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## Temperature calibration of Mg/Ca ratios in the intermediate water benthic foraminifer *Hyalinea balthica*

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[1] Core top samples from Indonesian and northeast Atlantic depth transects were used to calibrate Mg/Ca and  $\delta^{18}\text{O}$  in tests of the calcitic benthic foraminifer *Hyalinea balthica* to bottom water temperature between 4°C and 13°C. This shallow infaunal species is primarily abundant in neritic to upper bathyal sediments (<600 m). Both linear and exponential calibrations suggest a temperature sensitivity of ~12% per °C that is ~4 times higher than observed in other species of deep-sea benthic foraminifera. Culture experiments support the core top calibration. We find no discernible effect of salinity and saturation on Mg/Ca. Comparison between the measured benthic foraminiferal  $\delta^{18}\text{O}$  and predicted equilibrium values suggests that on average *H. balthica*  $\delta^{18}\text{O}$  is 0.64‰ ± 0.13‰ lower than predicted from

the equilibrium composition. To test the reliability of using paired *H. balthica* Mg/Ca and  $\delta^{18}\text{O}$  measurements for reconstructing seawater  $\delta^{18}\text{O}_{\text{sw}}$  and salinity, we apply this calibration to another depth transect from Cape Ghir off NW Africa, which was not included in the calibration. Based on error analysis of the calibration data and this validation test, we show that the uncertainty of reconstructing bottom water temperature and salinity from paired Mg/Ca and  $\delta^{18}\text{O}$  measurements of *H. balthica* is better than  $\pm 0.7^\circ\text{C}$  and  $\pm 0.69$  practical salinity scale, respectively. The small uncertainties allow for the reconstruction of seawater density to better than  $0.3\sigma_\theta$  units, which is precise enough for the identification of specific water masses and reconstruction of changes in their properties. We propose that the relatively high Mg content and temperature sensitivity of *H. balthica* might be due to minor, biologically mediated contribution of high-Mg calcite to the primarily low Mg calcite test, which is influenced by the ambient temperature. This hypothesis, if correct, suggests that benthic species with relatively high Mg/Ca may be better suited for deepwater temperature reconstructions than species that have thus far been more commonly used.

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## 1. Introduction

[2] Much of our understanding of the distribution of deepwater masses in the modern ocean comes from temperature and salinity measurements. This is because these two parameters uniquely define a water mass, which allows the identification of the contribution of different end-members to a water parcel and inferring circulation patterns. It is no surprise, therefore, that large efforts have been dedicated to developing geochemical proxies for temperature and salinity, which could provide similar capabilities for paleoceanographic studies. The magnesium to calcium ratio (Mg/Ca) in benthic foraminifera is currently the only proxy that allows for reconstruction of bottom water temperatures (BWTs) [Rosenthal *et al.*, 1997b]. When used with paired measurements of foraminiferal  $\delta^{18}\text{O}$ , it enables quantitative reconstructions of seawater  $\delta^{18}\text{O}$ , and with judicious assumptions, global ice volume and past ocean circulation. Indeed this method has provided new insights into the evolution of Earth's climate through the Cenozoic [e.g., Billups and Schrag, 2002; Billups, 2003; Lear *et al.*, 2000, 2004; Martin *et al.*, 2002].

[3] Initial calibrations of *Cibicidoides* spp. suggested a strong exponential dependence of Mg/Ca in these benthic foraminifera on temperature, with similar sensitivity to that observed in planktonic

foraminifera [Lear *et al.*, 2002; Rosenthal *et al.*, 1997b]. However, subsequent calibrations that supported a temperature effect on Mg/Ca also raised concerns about the precise relationship between BWT and Mg/Ca. First, a calibration of *C. pachyderma* from the Florida Straits suggested a dominant temperature control on Mg/Ca in the temperature range of  $\sim 6^\circ\text{C}$  to  $19^\circ\text{C}$  with a sensitivity of  $\sim 0.12 \text{ mmol mol}^{-1} \text{ per } ^\circ\text{C}$  [Marchitto *et al.*, 2007]. The higher temperature sensitivity suggested by the earlier studies [Lear *et al.*, 2002; Rosenthal *et al.*, 1997b] was attributed to contamination of the foraminiferal tests by secondary high-Mg overgrowths, which are common in Bahama Banks sediments [Curry and Marchitto, 2008]. The low temperature sensitivity implied a relatively large error in estimating BWT from Mg/Ca measurements in this species. For example, Marchitto *et al.* [2007] reported a standard error of estimate (SEE) of  $2.4^\circ\text{C}$  for their *C. pachyderma* calibration. This large error is a major hindrance for reconstructing seawater salinity from paired Mg/Ca and  $\delta^{18}\text{O}$  measurements in benthic foraminifera.

[4] A second complication is the evidence that at the colder end of the calibration, there is a significant carbonate-saturation effect (hereafter referred as  $\Delta[\text{CO}_3]$  effect) on benthic Mg/Ca [Martin *et al.*, 2002]. At low carbonate saturation levels (typically

$\Delta[\text{CO}_3]$  below  $20 \mu\text{mol kg}^{-1}$ ) [Elderfield *et al.*, 2006], the decrease in saturation has an increasingly larger effect on the Mg content of *Cibicidoides* tests, thus complicating BWT reconstructions. Above this threshold, the  $\Delta[\text{CO}_3]$  effect is arguably minimal [Elderfield *et al.*, 2006].

[5] Here we report a new Mg/Ca calibration in the foraminifer *Hyalinea balthica*, a shallow infaunal benthic species typically found in the temperature range of  $\sim 4^\circ\text{C}$ – $12^\circ\text{C}$ , and thus suitable for reconstructing the temperature of intermediate water masses. Furthermore, below we show that the temperature sensitivity of this species is apparently  $\sim 4$  times higher than found in *Cibicidoides* species. The low SEE of this calibration and lack of discernible  $\Delta[\text{CO}_3]$  effect not only allow for precise determination of past BWT, but also for reconstructing salinity with sufficient precision for estimating paleodensity, much in the way it is done in the modern ocean.

## 2. Ecology and Biogeography

[6] *Hyalinea balthica* (Schroeter) was first identified in 1783 in Recent sediments recovered from the Baltic Sea [Schroeter, 1783]. Its compressed, planispiral test typically has 9–12 chambers in the final whorl, with curved limbate sutures and a peripheral imperforate keel (Figure 1). It has an interiomarginal primary aperture with a thickened lip, and secondary apertures beneath umbilical flaps on both sides of the test [Murray, 1971]. *Hyalinea balthica* evolved in the late Pliocene, and has been recorded in the Atlantic, Pacific, and Indian Oceans, Gulf of Mexico, and Caribbean, Barents, North, and Mediterranean Seas. In the modern ocean, *H. balthica* is most abundant in cooler waters of the North Atlantic [van Morkhoven *et al.*, 1986]. It is primarily a neritic to upper bathyal species ( $< 600\text{m}$ ), but occasionally ranges as deep as  $\sim 1250\text{m}$  [Murray, 1971; van Morkhoven *et al.*, 1986].

[7] *Hyalinea balthica* has a preference for shallow infaunal microhabitats in the topmost sediment levels, where maximum densities are found [e.g., Fontanier *et al.*, 2002, 2008; Hess and Jorissen, 2009]. However, often some specimens are also present in deeper sediment layers, down to the zero oxygen level. Hess and Jorissen [2009] described uncommonly high densities of *H. balthica*, of about 1400 live specimens in a  $72 \text{ cm}^2$  core, at a 450 m deep site in Cape Breton canyon, on the French Atlantic coast. At this station, *Bolivina subaenariensis* (68%) and *H. balthica* (16%) strongly dominated the

extremely rich benthic foraminiferal faunas. According to Hess and Jorissen [2009], this low-diversity fauna, with a very low evenness, represented an early stage of ecosystem colonization following turbidite deposition. Consequently, they considered *H. balthica* as an opportunistic taxon, profiting from increased food availability by reproduction and increased growth rates. This interpretation is corroborated by the dominance of *H. balthica* in the faunas following the low-oxygen event S1 in the Aegean Sea, observed in cores from 260 m and 430 m depth [Abu-Zied *et al.*, 2008]. In a core from the Ionian Sea, sampled at 2345 m depth, *H. balthica* was the first colonizing taxon after the period of anoxic bottom water leading to the deposition of sapropel S5, which was totally devoid of benthic foraminifera (F. Jorissen, unpublished data, 2010). All *Hyalinea* specimens found in the first sample containing benthic foraminifera above S5 showed important test anomalies, probably due to the hostile environmental conditions encountered by these early colonizers. Finally, *H. balthica* is one of the few deep-sea benthic foraminifera that show shell growth in controlled laboratory conditions (C. Barras, unpublished data, 2010). In summary, *H. balthica* appears to be a highly opportunistic species that combines tolerance for stressed conditions with elevated reproductive rates and probably very high growth rates.

## 3. Methods

### 3.1. Study Sites

[8] Core top samples included in this study come from three regions in the Atlantic and Pacific Oceans (Figure 2): (1) Bali Basin and Makassar Straits in Indonesia (IND), (2) various sites along the northeastern Atlantic Ocean margin (ATL), and (3) Cape Ghir on the northwest African margin (CG). In the calibration, we include samples only from the first two regions to calculate the temperature-dependence of Mg uptake (Table 1). We use the same sample set to estimate the offset between measured  $\delta^{18}\text{O}$  on these samples and the expected equilibrium values. The calibrations are then applied to the third core top transect from Cape Ghir. BWTs and salinities estimated from paired benthic foraminiferal  $\delta^{18}\text{O}$  and Mg/Ca measurements on samples from this transect are compared with the hydrographic data as means of validating our calibrations and testing their accuracy. The three transects cover similar ranges in BWT, but are characterized by significantly different salinities. All the sites are overlain by supersaturated bottom water with respect to calcite (i.e.,  $\Delta[\text{CO}_3] >$



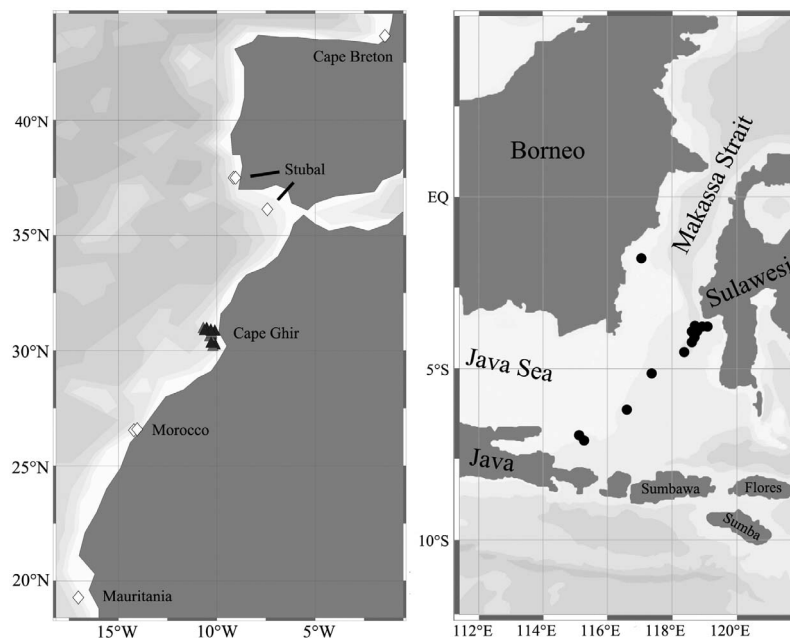
**Figure 1.** A picture of *Hylinea balthica* (source from [http://palaeo-electronica.org/2002\\_2/guide/rota.htm](http://palaeo-electronica.org/2002_2/guide/rota.htm)).

$0 \mu\text{mol kg}^{-1}$ ). Details of the study sites and sample collection are given below. The hydrographic data are based on in situ CTD casts. As can be seen in Figure 3, the Indonesian and the Cape Ghir cores represent continuous transects at these locations. In contrast, the “northeastern Atlantic” suite is a collection of samples from different sites influenced by different water masses.

### 3.1.1. Sulawesi Margins (Indonesia)

[9] The Indonesian samples come from a transect of cores on the southwestern Sulawesi margin in the Makassar Strait. All the samples were collected using a multicorer during the BJ8–03 cruise in 2003 [Rosenthal *et al.*, 2006]. Water in the main thermocline of the Makassar Strait derives pri-

marily from North Pacific Subtropical Water (NPSW) recognized as a salinity maximum at  $\sim 150$  m [Gordon, 2005]. At the bottom of the thermocline and down to  $\sim 600$  m, nearly all of the Indonesia Throughflow (ITF) water originates from North Pacific Intermediate Water (NPIW), recognized by a salinity minimum. Below that, the increase in salinity signifies the presence of modified Antarctic Intermediate Water (AAIW). Our Indonesian transect spans a range of  $\sim 330$  to  $900$  m associated with BWT, salinity and  $\Delta[\text{CO}_3]$  changes of  $\sim 16^\circ\text{C}$  to  $4^\circ\text{C}$ ,  $34.7$  to  $34.4$ , and  $\sim 140$  to  $70 \mu\text{mol kg}^{-1}$ , respectively [Rosenthal *et al.*, 2006]. Sedimentation rates are relatively high in this region ( $10$ – $100 \text{ cm kyr}^{-1}$ ) due to the large input of terrigenous sediment delivered by rivers. All core tops contain bomb radiocarbon suggesting a relatively modern age. Samples from the Indonesian cruise were Rose Bengal-stained to identify protoplasm in the tests and hence to separate “recently living” (stained) and “dead” (unstained) individuals [Corliss and Emerson, 1990]. The Indonesian samples were kept at  $\sim 4^\circ\text{C}$  until they were processed in the laboratory where they were preserved with 3.8% formalin solution containing Rose Bengal stain and buffered with Borax to  $\text{pH} \approx 8$ . The samples were then shaken in the staining solution for at least one week. The sediments were wet-sieved through  $63 \mu\text{m}$  mesh sieves, and the stained



**Figure 2.** Location map of core top sites used in this study. Solid circles and open diamonds mark sites used for the calibration in Indonesia and northeastern Atlantic, respectively. Solid triangles mark the Cape Ghir sites used for validation.



**Table 1.** Core Location, Hydrographic Data, and Mg/Ca Ratios in *H. Balthica*

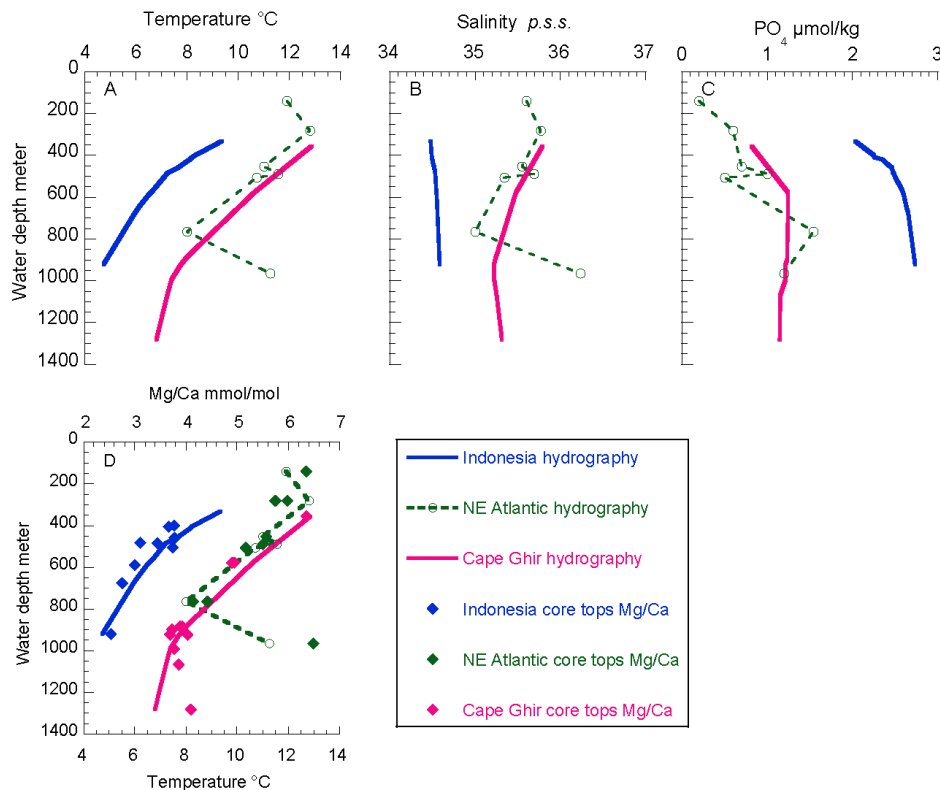
Core ID	Region	Latitude (°S)	Longitude (°E)	Water Type	Temperature Depth (°C)	Salinity	PO <sub>4</sub> (μmol/kg)	Mg/Ca <sup>a</sup> (mmol/mol)
<i>Calibration Data</i>								
BJ8-03 06MC	Indonesia, Bali Basin	-7.47	115.37	dead	920	4.74	34.583	2.73
BJ8-03 09MC	Indonesia, Bali Basin	-7.38	115.25	live	648	6.11	34.553	2.63
BJ8-03 11MC	Indonesia, Bali Basin	-7.40	115.20	live	590	6.47	34.546	2.60
BJ8-03 14MC	Indonesia, Bali Basin	-7.35	115.20	live	483	7.24	34.529	2.47
BJ8-03 16MC	Indonesia, Makassar	-7.32	115.18	dead	409	8.20	34.490	2.25
BJ8-03 20MC	Indonesia, Makassar	-6.77	116.97	dead	419	8.10	34.496	2.35
BJ8-03 24MC	Indonesia, Makassar	-5.01	117.45	dead	832	5.13	34.574	2.65
BJ8-03 31MC	Indonesia, Makassar	-3.88	119.45	dead	459	7.64	34.518	2.46
BJ8-03 33MC	Indonesia, Makassar	-3.88	119.45	dead	505	7.08	34.533	2.50
BJ8-03 35MC	Indonesia, Makassar	-3.88	119.43	dead	565	6.68	34.542	2.58
BJ8-03 45MC	Indonesia, Makassar	-3.89	119.48	dead	332	9.35	34.476	2.03
BJ8-03 49MC	Indonesia, Makassar	-3.88	119.42	dead	676	5.95	34.556	2.65
BJ8-03 56MC	Indonesia, Makassar	-3.88	119.45	live	405	8.23	34.489	2.25
BJ8-03 67MC	Indonesia, Makassar	-3.57	119.40	dead	401	8.29	34.488	2.25
BJ8-03 67MC	Indonesia, Makassar	-3.57	119.40	dead	401	8.29	34.488	2.25
BJ8-03 69MC	Indonesia, Makassar	-3.57	119.40	live	485	7.22	34.530	2.48
BJ8-03 70GGC	Indonesia, Makassar	-3.57	119.38	dead	482	7.25	34.529	2.47
BJ8-03 79MC	Indonesia, Makassar	-1.73	117.38	dead	440	7.86	34.505	2.40
MD39004-1	Gulf of Cadiz	36.23	-7.73	dead	966	11.3	36.236	1.2
S1	NW Africa, Mauritania	19.47	-17.01	dead	507	10.7	35.342	1.72
S24	NW Africa, Morocco	26.97	-14.00	dead	765	8.0	35.000	1.54
S24	NW Africa, Morocco	26.97	-14.00	dead	765	8.0	35.000	1.54
64PE252-57	NE Atlantic, Setubal	37.83	-9.25	dead	490	11.6	35.689	1
64PE252-58	NE Atlantic, Setubal	37.83	-9.01	dead	282	12.8	35.770	0.6
64PE252-58	NE Atlantic, Setubal	37.83	9.01	dead	282	12.8	35.770	0.6
0B5G	Cape Breton	43.67	-1.62	live	450	11.0	35.550	0.7
0B1D	Cape Breton	43.73	-1.17	live	140	11.9	35.600	0.2
<i>Validation Data</i>								
GeoB6008	Cape Ghir	30.85	-10.10	dead	355	12.86	35.70	0.81
GeoB6010 <sub>L</sub>	Cape Ghir	30.25	-10.08	dead	406	12.40	35.59	
GeoB6010	Cape Ghir	30.25	-10.08	dead	406	12.40	35.59	
GeoB6009 <sub>S</sub>	Cape Ghir	30.68	-10.28	dead	579	10.61	35.50	1.24
GeoB6009	Cape Ghir	30.68	-10.28	dead	579	10.61	35.50	1.24
GeoB8604 <sub>S</sub>	Cape Ghir	30.96	-10.52	dead	885	7.99	35.45	1.23
GeoB8604	Cape Ghir	30.96	-10.52	dead	885	7.99	35.45	1.23
GeoB6007	Cape Ghir	30.85	-10.27	dead	899	7.90	35.45	1.23
GeoB8601 <sub>L</sub>	Cape Ghir	30.85	-10.27	dead	924	7.74	35.49	1.21
GeoB8601	Cape Ghir	30.85	-10.27	dead	924	7.74	35.49	1.21
GeoB6011	Cape Ghir	30.32	-10.29	dead	993	7.38	35.49	1.21
GeoB8607	Cape Ghir	30.91	-10.36	dead	1068	7.21	35.51	1.15
GeoB6006	Cape Ghir	30.87	-10.63	dead	1282	6.79	35.61	1.14
<i>Cultured Samples</i>								
	Cape Breton	43.67	-1.62	live	450	7.9	35.8	4.03
	Cape Breton	43.67	-1.62	live	450	10.1	35.8	4.65
	Cape Breton	43.67	-1.62	live	450	12.7	35.8	5.99

<sup>a</sup>Note that in several core tops there were enough specimens only  $\delta^{18}\text{O}$  but not for Mg/Ca analysis.

samples were picked from the wet >63 μm fraction. After the stained specimens were picked, the residual sediments were washed in deionized water and dried in the oven at 60°C before the picking of “dead” specimens. Stained (“recently living”) and unstained (“dead”) samples were picked from the >150 μm size fraction of each sample.

### 3.1.2. Cape Ghir

[10] Samples from the Northwest African margin were collected with a multicorer between 30.845 and 30.957°N and 10.083–10.630°W during METEOR LEG M45 and Leg M58 in 1999 and 2002. At the subsurface, the predominant water mass in the eastern boundary of the subtropical gyre is Eastern North



**Figure 3.** (a–c) Temperature, salinity and dissolved phosphorous profiles from the three study sites at the Makassar Straits (Indonesia), northeast Atlantic and Cape Ghir. (d) *H. balthica* Mg/Ca ratios obtained from core tops in the three study sites.

Atlantic Central Water (ENACW), occupying density surfaces between 26.6 and 27.3 kg m<sup>-3</sup>. Below that, a salinity minimum of 35.2 practical salinity scale (pss) ( $\sigma_{\theta}$  = 27.3 to 27.6 kg m<sup>-3</sup>) provides evidence for strongly modified AAIW, whereas the salinity of 35.5 pss ( $\sigma_{\theta}$  > 27.6 kg m<sup>-3</sup>) indicates the presence of Mediterranean outflow water (MOW) at Cape Ghir [Knoll et al., 2002]. The core tops used in this experiment span 355 to 1282 m with BWT and salinity changes of 12.86°C to 6.79°C and 35.79 to 35.22 pss, respectively. We estimated the concentrations of total dissolved inorganic carbon (TCO<sub>2</sub>) and total alkalinity (TALK) based on the nearest GEOSECS [Bainbridge, 1981] and WOCE stations (30255B at 30.5°N and 11.5°E) [Schlitzer, 2000]. Using CO<sub>2</sub>sis.xls [Lewis and Wallace, 1998], we calculated values including [CO<sub>3</sub><sup>2-</sup>], pH (seawater scale), and the saturation state ( $\Omega$ ) for calcite [Lewis and Wallace, 1998] and obtained a  $\Delta$ [CO<sub>3</sub>] range of 101.9 to 60.2  $\mu$ mol kg<sup>-1</sup> for all sample sites. Sedimentation rates off Cape Ghir are extremely high, ranging from 70 to 210 cm kyr<sup>-1</sup> [Kuhlmann et al., 2004a; McGregor et al., 2007]. These high rates result from high terrigenous input and extensive local oceanic productivity, as well as

the presence of a sediment trough in this area [Kuhlmann et al., 2004b; Meggers et al., 2002; Sarnthein et al., 1982]. All core top samples from Cape Ghir were sampled and frozen in 1cm slices during METEOR cruises in 1999 and 2002. For this study, we sampled the top 1 cm of all multicore tubes, wet-sieved them through 63  $\mu$ m mesh sieves, washed them with deionized water and dried them in the oven at 60°C. From each sample, we picked up to 25 *H. balthica* tests from the 250–350  $\mu$ m size fraction, and where available also from 125 to 250  $\mu$ m and 350–450  $\mu$ m size fractions to evaluate possible secondary effects due to test size.

### 3.1.3. Northeastern Atlantic

[11] Three samples come from Atlantic sites along the northwestern African margins near Mauritania and Morocco at depths of 500 and 760 m. These sites are bathed by open North Atlantic Central Water. Based on TCO<sub>2</sub> and TALK data from the nearest WOCE station on the A05 Line [Millero et al., 2000], bottom water  $\Delta$ [CO<sub>3</sub>] concentration in these sites ranges from about 100 to 70  $\mu$ mol kg<sup>-1</sup>. The other 6 samples come from the Gulf of

Cadiz, Setubal and Cape Breton Canyons, spanning ~140 to 500 m and ~11°C–13°C. These sites are influenced by the warm and salty Mediterranean Outflow Water as reflected in higher temperatures and salinities relative to open ocean sites of the same depth. Based on TCO<sub>2</sub> and TALK data from the nearest WOCE station on the A25 Line [Rios and Perez, 2006], the bottom water Δ[CO<sub>3</sub>] concentration exceeds 100 μmol kg<sup>-1</sup> at all these sites.

### 3.1.4. Culture Samples

[12] The cultured *H. balthica* specimens came from station G in the Bay of Biscay (northeast Atlantic, 43°40'N 1°37'W), a 450 m deep site in Cape Breton Canyon [Hess and Jorissen, 2009], where uncommonly rich faunas of this species are encountered. At this site, BWT is 11.2°C and salinity is 35.5 pss. Sediment containing living specimens of *H. balthica* was sampled in June 2006 and stored in polyvinyl chloride transparent bottles filled with siphoned bottom water from the same core. All sediment samples were transported to the laboratory at the University of Angers (France) in cool boxes and stored at 10°C and 36 pss salinity, without addition of food in the lab. Prior to the start of culturing, adult specimens (>150 μm) were labeled using the Calcein-tagging method [Bernhard et al., 2004] in order to distinguish new chambers that calcified during the controlled-temperature culturing (unlabelled) from old chambers that formed prior to controlled experiments (labeled). Experiments were performed in closed systems (CS<sub>I</sub> as described by Barras et al. [2010]) at temperatures of 7.9°C ± 0.1°C, 10.1°C ± 0.1°C and 12.7°C ± 0.1°C. For each temperature experiment, 30 specimens of *H. balthica* were cultured (in an assemblage with other species) during 90 days and fed with fresh *Phaeodactylum tricornutum* diatoms. The salinity of culture water samples (35.8 ± 0.1) was measured weekly to verify that significant evaporation did not occur. The carbonate chemistry was both stable and similar in the different experiments (7.94 ± 0.04 for pH, NBS scale, and 2464 ± 28 μmol l<sup>-1</sup> for alkalinity). In each experiment, 9–10 specimens calcified from 2 to 8 new chambers (unlabelled) under our controlled conditions (4 chambers on average). These chambers were used for the laser ablation ICP-MS analysis.

## 3.2. Analytical Protocols

[13] Foraminiferal tests were cleaned using a protocol to remove clays, organic matter and metal oxides [Boyle and Keigwin, 1985] and modified

after Rosenthal et al. [1997a]. The foraminifera were gradually dissolved in trace metal clean 0.065N HNO<sub>3</sub> (OPTIMA<sup>®</sup>) and 100 μl of this solution was diluted with 300 μl trace metal clean 0.5N HNO<sub>3</sub> to obtain a Ca concentration of 4 ± 1 mmol L<sup>-1</sup>. Samples were analyzed by Finnigan MAT ElementXR Sector Field Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) operated in low resolution ( $m/\Delta m = 300$ ) following the method outlined in [Rosenthal et al., 1999]. Direct determination of elemental ratios from intensity ratios requires control of the sample Ca concentration; in each run six standard solutions with identical elemental ratios but variable Ca concentrations, which covered the range of Ca concentrations of the samples, were included. These solutions allow us to quantify and correct for the effects of variable Ca concentrations in a sample solution on the accuracy of Mg/Ca measurement (so-called matrix effects) based on the ratio of Ca concentrations [Rosenthal et al., 1999]. Matrix corrections are typically <0.1 mmol mol<sup>-1</sup> Mg/Ca.

[14] Instrument precision was determined by repeated analysis of three consistency standards over the course of this study. The long-term precision of the consistency standard with Mg/Ca of 1.10 mmol mol<sup>-1</sup> was ±1.5% (relative standard deviation), and the precisions of the consistency standards with Mg/Ca of 2.40 mmol mol<sup>-1</sup> and 6.10 mmol mol<sup>-1</sup> was about ±1.2%.

[15] For the analysis of the specimens grown under controlled conditions, foraminiferal tests that added new chambers were placed in a sodium hypochlorite bath (5% NaClO) for 20 min in order to remove all organic material. Subsequently, the specimens were rinsed 3 times with deionized water. Mg/Ca ratios were measured by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS, Micromass Platform) at Utrecht University. This technique allows us to measure trace element concentrations in individual chambers. Individual foraminiferal chambers were ablated using a 193 nm laser (GeoLas 200Q Excimer) in a helium flushed ablation chamber, which was coupled to the ICP-MS. A deep ultraviolet wavelength laser was used in order to guarantee the reproducibility of the ablation of the fragile tests. This type of laser was employed because carbonates do not absorb laser radiation well at higher wavelengths. Pulse repetition rate was set at 6 Hz with an energy density at the sample surface of 1 J cm<sup>-2</sup>. Ablation craters were 80 μm in diameter and the ablated calcite was analyzed with respect to time. Calibration was performed against U.S. National Institute of Standards



and Technology (NIST) SRM 610 glass with  $^{44}\text{Ca}$  as an internal standard. This calcium internal standard is ideal as this element is present at a constant concentration of 40%. This also allows direct comparison with wet chemical analyses [Reichert *et al.*, 2003]. A collision and reaction cell was used to give improved results by reducing spectral interferences on the minor isotopes of Ca ( $^{42}\text{Ca}$ ,  $^{43}\text{Ca}$ , and  $^{44}\text{Ca}$ ). The glass standard SRM 610 was measured with a higher energy density ( $4\text{ J cm}^{-2}$ ) than the calcite samples. To check whether using different ablation energy biases the analyses, a matrix-matched standard was included, which showed that, although a different energy density was used for the glass and calcite standard, Mg/Ca values are statistically identical [Dueñas-Bohórquez *et al.*, 2009]. Based on repetitive analyses of the calcite standard throughout the analytical period, relative precision of the LA-ICP-MS analyses for Mg was better than 2.3%. Simultaneously monitoring  $^{42}\text{Ca}$ ,  $^{43}\text{Ca}$  and  $^{44}\text{Ca}$  showed isotopic ratios expected on the basis of their natural relative abundances. Accuracy for each individual analysis was calculated using the Glitter software, which was also used to calculate elemental concentrations (Glitter, LA-ICP/MS Data Reduction and Display, GEMOC, CSIRO, Maquarie Research Limited, 1999–2000).

[16] Isotope measurements for the Indonesian samples were done at Woods Hole Oceanographic Institution using a Kiel device coupled to a Finnigan MAT 253 mass spectrometer with the Kiel III Carbonate Device. Samples from Cape Ghir were analyzed in the stable isotope laboratory at University of Bremen using a Finnigan MAT 251 mass spectrometer equipped with an automatic carbonate preparation device. Stable isotope values are reported versus V-PDB by analyzing limestone standard and an internal laboratory standard during each run. For both laboratories, the long-term external precision of  $\delta^{18}\text{O}$  analysis was better than 0.08‰.

## 4. Results and Discussion

### 4.1. Mg/Ca Temperature Calibration

[17] Mg/Ca ratios in *H. balthica* tests from all three locations decrease with increasing water depth in a pattern consistent with the in situ thermocline structure at each site. The agreement between the Mg/Ca data and in situ temperatures is seen not only in the two continuous transects from Indonesia and Cape Ghir, but also in the individual

sites from the northeast Atlantic group (Figure 3d). For example, the Mg/Ca data from the Gulf of Cadiz at 966 m show much warmer and saline conditions at this site, relative to open ocean sites at the same depth, thus reflecting the influence of the warm, salty Mediterranean Outflow Water. Likewise, low Mg/Ca from the shallow sample (above 200 m in Figure 3) at Cape Breton reflects the influence of the relatively cool North Atlantic Central Water in this site. This tight match, which is not seen in comparison with salinity and dissolved phosphorous concentration, supports the role of temperature as an important control on Mg uptake into the foraminiferal tests. We find no significant difference in Mg/Ca data obtained on stained and unstained tests, suggesting that the “dead” samples represent the modern conditions with no diagenetic modification. Likewise, we find no significant differences among specimens of different sizes from the same sample. In fact, calibrations based on specific size fractions are not statistically different from the calibration derived from all sizes. A calibration of Mg/Ca data from the Indonesian and North Atlantic transects (excluding samples from Cape Ghir) shows a very strong correlation with bottom water temperatures (Figure 4a). Applying both linear and exponential fits to this data set, we obtain the following calibrations:

$$\text{Mg/Ca} = (0.520 \pm 0.036)\text{BWT} - (0.307 \pm 0.323)(r^2 = 0.917) \quad (1)$$

$$\text{Mg/Ca} = (1.327 \pm 1.08)\exp[(0.123 \pm 0.009)\text{BWT}] \cdot (r^2 = 0.903) \quad (2)$$

The statistical analysis (ANOVA) of these regressions suggests that the intercept is within error of zero. Consequently, we calculate a third equation where we force the intercept through zero:

$$\text{Mg/Ca} = (0.488 \pm 0.03)\text{BWT}(r^2 = 0.913) \quad (3)$$

[18] It is important to note here that because *H. balthica* is not found in temperatures below 4°C, the lower end of the calibration is neither well constrained nor applicable to any down-core reconstruction. Notably, all three equations give similar estimates of bottom water temperatures (BWTs), yield correlation coefficients of >0.9, and are associated with the same error of estimates. Within the temperature range of 4°C–13°C, both linear fits (equations (1) and (3)) yield statistically indistinguishable regression lines (Figure 4a). The calibration suggests that the temperature sensitivity

for Mg incorporation into *H. balthica* tests is ~4 times higher than observed in other calcitic benthic foraminifera. For example, *Marchitto et al.* [2007] report a temperature sensitivity of 0.12 mmol mol<sup>-1</sup> per °C for *C. pachyderma*, and *Elderfield et al.* [2009] report a temperature sensitivity of ~0.07 mmol mol<sup>-1</sup> per °C for *Uvigerina* spp. In Figure 4b, we compare our *H. balthica* data with *C. pachyderma* data from the Great Bahama Banks (GBB) [*Marchitto et al.*, 2007] and our new *C. pachyderma* data from Indonesian core tops. Our own *C. pachyderma* data from the same Indonesian transect used for this study are consistent with the GBB calibration, suggesting that the difference between *H. balthica* and *C. pachyderma* is unlikely to be related to sample cleaning or diagenetic issues. The consistency between the Atlantic and Pacific *C. pachyderma* data further supports this argument, because each data set represents very different hydrographic and depositional conditions.

[19] It is interesting to note that below ~7°C, *C. pachyderma* data from both the Atlantic and Pacific Oceans suggest a steeper slope than above ~7°C. This apparently higher sensitivity occurs in saturated waters, well above the threshold proposed for the Δ[CO<sub>3</sub>] effect [*Elderfield et al.*, 2006]. One possible explanation for the change in the steepness of the slope of *C. pachyderma* is that the temperature sensitivity is suppressed at high Δ[CO<sub>3</sub>] concentration [*Bryan and Marchitto*, 2008]. It is also possible that the warm and cold water forms are two genetically distinct, but morphologically close species, with a different Mg removal efficiency. A full discussion of this change is beyond the scope of this paper, but should be addressed elsewhere.

[20] *H. balthica* exhibits higher Mg/Ca ratios and greater temperature sensitivity than *C. pachyderma* within the same temperature range and similarly high Δ[CO<sub>3</sub>]. The higher temperature sensitivity results in a low SEE of the calibration (~0.38 mmol mol<sup>-1</sup> for the linear equations). This translates to temperature uncertainties of about 0.7°C and 0.8°C using equations (1) and (3), respectively. For the exponential equation, we calculate SEE of 0.8°C. These estimates are significantly lower than the SEE of 2.4°C reported for the *C. pachyderma* calibration [*Marchitto et al.*, 2007].

[21] Support for our core tops calibration comes from the analysis of *H. balthica* specimens grown under controlled experimental conditions. Because of the limited number of specimens available for these analyses, we analyzed Mg/Ca ratios using

LA-ICP-MS, allowing the analysis of multiple chambers of single specimens. Despite scatter both within a single specimen and among different tests grown under identical conditions, the average sensitivity of Mg/Ca to temperature is very similar to the core tops calibration (Figure 4c):

$$\text{Mg/Ca} = (0.413 \pm 0.097)\text{BWT} - (0.645 \pm 1.0)(r^2 = 0.466) \quad (4)$$

[22] The within- and between-test variability is comparable to that previously observed for both benthic [*Dissard et al.*, 2010; *Reichart et al.*, 2003] and planktonic foraminifera [*Dueñas-Bohórquez et al.*, 2009; *Sadekov et al.*, 2008]. These results are consistent with a recent analysis of Mg/Ca and Sr/Ca by secondary ion mass spectrometry (SIMS), showing high variability among and within single chambers of *H. balthica*, which cannot simply be ascribed to environmental conditions [*Allison and Austin*, 2008]. On average, however, the calibration obtained from the culture experiments is in remarkable agreement with the core top calibrations supporting the strong sensitivity of *H. balthica* Mg/Ca to temperature (Figure 4c).

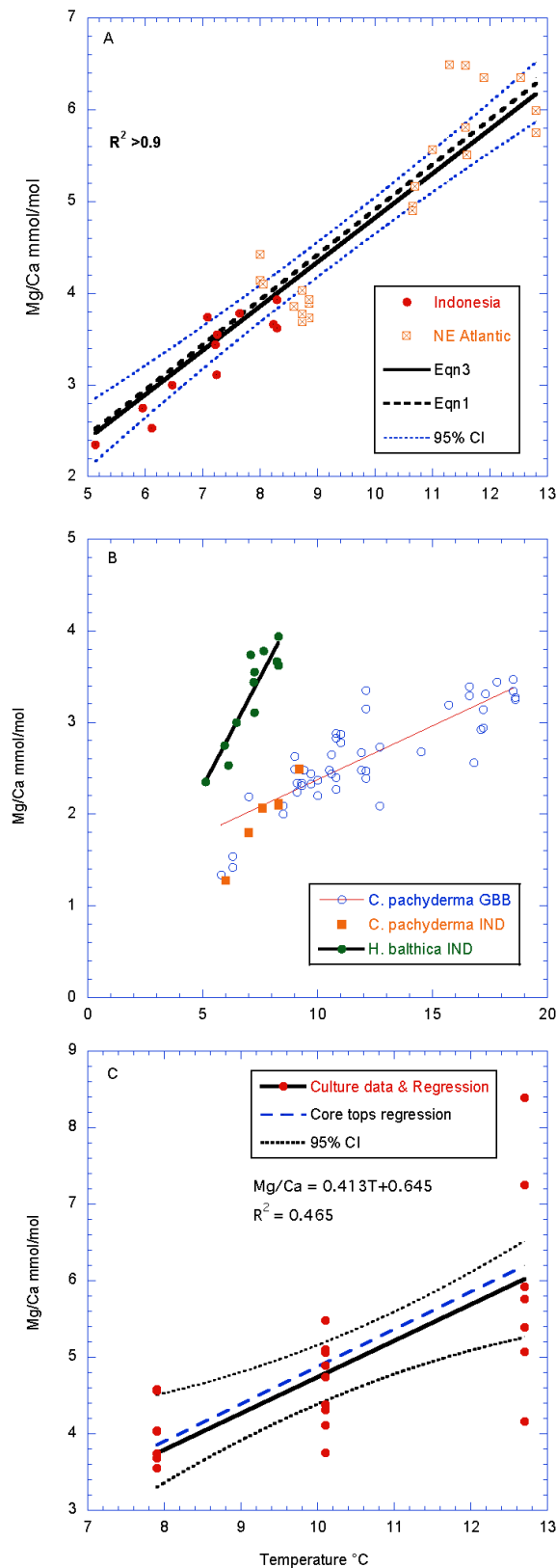
## 4.2. Oxygen Isotope Calibration

[23] We assess the consistency between the measured oxygen isotopic composition of *H. balthica* and expected values at equilibrium, using the core top samples from Indonesia (Table 2). First, we estimate the oxygen isotopic composition of seawater (δ<sup>18</sup>O<sub>sw</sub>) at each site using the regional relationship of

$$\delta^{18}\text{O}_{\text{sw}}(\text{‰SMOW}) = 0.411\text{S} - 14.17 \quad (5)$$

where S is salinity.

[24] This relationship is based on the modeled δ<sup>18</sup>O<sub>sw</sub> data from *LeGrande and Schmidt* [2006] covering the area between 8.5°N and 10.5°S and 106.5°E and 119.5°E and a water depth of 300–3000 m; unfortunately, only few direct observations are available from a remote GEOSECS station (#438 at 19.49°S and 101.29°E) and they do not define any trend. Because of the limited number of measurements in this area and their large scatter, we choose to use the modeled data. Next, we use the estimated δ<sup>18</sup>O<sub>sw</sub> values and in situ temperatures (BWT in °C) to calculate the predicted benthic foraminiferal δ<sup>18</sup>O<sub>eq</sub> composition at each site based on the linear (equation (6)) and



nonlinear (equation (7)) isotopic equations from Shackleton, [1974]:

$$\delta^{18}O_{eq}(\text{‰PDB}) = ((4\delta^{18}O_{sw}(\text{‰SMOW}) - BWT + 16.9)/4) - 0.27 \quad (6)$$

$$\delta^{18}O_{eq}(\text{‰PDB}) = \delta^{18}O_{sw}(\text{‰SMOW}) - 0.27 + (4.38 - (4.38^2 - 0.4(16.9 - BWT))^{1/2})/0.2 \quad (7)$$

The comparison between the measured benthic foraminiferal values and the predicted equilibrium values using the linear equation (6) suggests that on average, *H. balthica*  $\delta^{18}O$  composition is  $0.69\text{‰} \pm 0.13\text{‰}$  lower than predicted from the equilibrium composition. For the nonlinear equation (7), we calculate an offset of  $0.60\text{‰} \pm 0.14\text{‰}$ , which is not statistically different from the former  $\delta^{18}O$  value. Given the lack of direct  $\delta^{18}O_{sw}$  measurements at the core sites, we cannot determine whether the variability in the foraminiferal data is due to the uncertainty in the bottom water  $\delta^{18}O_{sw}$  values or is a reflection of the fact that *H. balthica* is a shallow infaunal species and therefore may not be a reliable recorder of bottom  $\delta^{18}O_{sw}$ .

### 4.3. Validation and Estimation of Errors

[25] To test the validity and accuracy of our temperature calibration, we apply the three equations to the core top data from Cape Ghir, which were not included in the calibration (Table 3). The comparison between the hydrographic and Mg/Ca-derived BWTs shows offsets (i.e.,  $\Delta^{\circ}C = \{\text{measured-T}\} - \{\text{estimated-T}\}$ ) of 0.7, 0.8 and 0.6°C for equations (1), (2), and (3), respectively. The largest offset is seen for the deepest sample and might suggest transport of benthic foraminifera from shallower sites. Except for this one sample, temperatures calculated for all the other samples fall within the predicted

**Figure 4.** (a) Calibration of *H. balthica* Mg/Ca ratios from Indonesia and northeast Atlantic core tops versus bottom water temperatures yield three equations. Dashed black line represents equation (1),  $Mg/Ca = 0.520BWT - 0.307$ , whereas solid black line represents equation (3),  $Mg/Ca = 0.488BWT$ . Dotted lines mark the 95% confidence intervals (CI). (b) Comparison of *H. balthica* Mg/Ca ratios from Indonesia and the northeast Atlantic core tops with Mg/Ca data in *C. pachyderma* from Great Bahama Banks [Marchitto *et al.*, 2007] and from our Indonesian core tops. (c) Calibration of cultured *H. balthica* tests obtained by multiple LA-ICP-MS analyses of individual specimens. The thin black line marks the regression of this data set, the dashed blue line represents the core tops linear regression, and the dotted lines signify the 95% confidence intervals.

**Table 2.** A Comparison Between Foraminiferal and Predicted Equilibrium  $\delta^{18}\text{O}$  Data in the Indonesian BJ8–03 Cores<sup>a</sup>

Core ID	Type	Water Depth (m)	Temperature (°C)	Salinity	Calculated $\delta^{18}\text{O}_{\text{sw}}$ (%SMOW)	Measured $\delta^{13}\text{C}$ (‰PDB)	Measured $\delta^{18}\text{O}_c$ (‰PDB)	Equilibrium $\delta^{18}\text{O}^d$ (‰PDB)	Equilibrium $\delta^{18}\text{O}^e$ (‰PDB)	$\Delta\delta^{18}\text{O}$ (eq-meas)	$\Delta\delta^{18}\text{O}$ (eq-meas)
06MC	dead	920	4.74	34.583	0.044	-1.77	1.96	2.81	2.75	0.86	0.79
06MC	dead	920	4.74	34.583	0.044	-1.89	1.95	2.81	2.75	0.86	0.80
09MC	live	648	6.11	34.553	0.031	-1.34	1.73	2.46	2.38	0.73	0.66
11MC	live	590	6.47	34.546	0.028	-0.88	1.91	2.37	2.29	0.46	0.38
14MC	dead	483	7.24	34.529	0.021	-1.28	1.62	2.17	2.08	0.54	0.46
14MC	dead	483	7.24	34.529	0.021	-1.38	1.57	2.17	2.08	0.60	0.51
16MC	dead	409	8.20	34.490	0.005	-1.28	1.41	1.91	1.82	0.50	0.41
16MC	dead	409	8.20	34.490	0.005	-1.72	1.45	1.91	1.82	0.46	0.37
20MC	dead	419	8.10	34.496	0.008	-0.94	1.26	1.94	1.85	0.67	0.58
20MC	dead	419	8.10	34.496	0.008	-1.57	1.05	1.94	1.85	0.89	0.80
31MC	dead	459	7.64	34.518	0.017	-1.25	1.53	2.06	1.97	0.53	0.44
33MC	dead	505	7.08	34.533	0.023	-1.45	1.45	2.21	2.12	0.76	0.67
35MC	dead	565	6.68	34.542	0.027	-1.35	1.69	2.31	2.23	0.63	0.54
45MC	dead	332	9.35	34.476	-0.001	-2.16	0.99	1.62	1.53	0.63	0.54
45MC	dead	332	9.35	34.476	-0.001	-1.86	0.78	1.62	1.53	0.84	0.75
49MC	dead	676	5.95	34.556	0.033	-1.44	1.78	2.50	2.42	0.72	0.65
56MC	dead	405	8.23	34.489	0.005	-1.54	1.26	1.90	1.81	0.64	0.55
56MC	dead	405	8.23	34.489	0.005	-1.32	1.29	1.90	1.81	0.62	0.53
67MC	dead	401	8.29	34.488	0.005	-2.04	1.09	1.89	1.80	0.79	0.71
69MC	dead	485	7.22	34.530	0.022	-1.39	1.41	2.17	2.09	0.76	0.67
69MC	dead	485	7.22	34.530	0.022	-1.46	1.35	2.17	2.09	0.83	0.74
79MC	dead	440	7.86	34.505	0.011	-1.20	1.21	2.00	1.91	0.79	0.70
79MC	dead	440	7.86	34.505	0.011	-1.44	1.27	2.00	1.91	0.73	0.64
Ave. (eq-meas $\delta^{18}\text{O}$ )										0.69	0.60
SD										0.13	0.14
%RSD										19%	23%

<sup>a</sup>Predicted equilibrium  $\delta^{18}\text{O}$  is calculated using both the linear and nonlinear equations from *Shackleton* [1974]. The term eq-meas stands for the difference between equilibrium and measured values.

<sup>b</sup>Using Local  $\delta^{18}\text{O}_{\text{sw}}$ -salinity relationship Indonesia  $\delta^{18}\text{O}_{\text{sw}} = 0.411\text{S} - 14.17$ . Here "sw" is defined as seawater.

<sup>c</sup>Here "c" stands for calcite.

<sup>d</sup>Using *Shackleton* [1974] linear equation.

<sup>e</sup>Using *Shackleton* [1974] nonlinear equation.



**Table 3.** Reconstruction of BWTs in Cape Ghir Using the Three Calibration Equations<sup>a</sup>

Core ID	Temperature (°C)	Mg/Ca (mmol/mol)	Estimated Temperature <sup>b</sup> (°C)	$\Delta^b$ (°C)	Estimated Temperature <sup>c</sup> (°C)	$\Delta^c$ (°C)	Estimated Temperature <sup>d</sup> (°C)	$\Delta^d$ (°C)
GeoB6008	12.86	6.35	12.8	0.06	12.4	0.49	13.0	-0.15
GeoB6010 <sub>L</sub>	12.40	5.81	11.8	0.63	11.7	0.75	11.9	0.49
GeoB6010	12.40	6.48	13.1	-0.66	12.5	-0.14	13.3	-0.88
GeoB6009 <sub>S</sub>	10.61	4.95	10.1	0.50	10.3	0.27	10.1	0.47
GeoB6009	10.61	4.90	10.0	0.61	10.3	0.36	10.0	0.58
GeoB8604 <sub>S</sub>	7.99	3.89	8.1	-0.08	8.4	-0.39	8.0	0.02
GeoB8604	7.99	3.93	8.2	-0.16	8.5	-0.48	8.1	-0.07
GeoB6007	7.90	3.73	7.8	0.13	8.1	-0.15	7.7	0.25
GeoB8601 <sub>L</sub>	7.74	3.69	7.7	0.05	8.0	-0.21	7.6	0.18
GeoB8601	7.74	4.03	8.3	-0.60	8.7	-0.93	8.3	-0.52
GeoB6011	7.38	3.77	7.8	-0.46	8.1	-0.75	7.7	-0.34
GeoB8607	7.21	3.86	8.0	-0.80	8.3	-1.11	7.9	-0.70
GeoB6006	6.79	4.10	8.5	-1.69	8.8	-2.03	8.4	-1.62
Predicted SEE				0.7		0.8		0.8
SD of $\Delta^c$				0.7		0.8		0.6

<sup>a</sup>Here  $\Delta$  is the difference between the measured hydrographic and reconstructed temperatures. Equations (1), (2), and (3) are given in the main text.

<sup>b</sup>Equation (1).

<sup>c</sup>Equation (2).

<sup>d</sup>Equation (3).

SEE (Figure 5a). In general, the two linear equations show a better accuracy than the exponential equation, with average offsets of 2% and 3.5% from the hydrographic data, respectively.

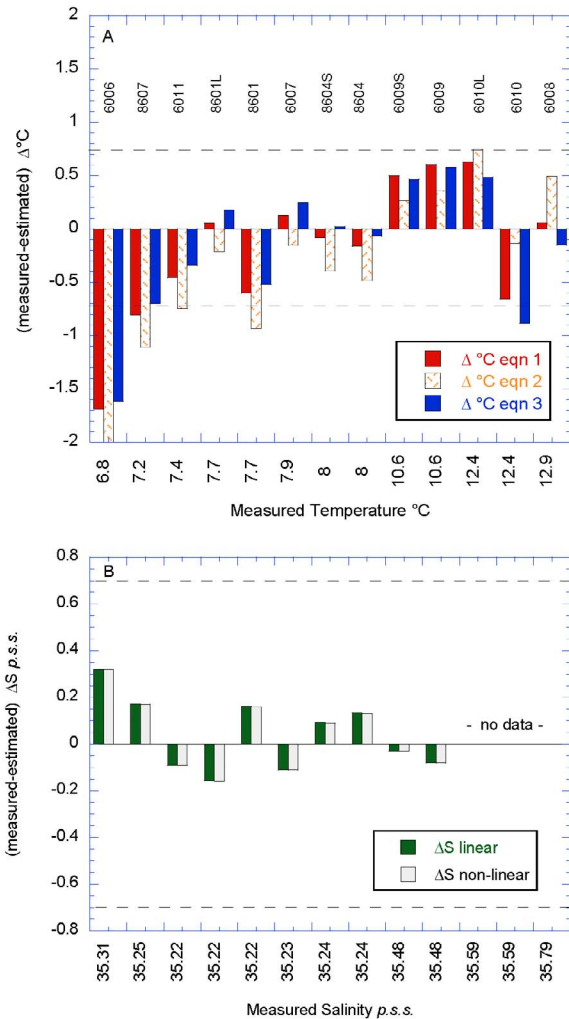
[26] Next, we test the reliability of using paired *H. balthica* Mg/Ca and  $\delta^{18}\text{O}$  measurements for reconstructing seawater  $\delta^{18}\text{O}_{\text{sw}}$  and salinity from the Cape Ghir data (Table 4). The  $\delta^{18}\text{O}_{\text{sw}}$  composition is calculated using the linear (6) and nonlinear (7) equations of *Shackleton* [1974], where BWTs are calculated from Mg/Ca using equation (3) rather than using the hydrographic data. For intermediate water masses in the Cape Ghir region, we use the relationship of  $\delta^{18}\text{O}_{\text{sw}} (\text{‰SMOW}) = 0.555S - 18.98$ , which we derived from the model data of *LeGrande and Schmidt* [2006]. We use this relationship to calculate seawater salinities from the estimated  $\delta^{18}\text{O}_{\text{sw}}$  values. The estimated standard deviation for absolute salinity reconstructions is  $\pm 0.69$  pss [*Schmidt*, 1999]. However, except for one sample all other reconstructed salinities in Cape Ghir depart from the hydrographic data by less than 0.2 pss using both the linear and nonlinear isotopic equations (Figure 5b). Using BWTs derived from the other two Mg/Ca-temperature equations does not significantly affect these estimates.

[27] The accuracy in reconstructing bottom water temperature and salinity using paired  $\delta^{18}\text{O}$  and Mg/Ca measurements in *H. balthica* is largely a result of its high sensitivity to temperature. In fact, the small errors associated with these estimates allow using these measurements to differentiate

among different water masses based on their densities. Propagating the errors associated with our temperature ( $\pm 0.7^\circ\text{C}$ ) and salinity ( $\pm 0.69$  pss) estimates for the Cape Ghir samples indicates that the SEE for estimating water density is better than  $0.3\sigma_\theta$  units. This is visually demonstrated in Figure 6, where we compare the instrumental and foraminiferal-based measurements on a *T-S* plot. Using this method, we calculate the Cape Ghir water mass densities to within  $\sim 0.2\sigma_\theta$ , consistent with the calculated SEE. This relatively small error allows the identification of the different water masses in this region. Figure 6 clearly demonstrates the applicability of this method with the calibration data set from Cape Ghir. On the *T-S* plot, we show that the reconstructed densities from samples overlain by ENACW, AAIW and MOW water masses yield significantly different values that within the  $0.2\sigma_\theta$  errors are consistent with the densities of the respective water masses. Indeed, this method has already been used to study the interaction between climate change in the northern North Atlantic and changes in meridional ocean circulation [*Bamberg et al.*, 2010]. It is noteworthy that in down-core reconstruction, the errors can be further reduced by using either smoothed or binned data, which is often done in high-resolution records.

## 5. Geochemical and Paleoceanographic Implications

[28] The high temperature sensitivity of *H. balthica* raises the question of whether other nontemperature



**Figure 5.** (a) Difference between hydrographic and reconstructed bottom water temperatures. The latter were reconstructed from core top Mg/Ca ratios in *H. balthica* from Cape Ghir using the three calibration equations. (b) Difference between hydrographic and reconstructed bottom water salinities. The latter were estimated from paired  $\delta^{18}\text{O}$  and Mg/Ca measurements using the linear and nonlinear isotopic equations of Shackleton [1974]. The dashed lines on both figures represent 1 SEE of the calibration. The core IDs are given on the top panel. See Tables 3 and 4 for details.

effects might also influence the Mg uptake into its test. Recent studies have suggested that the degree of carbonate saturation has a significant influence on Mg/Ca in certain species of benthic foraminifera [Elderfield et al., 2006; Martin et al., 2002; Rosenthal et al., 2006]. In particular, at low  $\text{CaCO}_3$  saturation levels, these studies show a significant correlation between benthic foraminiferal Mg/Ca and the degree of saturation, which leads to an apparent stronger

temperature response. For example, Elderfield et al. [2006] show apparent temperature sensitivities of *Cibicidoides* species on the order of 0.44–0.77  $\text{mmol mol}^{-1}$  per  $^\circ\text{C}$ , significantly higher than the 0.12  $\text{mmol mol}^{-1}$  per  $^\circ\text{C}$  estimated for *C. pachyderma* at temperatures above  $5^\circ\text{C}$  [Marchitto et al., 2007]. Consistent results have been found for *C. wuellerstorfi* and other benthic species for temperatures below  $3^\circ\text{C}$  [Healey et al., 2008]. Both studies attribute the apparent high sensitivity to temperature at the cold end of the calibration to an additional  $\Delta[\text{CO}_3]$  effect on the order of  $0.0086 \pm 0.0006$   $\text{mmol mol}^{-1}$  Mg/Ca per  $\mu\text{mol kg}^{-1}$   $\Delta[\text{CO}_3]$  that becomes significant below  $3^\circ\text{C}$ . It is difficult, however, to compare our data with those from *Cibicidoides* spp. As discussed above, *H. balthica* is a shallow infaunal species and therefore is affected more by the pore water than overlying bottom water chemistry. The very negative  $\delta^{13}\text{C}$  values (Tables 2, 4, and 5) are consistent with a subsurface habitat, where the degradation of organic matter leads to very light carbon isotopic composition of total  $\text{CO}_2$  ( $\text{TCO}_2$ ) in the pore water [McCorkle et al., 1990; Tachikawa and Elderfield, 2002]. The generation of organic acids during organic matter remineralization could lower the pH and  $[\text{CO}_3]$  ion activity of the pore water, possibly leading to unsaturated conditions [Archer et al., 1989; Emerson and Bender, 1981; Zeebe, 2007]. However, dissolution of carbonate in sediments and diffusion from the overlying bottom water may buffer the pH, thereby maintaining saturated conditions. In either scenario, the saturation state of the pore waters is likely to be very different than the overlying bottom water. In principle, it is possible that pore waters in sediments from our Indonesian sites are characterized by lower  $[\text{CO}_3]$  due to the relatively high organic C to  $\text{CaCO}_3$  ratio and lower bottom water  $[\text{CO}_3]$  relative to the Atlantic sites, and this may be the cause of the apparent high temperature sensitivity. While we cannot rule out this possibility, there are three lines of evidence to argue otherwise. First, calibrations of Mg/Ca versus temperature at individual sites (i.e., Indonesia and Atlantic) yield very similar equations, which are statistically the same as the one discussed above (Figure 4). Second, the tight correlation and the constant scatter along the calibration suggest that temperature rather than saturation state is the main control on Mg/Ca. Third, we note the lack of any correlation at the  $\alpha = 0.05$  significance level between the foraminiferal Mg/Ca and  $\delta^{13}\text{C}$ , which presumably relates to the pore water chemistry ( $r = 0.11$ ,  $n = 27$ ,  $p = 0.95$ ). Based on these three lines of evidence, we conclude that there is no strong support for a saturation bias.

**Table 4.** Temperature and Salinity in Cape Ghir, GeoB Cores as Estimated From  $\delta^{18}\text{O}$  and Mg/Ca Measurements<sup>a</sup>

Core ID	Hydrographic Salinity <sup>b</sup> (pss)	Estimated Temperature <sup>c</sup> (°C)	Measured $\delta^{13}\text{C}$ (‰PDB)	Measured $\delta^{18}\text{O}_c^d$ (‰PDB)	$\delta^{18}\text{O}_{\text{sw}}^e$ (%SMOW Linear)	Estimated Salinity <sup>f</sup> (pss)	$\Delta\text{S}$ Linear (pss)	$\delta^{18}\text{O}_{\text{sw}}^g$ (%SMOW Nonlinear)	Estimated Salinity (pss)	$\Delta\text{S}$ Nonlinear (pss)
6008	35.788	13.0		1.24	1.232	36.457 <sup>h</sup>		1.17	36.64 <sup>h</sup>	
6009 <sub>S</sub>	35.475	10.1	-1.44	1.24	0.516	35.447	-0.03	0.63	35.443	
6009	35.475	10.0	-1.44	1.24	0.487	35.395	-0.08	0.63	35.392	-0.03
8604 <sub>S</sub>	35.243	8.0	-0.71	1.73	0.456	35.337	0.09	0.46	35.335	-0.08
8604	35.243	8.1	-0.71	1.73	0.478	35.378	0.13	0.46	35.376	0.09
6007	35.234	7.7	-1.08	1.69	0.338	35.124	-0.11	0.40	35.119	0.13
8601 <sub>L</sub>	35.220	7.6	-1.21	1.68	0.305	35.063	-0.16	0.35	35.058	-0.11
8601	35.220	8.3	-1.21	1.68	0.480	35.381	0.16	0.35	35.380	-0.16
6011	35.222	7.7	-1.35	1.68	0.342	35.131	-0.09	0.25	35.127	0.16
8607	35.249	7.9	-1.15	1.79	0.501	35.421	0.17	0.32	35.418	-0.09
6006	35.314	8.4	-1.32	1.78	0.619	35.634	0.32	0.21	35.633	0.17
SD of $\Delta\text{S}$ (pss)								0.16		0.16
SE of $\Delta\text{S}$ (pss)								0.05		0.05
%RSE								0.16%		0.14%

<sup>a</sup>Here  $\Delta\text{S}$  is the difference between reconstructed and hydrographic salinity.

<sup>b</sup>Hydrographic salinity based on CTD data from Knoll *et al.* [2002].

<sup>c</sup>Here “c” stands for calcite.

<sup>d</sup>Derived from the Mg/Ca data using calibration equation (3).

<sup>e</sup>Based on Shackleton [1974] linear equation and corrected for 0.69‰ offset. Here “sw” is defined as seawater.

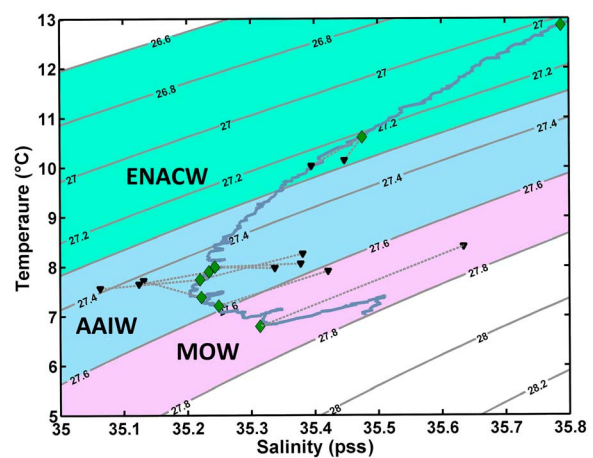
<sup>f</sup>Based on LeGrande and Schmidt [2006] equation:  $\delta^{18}\text{O}_{\text{sw}} = 0.555\text{S} - 18.98$ .

<sup>g</sup>Based on Shackleton [1974] nonlinear equation and corrected for 0.6‰ offset.

<sup>h</sup>Likely a bad analysis.

[29] The initial calibration of *C. pachyderma* Mg/Ca, which is based on samples from the Little Bahama Banks, suggested relatively high temperature sensitivity of about 10% per °C [Rosenthal *et al.*, 1997b]. Similar sensitivity was obtained for other benthic species, including *Oridorsalis umbonatus* and *Melonis barleeanum* [Lear *et al.*, 2002]. However, subsequent calibration of *C. pachyderma* from core tops in the Florida Straits indicated a significantly lower sensitivity of Mg/Ca to BWT of  $\sim 0.12$  mmol mol<sup>-1</sup> per °C at temperatures above 5.8°C. Using a microanalysis technique (SIMS) to avoid diagenetic overgrowths, Curry and Marchitto [2008] found a similar low sensitivity for *C. pachyderma* samples from Bahama Banks core tops and therefore suggested that the apparent high sensitivity reported in the earlier studies [Lear *et al.*, 2002; Rosenthal *et al.*, 1997b] was due to “contamination” of the tests by high-Mg overgrowths in the shallow, carbonate-rich sediments of Little Bahama Banks. These conditions are unique, however, to Little Bahama Banks and are not likely to occur in our sites. Hence, it is unlikely that diagenetic alteration of the tests is responsible for the high sensitivity found in this study for *H. balthica*. This conjecture is supported by the fact that whenever available, we find no significant difference in Mg/Ca among the “recently living” (i.e., stained), the dead specimens and the results from the culture experiments. Given these circumstantial lines of evidence, we suggest that the accu-

racy of our reconstruction of temperature and salinity from Cape Ghir sediments, and the small errors associated with estimates of these, strongly supports



**Figure 6.** Temperature and salinity estimates based on paired  $\delta^{18}\text{O}$  and Mg/Ca measurements from core top *H. balthica* in Cape Ghir (reversed black triangles) are compared with the modern CTD profile. Each core top data point is connected with a dashed line to the actual measurements in the core top site (marked with green diamonds). Note that the mismatch between reconstructed and modern results is an uncertainty of less than  $0.2 \sigma_\theta$  in estimating the water densities. ENACW, Eastern North Atlantic Central Water; AAIW, Antarctic Intermediate Water; MOW, Mediterranean Outflow Water.

**Table 5.** Isotope Data for the Northeastern Atlantic Samples

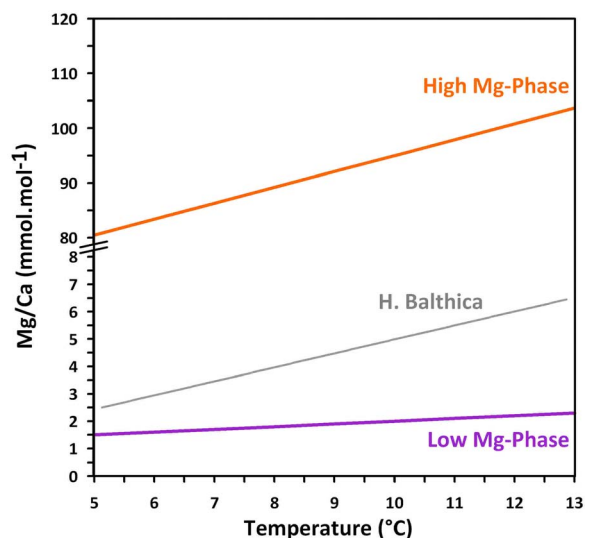
Core	Region	Depth (m)	$\delta^{13}\text{C}$ (‰PDB)	$\delta^{18}\text{O}$ (‰PDB)
S24	NW Africa, Morocco	765	-1.65	1.00
S1	NW Africa, Mauritania	507	-2.06	1.00
MD39004-1	Gulf of Cadiz	966	-0.88	2.59
64PE252-57	NE Atlantic, Setubal	490	-0.76	1.72
64PE252-57	NE Atlantic, Setubal	490	-1.05	1.62
64PE252-58	NE Atlantic, Setubal	282	-0.84	1.15
0B5G	Cape Breton	450	-2.51	1.02
0B1D	Cape Breton	140	-3.28	0.78

the argument that temperature is the dominant control on Mg/Ca in *H. balthica* tests.

[30] Given the discussion above, we submit that the Mg/Ca temperature sensitivity in *H. balthica* is indeed substantially higher than observed in other bathyal-abyssal (>2000 m) benthic foraminifera. This raises the question of why? And what can we learn about other species that might exhibit equally high temperature dependence? Based on their studies of the shallow water benthic hyaline foraminifer *Amphistegina lobifera*, *Bentov and Erez* [2006] have suggested that differences in the Mg/Ca of benthic foraminifera might be biologically determined by variable proportions of high- and low-Mg calcites that form the foraminiferal test. According to that hypothesis, the biologically mediated change in the ratio between these minerals is the primary cause for both the large range in Mg/Ca ratios among benthic foraminifera and for the large variability within individual tests. If so, the higher Mg/Ca of *H. balthica* relative to *C. pachyderma* indicates a greater proportion of high-Mg calcite in this species. Furthermore, *Bentov and Erez* [2006] also propose that the relative abundance of high- and low-Mg calcites in individual tests of the same species might be controlled by environmental conditions, mainly temperature [*Bentov and Erez*, 2006, Figure 3]. This model could explain the high temperature sensitivity of *H. balthica* relative to *Cibicidoides* spp.

[31] In Figure 7, we present a modified version of the *Bentov and Erez* model and assume the following: (1) the high-Mg phase has Mg/Ca ratio of about 100 mmol mol<sup>-1</sup>, similar to observations of high-Mg calcitic benthic foraminifera [*Toyofuku et al.*, 2000], and (2) the temperature sensitivities of the low- and high-Mg phases are about 0.12 and 2.2 mmol mol<sup>-1</sup> per °C, respectively [*Marchitto et al.*, 2007; *Toyofuku et al.*, 2000]. Under these assumptions, an increase in the high-Mg content of the test from 1% at 4°C to 4% at 12°C is consistent with the observed Mg/Ca changes in our calibration.

This model is not meant to determine the actual proportion between the two phases, but rather to demonstrate the possibility that such a mechanism could explain the higher temperature sensitivity of *H. balthica*. If the model is correct, then it predicts that foraminiferal species with generally higher Mg/Ca content may also show higher temperature sensitivities. For example, the preliminary calibration of another infaunal species, *Globobulimina affinis*, which has similar Mg/Ca as *H. balthica*, suggests similarly high temperature sensitivity [*Skinner and Elderfield*, 2007]. While this hypothesis needs further testing, it may direct us toward benthic species that may be better suited for deep-water temperature reconstructions than the commonly used species at present.



**Figure 7.** A model describing the Mg/Ca change in *H. balthica* tests (gray line) in response to a hypothetical temperature-dependent increase (from 1% to 4%) in the content of high-Mg calcite (orange) in the low-Mg (purple) calcitic test. We assume much higher Mg concentration and much higher temperature sensitivity in the former phase (note the logarithmic scale).



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