al., 2002] as our independent calcite dissolution proxy because it has been calibrated against model-derived estimates of percent calcite dissolved. The model (Muds) [Archer et al., 2002] takes into account both bottom water $\Delta$CO$_3^-$ and respiratory calcite dissolution in the sediments [Mekik et al., 2002, 2007] when calculating percent calcite dissolved for each coring location. Subsequent to MFI’s calibration, Mekik and François [2006] demonstrated clear, linear relationships between Mg/Ca in P. obliquiloculata and G. menardii shells and both bottom water $\Delta$CO$_3^-$ and MFI-based percent calcite dissolved estimates for core top samples on the OJP (where variations in sea surface temperatures are minimal), and thereby independently corroborated the validity of MFI as a dissolution proxy. Later, F. Mekik and L. Raterink (Effects of surface ocean conditions on the quantification of deep sea calcite dissolution using shell weight and fragmentation on planktonic foraminifers, submitted to Paleoceanography, 2007, hereinafter referred to as Mekik and Raterink, submitted manuscript, 2007) found no clear correlation between MFI and water temperature at 75 m depth for samples subjected to similar dissolution (Figure 1) indicating that MFI clearly meets our criteria of temperature insensitivity.

3. Methods

3.1. Sampling Method

[12] We used 56 core top samples from the eastern equatorial Pacific (EEP) and OJP (Figure 2) to generate MFI and Mg/Ca data from five species of planktonic foraminifers: Globigerina bulloides, Pullemnaitia obliquiloculata, Globorotalia tumida, G. menardii and N. dutertrei. These regions provide samples subjected to a wide range of sea surface temperature and deep sea calcite dissolution which is useful for isolating their respective effects on Mg/Ca of foraminifer shells. The OJP, in particular, provides a test area where temperature is almost invariable, but where there is a strong gradient of dissolution with water depth. All Mg/Ca data from the EEP and Mg/Ca from G. bulloides are new. Mg/Ca data from OJP for the other four species were published by Mekik and François [2006].

[13] All samples are from gravity cores to minimize core top disturbance. About half of our samples overlap with those used by Loubere [2001] who measured $\delta^{18}$O and $\delta^{13}$C from N. dutertrei shells. The regional $\delta^{18}$O and $\delta^{13}$C map produced by Loubere [2001] confirms that our core tops are modern. Mekik et al. [2007] generated additional $\delta^{18}$O data for five of our deepest cores and excluded two of these five samples because their $\delta^{18}$O were more consistent with LGM...
values. Further corroboration that our samples are modern come from the rain ratio maps [Mekik et al., 2002, 2007] generated from most of the same samples used herein, which show regional surface ocean productivity patterns consistent with satellite-based productivity estimates [Behrenfeld and Falkowski, 1997] for the EEP.

[1] One of the species we analyzed, G. bulloides, is a surface dweller (0–60 m habitat depth [Schiebel et al., 1997]), and the other four are thermocline dwellers: P. obliquiloculata (50–100 m [Anand et al., 2003] and 50 m [Farmer et al., 2007]), G. menardii (50–100 m [Be, 1960] and 75 m [Farmer et al., 2007]), N. dutertrei (50–100 m [Anand et al., 2003] but most common in the deep chlorophyll maximum [Fairbanks et al., 1982; Fairbanks and Wiebe, 1980; Loubere, 2001]) and G. tumida (50–100 m, [Schweitzer and Lohmann, 1991] and 135–175 m [Farmer et al., 2007]). All five foraminifers typically prefer tropical and subtropical regions (H. Hilbrecht, Extant planktic foraminifera and the physical environment in the Atlantic and Indian Oceans, Mitteilungen aus dem Geologischen Institut der Eidgenossische Technische Hochschule and Universitat Zürich, Neue Folge 300, 93 pp., Zurich, Switzerland, 1996, available at http://www.ngdc.noaa.gov/mgg/geology/hh1996/, hereinafter referred to as Hilbrecht, report, 1996), except G. bulloides which is common in northern and southern high latitudes as well as upwelling zones in the tropics [Brock et al., 1992; Duplessy et al., 1981; Hemleben et al., 1985; Kipp, 1976; Theide, 1983; van Leeuwen, 1989; Zhang, 1985; Hilbrecht, report, 1996]. High- and low-latitude populations of this species may be distinct [Schmidt and Mulitza, 2002; Kucera and Darling, 2002; Darling et al., 2003], and cryptic species may be present within each population [Darling et al., 2003].

[15] All temperature estimates for surface waters are from Locarnini et al. [2006]. Our full temperature, Mg/Ca and MFI data set, including the number of foraminifers used per measurement, are available as online auxiliary material\footnote{Auxiliary materials are available at ftp://ftp.agu.org/apend/pa/2007pa001504.}. We selected the habitat depths for each species by looking for the best relationship between Mg/Ca and temperature estimates at 30, 50, 75, 100 and 125 m. For G. bulloides, the best relationship is obtained with temperature at 30 m which fits well with the habitat depth reported by Schiebel et al. [1997]; for P. obliquiloculata, the best fit is at 50 m which is corroborated by Farmer et al.’s [2007] work; for G. menardii, we obtain a depth of 75 m which matches Farmer et al.’s [2007] estimate; and for G. tumida the best fit is at 125 m water depth, which is also the medial value between the habitat depth estimates for this species by Schweitzer and Lohmann [1991] and Farmer et al. [2007]. On the other hand, we are unable to find a good statistical relationship between Mg/Ca in N. dutertrei shells and temperature at any uniform depth. N. dutertrei are known to prefer the deep chlorophyll maximum [Fairbanks et al., 1982; Fairbanks and Wiebe, 1980], and habitat depths for this species were estimated using Loubere’s [2001] isotopic equilibrium depths based on a combination of $\delta^{18}$O and $\delta^{13}$C from N. dutertrei shells. For samples beyond Loubere’s [2001] data set (those from the OJP and some samples from the EEP) the average temperature between 50 and 75 m is used because this is the general habitat depth range for N. dutertrei in Loubere’s [2001] work.

3.2. Sample Preparation

[16] Foraminifers were picked within small size ranges (~100 $\mu$m or smaller) but from larger foraminifer size groups than is commonly used in Mg/Ca work [e.g., Anand...
standard solutions gravimetrically and all standard and sample solutions were made with 0.075 M nitric acid. We measured $^{44}$Ca to determine [Ca] in all standards and samples. Matrix effects on Mg/Ca and polyatomic interferences on Ca are insignificant in the concentration ranges we used in our analyses [Rosenthal et al., 1999].

We made duplicate measurements by dissolving two separately picked and cleaned foraminifer populations from each species, in each sediment sample where we had sufficient number of foraminifers within our designated size ranges. Figure 3 illustrates the reproducibility between all our duplicates in relation to the analytical error associated with each measurement. In Table 1, $\phi$ represents the difference between two replicate Mg/Ca measurements for the same species in the same sediment sample. Mean $\phi$ for all measurements is 0.12 mmol/mol, and the standard deviation in $\phi$ for all measurements is 0.1 mmol/mol. The variation coefficient of Mg/Ca in Table 1 is the ratio of the standard deviation for $\phi$ in each species to the mean Mg/Ca from all measurements on that species, represented as a percentage. Analytical error margins for all data points (shown as bars on all graphs) are calculated on counting statistics (66% confidence interval) for the ratio of Mg and Ca to our internal standard (indium) and the uncertainties on the intercept and slope of the linear regressions obtained with our standard solutions.

### 4. Results

#### 4.1. *Globigerina bulloides*

[20] Figure 4a shows a strong relationship between Mg/Ca in *G. bulloides* and sea surface temperature at 30 m water depth in samples from the EEP and OJP. We observe a spread of Mg/Ca values (Mg/Ca “tail”) at ~29°C. These samples are from the OJP and represent a wide range of calcite dissolution. The data in Figure 4a are color-coded to reflect the extent of dissolution to which each sample was subjected. MFI’s error margin is 10–15% dissolved [Mekik et al., 2002]. We used that margin as the width of our dissolution brackets.

[21] A clear dissolution signal would be documented by a gradual color transition from red to green, which is not observed. This indicates that while Mg/Ca in *G. bulloides* is sensitive to temperature, it is not systematically affected by postdepositional dissolution. This is confirmed by the lack of correlation between Mg/Ca and MFI-based percent dissolved estimates (Figure 4b). Color coding clearly documents the overwhelming influence of temperature. Dekens et al. [2002] found a similar sensitivity to temperature and hardly any sensitivity to dissolution in their work with Mg/Ca from

### Table 1. Mean $\phi$ and Variation Coefficients for Mg/Ca in Five Species

<table>
<thead>
<tr>
<th>Foraminifer</th>
<th>Mean $\phi$, mmol/mol</th>
<th>Variation Coefficient, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>G. bulloides</em></td>
<td>0.13</td>
<td>2.9</td>
</tr>
<tr>
<td><em>P. obliquiloculata</em></td>
<td>0.09</td>
<td>4</td>
</tr>
<tr>
<td><em>G. menardii</em></td>
<td>0.13</td>
<td>6.6</td>
</tr>
<tr>
<td><em>N. dutertrei</em></td>
<td>0.16</td>
<td>8.8</td>
</tr>
<tr>
<td><em>G. tumida</em></td>
<td>0.1</td>
<td>6.5</td>
</tr>
</tbody>
</table>
4.1. *G. ruber* and *G. sacculifer*, both of which are also surface dwellers. In contrast, Regenberg et al. [2006] found a significant dissolution influence on Mg/Ca in *G. ruber* and *G. sacculifer.

4.2. *Pulleniatina obliquiloculata*  
[22] Figure 5 illustrates plots of Mg/Ca from *P. obliquiloculata* shells versus temperature at 50 m water depth and Mg/Ca versus MFI-based percent calcite dissolved in samples from the EEP and OJP. We use the same color coding to identify the impact of calcite dissolution on the temperature signal (Figure 5a), and a similar color code to reflect the impact of temperature on the dissolution signal in Mg/Ca (Figure 5b). On the temperature graph (Figure 5a) we can identify several dissolution tails (at 24°C, 25°C and 29°C) which display a clear color transition. For a given temperature, the samples subjected to higher dissolution clearly have lower Mg/Ca (green). Likewise when we plot Mg/Ca versus MFI-based percent calcite dissolved (Figure 5b), we can see clear grouping of colors and numerous temperature tails with easily observable color transitions. These results indicate that Mg/Ca in *P. obliquiloculata* is systematically affected by both calcification temperature and postdepositional calcite dissolution.

4.3. *Globorotalia tumida*  
[23] Figure 6 shows the relationship between Mg/Ca from *G. tumida* shells and temperature at 125 m and MFI-based...
percent calcite dissolved. The correlation with temperature is weak, and a wide spread of Mg/Ca values are found at 26°C. Color coding (Figure 6a) indicates that this tail bears a weak relationship with dissolution. Correlation between Mg/Ca and MFI for this species (Figure 6b) is also weak. Factors besides temperature and dissolution that are yet to be identified thus appear to also affect the Mg/Ca of this species significantly.

4.4. Neogloboquadrina dutertrei

[24] Plotting Mg/Ca in *N. dutertrei* shells versus temperature (Figure 7a) at *N. dutertrei* habitat depths (data for habitat depths from Loubere [2001]) shows a strong correlation with temperature and possible but ambiguous dissolution tails. This suggests that temperature may have a significant effect on the Mg/Ca for this species. However, we also obtain a significant correlation when plotting Mg/Ca against MFI-based percent calcite dissolved (Figure 7b) and several temperature tails are clearly visible at ~45%, 62% and 76% dissolved.

4.5. Globorotalia menardii

[25] Plotting Mg/Ca in *G. menardii* shells against temperature at 75 m (Figure 8a) results in a poor correlation and clear dissolution tails are identified by progressive color transitions at 23°C, 24°C and 29°C. On the other hand, we find a good linear relationship between Mg/Ca in this species and MFI-based percent calcite dissolved (Figure 8b) with little evidence for significant temperature tails, indicating
that Mg/Ca for this species is mainly controlled by calcite dissolution.

5. Discussion

5.1. Is Dissolution Significantly Affecting Mg/Ca?

[26] Our results show that the strength of the dissolution signal in Mg/Ca from foraminifer shells is species-specific (as demonstrated by other studies such as Dekens et al. [2002], Fehrenbacher et al. [2006], and Regenberg et al. [2006]). G. bulloides Mg/Ca shows no relationship with MFI-based percent dissolved estimates in samples from the EEP and the OJP (Figure 4b). According to Dekens et al. [2002], it is not uncommon for surface dwellers (G. ruber and G. sacculifer in their work) to be more sensitive to temperature and much less so to dissolution or $\Delta$CO$_2$. This is good news for SST reconstructions because the Mg/Ca of surface dwellers may not require correction for calcite dissolution. However, Regenberg et al.’s [2006] results contradict this finding and the generality of this conclusion requires further assessment. We observe variations in Mg/Ca in G. bulloides in OJP samples (2.72–3.5 mmol/mol, Figure 4a) that are 1 order of magnitude larger than the mean reproducibility between G. bulloides sample duplicates (2.2%) where surface ocean temperatures at 30 m are mostly invariable (29.1°C–29.3°C). Elucidating the cause of this variation requires further study. Although McConnell and Thunell [2005] have shown in sediment trap work that Mg/Ca in G. bulloides records seawater temperatures as high as 33°C, it is plausible that the OJP is at the upper limit of temperature sensitivity of Mg/Ca in G. bulloides shells since this species is more typical of high-latitude regions.
and upwelling zones in tropical seas [Brock et al., 1992; Duplessy et al., 1981; Hemleben et al., 1985; Kipp, 1976; Thiede, 1983; van Leeuwen, 1989; Zhang, 1985; Hilbrecht, report, 1996]. Another possibility is that there are cryptic species of G. bulloides on the OJP. Kucera and Darling [2002] describe 6 genetically distinct groups in the G. bulloides morphotype. Also, Darling et al.'s [2003] study clearly demonstrates multiple cryptic species among G. bulloides in the Santa Barbara Channel. Thus undetected cryptic species or genotypes may also be at play in the OJP, however accurately resolving this issue requires the generation of genetic data which is beyond the scope of our work.

In contrast to G. bulloides, we see a clear influence of dissolution on the Mg/Ca of the four deeper dwelling foraminifer species. We observe clear tails in the temperature versus Mg/Ca graphs for P. obliquiloculata which can clearly be related to dissolution (Figure 5). Similar but less defined tails are also present in the graphs for N. dutertrei (Figure 7). Plotting MFI-based percent dissolved against Mg/Ca from G. menardii (Figure 8b) shows a strong linear relationship between MFI-based percent calcite dissolved estimates. This suggests that Mg/Ca in this species, like MFI, may serve as an independent and mostly temperature-insensitive calcite dissolution proxy but more data from geographically diverse regions is needed to corroborate this finding. Mg/Ca for G. tumida, which has keeled shells and belongs to the same genus, Globorotalia, as G. menardii, appears to be affected both by temperature and dissolution; but poorer correlations (Figure 6) suggest that at least one other factor is also having an important impact. This factor could be one of many variables such as: (1) Variations in surface ocean salinity. However, early studies have shown that salinity is a minor factor controlling Mg/Ca ratios in foraminifers until salinity variations of 10% or more are reached [Nürnberg et al., 1996; Lea et al., 1999]. Salinity variability across our entire study region in the EEP is about 1% [Antonov et al., 2006] so this is an unlikely effect on our results. (2) Cryptic species within our G. tumida population. There is evidence of cryptic speciation among Globorotaliids [Norris et al., 1996], though this has not been specifically related to G. tumida. While this may likely be affecting our results, it is very difficult to ascertain without genetic data. (3) Globorotaliids tend to calcify in multiple water depths during their lifetime [Elderfield et al., 2002] and therefore their shell chemistry may be recording multiple temperatures.

5.2. Can Mg/Ca–Based Temperature Estimates be Corrected for Dissolution?

While Mg/Ca of surface dweller G. bulloides does not require a dissolution correction to evaluate surface temperature, our data clearly indicate that this is not the case for deeper dwelling P. obliquiloculata and N. dutertrei. Quantifying the effect of calcite dissolution is a prerequisite before using the Mg/Ca ratio of these species to estimate their temperature of calcification and potentially reconstruct past changes in thermocline temperature. We attempt to address this problem in two ways: (1) by multiple regression analysis and (2) by grouping our samples into dissolution brackets (10–15% dissolved) and deriving individual Mg/

![Figure 10. Mg/Ca in N. dutertrei versus temperature in three dissolution brackets defined by MFI.](image-url)
Ca–based temperature equations within each dissolution bracket.

[29] We performed multiple linear regression analysis using water temperature and MFI-based percent calcite dissolved as two independent variables against Mg/Ca as the dependent variable.

[30] For G. bulloides, the linear regression coefficient for percent dissolved is zero, confirming that calcite dissolution has insignificant impact on the Mg/Ca of this species.

[31] For P. obliquiloculata, the correlation between measured and predicted Mg/Ca improves markedly when taking into account both temperature and percent dissolved ($R^2 = 0.93$ versus $R^2 = 0.80$ for temperature alone, Figure 9). The equation derived from the multiple linear regression ($T = (Mg/Ca + (0.15%\text{diss}) + 1.7)/0.17$; where percent diss is the MFI-based estimate of calcite percent dissolution) provides a means of calculating temperature at 50 m depth from Mg/Ca in P. obliquiloculata and MFI.

[32] On the other hand, for N. dutertrei, the linear regression does not improve when taking into account dissolution in addition to temperature ($R^2 = 0.83$ versus $R^2 = 0.86$ for temperature alone). However, we note a systematic decrease in the temperature sensitivity of N. dutertrei Mg/Ca with increasing calcite dissolution (Figure 10), which may explain the failure of the multiple linear regression. Reconstruction of temperature at the chlorophyll maximum using Mg/Ca in this species may thus be better achieved by using different temperature equations for different levels of calcite dissolution, but more data are needed to consolidate the preliminary calibrations reported in Figure 10.

[33] The regression for Mg/Ca in G. tumida is slightly improved when taking into account both temperature and dissolution but remains comparatively weak ($R^2 = 0.72$ versus $R^2 = 0.68$ for temperature alone). Dissolution has a noticeable effect (e.g., a 50% change in dissolution generates a change in Mg/Ca equivalent to 5°C), but the lower regression coefficients suggest that factor(s) yet to be identified affect the Mg/Ca of this species significantly.

[34] In contrast to the other species studied here, Mg/Ca in G. menardii depends almost only on calcite dissolution. The linear regression marginally improves when taking into account temperature in addition to dissolution ($R^2 = 0.83$ versus $R^2 = 0.80$ for dissolution alone, Figure 11). Temperature has thus a noticeable effect on the Mg/Ca of this species but it is very small (a 10°C change in temperature produces a change in Mg/Ca equivalent to 7% changes in calcite dissolution). The equation percent diss = (2.9–Mg/Ca + (0.02 T))/0.028 could be used to take into account this small effect, if temperature can be independently estimated.

Figure 11. Correlation between measured and predicted Mg/Ca (mmol/mol) in G. menardii using (a) only temperature as the independent variable and (b) both temperature and MFI-based percent calcite dissolved as independent variables.

Figure 12. Schematic summary diagram showing relative sensitivity index (I) values for each species.
5.3. Comparison of Interspecific Sensitivity to Temperature and Dissolution in Mg/Ca from Foraminifer Tests

[35] Figure 12 is a schematic summary diagram illustrating the relative sensitivity of the species examined herein to temperature as one end-member and dissolution as the other. Relative sensitivities were quantified by calculating the change in Mg/Ca resulting from a 10°C change in temperature (Δ(Mg/Ca)°) and from a 50% change in calcite dissolution (Δ(Mg/Ca)D) using the equations obtained from multiple linear regression (Table 2). A relative sensitivity index (I) was calculated as

\[ I = \frac{\Delta(Mg/Ca)^T}{\Delta(Mg/Ca)^T + \Delta(Mg/Ca)^D} \]

[36] G. bulloides Mg/Ca does not carry a significant dissolution signal and has a relative sensitivity index of 1. A species whose Mg/Ca would be affected by dissolution and totally independent of temperature would have a relative sensitivity index of zero. Data compiled in Table 2 indicate that the importance of calcite dissolution increases from P. obliquiloculata (I = 0.69), to G. tumida (I = 0.66), N. dutertrei (I = 0.54), and G. menardii (I = 0.12) (Figure 12).

6. Conclusions

[37] Mg/Ca in tests of G. bulloides, P. obliquiloculata, G. menardii, N. dutertrei and G. tumida has species-specific responses to calcification temperature and postdepositional dissolution. We can use MFI as a temperature-insensitive independent calcite dissolution proxy to quantify the dissolution signal in Mg/Ca and correct temperature estimates made with Mg/Ca ratios for dissolution.

[38] Mg/Ca from G. bulloides, a surface dweller, has strong sensitivity to temperature and no quantifiable relationship with MFI-based percent dissolved estimates (Figure 4). Mg/Ca in this species, as for other surface dwellers, appears to provide a pure temperature signal although some variability beyond analytical error remains unexplained.

[39] The other four foraminifers analyzed are all thermocline dwellers. P. obliquiloculata has the strongest sensitivity to temperature but also carries a significant dissolution signal (Figure 5). Multiple linear regression taking into account temperature and calcite dissolution provides an equation which explains nearly all the variability in Mg/Ca in our samples (R² = 0.93, Figure 9b) and which can be used to reconstruct past changes in upper thermocline temperature. Mg/Ca in N. dutertrei shells also carries both a temperature and a dissolution signal, but is significantly less sensitive to temperature (Figure 7) than Mg/Ca in P. obliquiloculata. There is also a clear decreasing trend in temperature sensitivity with dissolution (Figure 10). We derived preliminary calibration curves to reconstruct temperature with Mg/Ca in N. dutertrei within three calcite dissolution brackets which could be used to estimate past changes in seawater temperature at the deep chlorophyll maximum. The validity of these equations still needs to be further tested. Mg/Ca from G. tumida is also sensitive to temperature and dissolution (Figure 8) but these two variables alone cannot explain all the variability observed (R² = 0.72). The usefulness of this species hinges on the identification and quantification of the additional factor(s) affecting its Mg/Ca. Finally, Mg/Ca from G. menardii is most sensitive to calcite dissolution but carries a small temperature signal (Figure 12). Mg/Ca from G. menardii is not useful for reconstructing thermocline temperature but could help in reconstructing calcite dissolution, like MFI, if thermocline temperatures can be independently estimated.

[40] Combining temperature reconstructions using Mg/Ca from these different species and MFI will provide important information on the evolution of upper water column thermal structure of low-latitude oceans.

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