Marine Micropaleontology 107 (2014) 32–43

Contents lists available at ScienceDirect

Marine Micropaleontology

journal homepage: www.elsevier.com/locate/marmicro

Research paper

Variability in calcitic Mg/Ca and Sr/Ca ratios in clones of the benthic foraminifer *Ammonia tepida*

L.J. de Nooijer [a,*], E.C. Hathorne [b], G.J. Reichart [a,c], G. Langer [d], J. Bijma [e]

[a] Royal Netherlands Institute for Sea Research, Landsdiep 4, 1797 SZ 't Horntje, The Netherlands
[b] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1–3, 24148 Kiel, Germany
[c] Utrecht University, Department of Geochemistry, Budapestlaan 4, 3584 CD, Utrecht, The Netherlands
[d] Cambridge University, Department of Earth Sciences, Downing Street, Cambridge CB2 3EQ, United Kingdom
[e] Alfred Wegener Institute, Am Handelshafen 12, 27570 Bremerhaven, Germany

ARTICLE INFO

Article history:
Received 4 January 2013
Received in revised form 27 January 2014
Accepted 4 February 2014
Available online 13 February 2014

Keywords:
Benthic foraminifera
Mg/Ca
Sr/Ca
Laser Ablation ICP-MS
Inter-individual variability
Intra-individual variability

ABSTRACT

Biological activity introduces variability in element incorporation during calcification and thereby decreases the precision and accuracy when using foraminifera as geochemical proxies in paleoceanography. This so-called 'vital effect' consists of organismal and environmental components. Whereas organismal effects include uptake of ions from seawater and subsequent processing upon calcification, environmental effects include migration- and seasonality-induced differences. Triggering asexual reproduction and culturing juveniles of the benthic foraminifer *Ammonia tepida* under constant, controlled conditions allow environmental and genetic variability to be removed and the effect of cell-physiological controls on element incorporation to be quantified. Three groups of clones were cultured under constant conditions while determining their growth rates, size-normalized weights and single-chamber Mg/Ca and Sr/Ca using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Results show no detectable ontogenetic control on the incorporation of these elements in the species studied here. Despite constant culturing conditions, Mg/Ca varies by a factor of ~4 within an individual foraminifer while intra-individual Sr/Ca varies by only a factor of 1.6. Differences between clone groups were similar to the intra-clone group variability in element composition, suggesting that any genetic differences between the clone-groups studied here do not affect trace element partitioning. Instead, variability in Mg/Ca appears to be inherent to the process of bio-calcification itself. The variability in Mg/Ca between chambers shows that measurements of at least 6 different chambers are required to determine the mean Mg/Ca value for a cultured foraminiferal test with a precision of ≤10%.

1. Introduction

Incorporation of various trace elements into foraminiferal calcite is affected by environmental parameters and therefore, calcitic element/calcium ratios are widely used to reconstruct marine paleoenvironments. For example, foraminiferal Mg/Ca ratios have been shown to be primarily correlated with seawater temperature (e.g. Nürnberg et al., 1996) and are used in combination with test calcite $\delta^{18}O$ to reconstruct paleo-seawater $\delta^{18}O$ (e.g. Elderfield and Ganssen, 2000; Lear et al., 2000), and estimate salinity. Elevated Mg-incorporation into calcite at higher temperatures has also been reported from inorganic precipitation experiments (Mucci, 1987; Oomori et al., 1987). However, the relative increase in Mg/Ca with temperature for foraminifera is greater than reported for inorganically precipitated calcites (~10% per °C compared to <5% per °C, respectively), suggesting that foraminiferal Mg/Ca is largely controlled by biological activity (Rosenthal et al., 1997; Erez, 2003; De Nooijer et al., 2009a, 2009b; Wit et al., 2012). The cellular control on Mg-incorporation is also reflected by the low Mg/Ca ratios of most foraminiferal species compared to calcite precipitated from seawater (Blackmon and Todd, 1959; Bentov and Erez, 2006). Furthermore, Mg/Ca varies also within single individual foraminifer tests (e.g. Hathorne et al., 2003; Toyofuku and Kitazato, 2005) and through chamber walls (e.g. Eggins et al., 2004; Sadekov et al., 2005; Kunioka et al., 2006; Hathorne et al., 2009).

The origin of intra-individual and intra-chamber wall Mg/Ca heterogeneity in benthic and planktonic species remains enigmatic. Previous work suggested that ontogenetic (i.e. life-stage related) changes can be responsible for intra- and inter-test Mg/Ca variability in benthic foraminifera (Hintz et al., 2006; Filipsson et al., 2010; Raitzsch et al., 2011a; Diz et al., 2012). Ontogeny can affect trace element partitioning through changes in physiology, growth rate or changes in surface area-volume ratios. Migration into different environments with age and life-stage may be responsible for part of the observed effects, but this is an environmental control rather than ontogeny as such. Additionally, inter-individual variability in Mg/Ca

* Corresponding author. Tel.: +49 222 369380.
E-mail address: ldenooijer@nioz.nl (L.J. de Nooijer).

http://dx.doi.org/10.1016/j.marmicro.2014.02.002
0377-8398/

may potentially be caused by genetic differences between individuals of the same species (Numberger et al., 2009).

In a number of species, foraminiferal Sr/Ca is positively correlated with temperature (Rathburn and De Deckker, 1997; Reichart et al., 2003; Mortyn et al., 2005; Rosenthal et al., 2006; Kisakürek et al., 2011), salinity (Dissard et al., 2010a; Kisakürek et al., 2011) and seawater Sr/Ca (Delaney et al., 1985; Elderfield et al., 2000; Raitzsch et al., 2010). Reported inter- and intra-individual variability in Sr/Ca is smaller than observed for Mg/Ca (e.g. Dueñas-Bohórquez et al., 2009, 2011a). The partition coefficient for Sr incorporation is closer to that found in inorganic precipitation experiments (e.g. Lorens, 1981; Delaney et al., 1985; Tesoriero and Pankow, 1996; Dissard et al., 2010a) when compared to Mg incorporation (e.g. Delaney et al., 1985; Mucci, 1987; Nürnberg et al., 1996). This difference suggests that incorporation of Sr is not under the same biological control as Mg, and that the relatively weak control causes a more homogenous inter-species, intra-species and intra-individual Sr-incorporation.

The elemental and isotopic composition of individual tests is increasingly used for estimating past inter and intra-annual change, such as seasonality (Wit et al., 2010; Ganssen et al., 2011; Haarmann et al., 2011; Khider et al., 2011). The accuracy of such reconstructions, however, critically relies on the ability to distinguish vital effect-related variability from that caused by the environment. Here, we cultured genetically identical individuals of the shallow-water benthic foraminifer *Ammonia tepida* under constant environmental conditions, monitoring ontogenetic variability to constrain the intrinsic natural amplitude of Mg/Ca and Sr/Ca variability between and within individuals. *Ammonia* spp. produce calcite with a very low Mg/Ca (~1 mmol/mol), indicating a strong biological control on Mg-incorporation. This implies that changes in this biological control are also expected to have a relatively large impact compared to other foraminiferal species. Hence by studying this species we are able to capture the maximum impact related to variability in the vital effect. The intrinsic natural variability of Mg/Ca and Sr/Ca ratios ultimately determines how well we will be able to constrain past seasonal temperature variability and provides constraints for the biologically induced noise in reconstructions.

2. Methods

2.1. Culturing and reproduction

Surface sediments were collected from the muddy intertidal flats near Dorum, Northwestern Germany (53°44′16 N, 8°30′53 E) in Autumn 2008. Average Wadden Sea water temperature in October is ~13 °C, with an average diurnal variability of ~1 °C (Van Aken, 2008). Upon return to the laboratory, sediment was sieved over 1-mm screens to remove the largest macrofauna and stored at 10 °C. Prior to incubation, small amounts of sediment were sieved over a 250 μm-screen to retrieve large living individuals of *Ammonia tepida*. Individuals with brightly yellow colored cytoplasm were regarded as living and isolated for incubation. Four groups of 25 individuals were placed in Petri dishes with approximately 50 mL of 0.2 μm-filtered North Sea water (salinity 32), fed with living *Dunaliella salina* by adding 300 μL of a densely concentrated algae culture (approximately 3×10^6 cells/mL) and brought instantaneously to 25 ± 0.5 °C at which they were kept until reproduction.

Of all incubated specimens, 6 adult, megalospheric foraminifera underwent asexual reproduction at regular intervals, resulting in the production of 50–300 megalospheric, one-chambered juveniles emerging from the same adult test. Regular inspection of the foraminifera allowed recognition of reproduction when the juveniles were still in close proximity of their parent (Fig. 1). The size of these one-chambered juveniles ranges from approximately 20 to 30 μm, suggesting that they are gamonts (as opposed to schizonts; Goldstein and Moodley, 1993; Stouff et al., 1999). These juveniles were isolated from their parent test and kept together in a new Petri dish. All juveniles

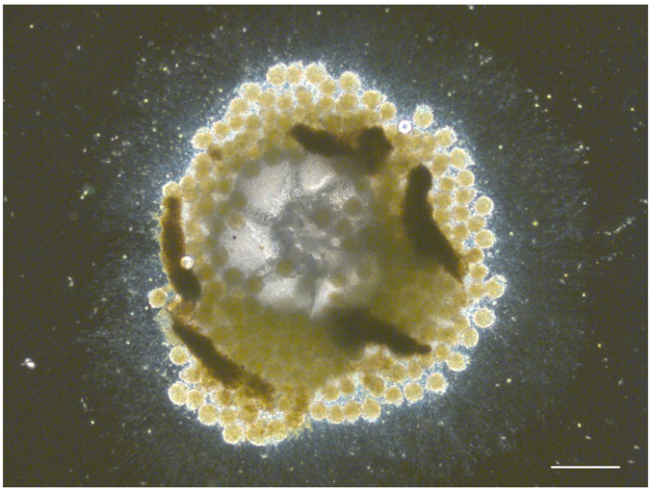

Fig. 1. Asexual reproduction in *Ammonia tepida*. The empty test of the adult (i.e. 'parent') individual is surrounded by approximately 200 juveniles that have emerged from the aperture. The single-chambered juveniles form a relatively large and dense pseudopodial network that they use to move away from the parent in the following hours. Clone groups were recognized and isolated when they were still in the vicinity of the parent test to prevent mixing of offspring from multiple reproductive events. The dark masses are remains of the food cyst that surrounded the adult foraminifer before reproduction. Scale bar = 100 μm.

resulting from one asexual reproductive event (i.e. having the same individual parent) will be referred to as a 'clone group'. Since the parents of these clone groups come from the same sample location, it may be that the different clone groups are genetically closely related. Juveniles from three of these clone groups were cultured in three separate Petri dishes and fed once a week. The water in these dishes was changed every two days. At the beginning and end of the incubations, salinity (32.2 ± 0.2) and pH (8.14 ± 0.05, NBS scale) were measured using a 330i WTW conductivity meter and WTW pH3000 with Schott BlueLine Electrodes, respectively. Culture media subsampled for DIC (2193 ± 29 μM) was filtered over 0.2 μm filters and measured photometrically using an XY-2 sampler (Bran + Lübbe GmbH, Norderstedt, Germany). Subsamples were also analyzed for $[Mg^{2+}]$ (49 ± 2 mmol/kg), $[Ca^{2+}]$ (9.5 ± 0.05 mmol/kg) and $[Sr^{2+}]$ (90 ± 0.8 μmol/kg) using ICP-OES. Uncertainties for these concentrations (±1 standard deviation) represent differences between replicate measurements (n = 4).

The three other clone groups were used to determine the growth rates by determining size of individuals by regular observation under an inverted microscope and counting the number of chambers of each individual. After 3 weeks of incubation in the same artificial seawater in which the other three clone groups were cultured, specimens were taken out and cleaned. Specimens both from the culturing experiment and from the incubation to determine growth rates were placed in buffered NaOCl (15%) for 24 h to remove organic material. Individuals were then rinsed several times with double deionized water and dried at 60 °C for several hours. Multiple individuals from one group with the same number of chambers (ranging from 6 to 16 chambers) were weighed on a UMX2 microbalance (Mettler Toledo, precision ± 0.1 μg) to determine "chamber-normalized" weights. Other studies have reported size-normalized weights based on the diameter (e.g. De Moel et al., 2009; Beer et al., 2010) of analyzed individuals, but to facilitate comparison of growth with the LA-ICP-MS data (see Section 3.3) size-normalized weights and growth rates are expressed per total number of chambers.

Since a large number of geno- and morphotypes have been reported for *Ammonia* (e.g. Holzmann and Pawlowski, 1997; Debenay et al., 1998; Holzmann and Pawlowski, 2000; Hayward et al., 2004), culturing individuals from one clone group overcomes the potential imprint of genetic variability on calcite chemistry. This is particularly important since the genus of *Ammonia* is widely studied, but named differently

by different researchers. At our sampling location, 'Ammonia molecular type T6' is the dominant morphotype (Hayward et al., 2004), and will be referred to here as *A. tepida*.

2.2. LA-ICP-MS

Three laser ablation systems coupled to inductively coupled plasma-mass spectrometers (LA-ICP-MS) were used during the course of this study (Table 1). The majority of analyses were conducted at the University of Bremen using a solid state 193 nm laser ablation system (New Wave Research) coupled to an Element2 (Thermo Scientific) sector field ICP-MS. The ICP-MS was run in low resolution mode without the shield torch and the measurement routine took 1.4 s to cycle through the masses. Masses monitored were ^{11}B, ^{25} Mg, ^{27}Al, ^{43}Ca, ^{55}Mn, ^{66}Zn, ^{88}Sr, ^{137}Ba and ^{238}U. All ablations were conducted in He and lasted up to 60 s before the shell wall was penetrated using laser spots of 35 or 75 μm in diameter, a repetition rate of 5 Hz, and a laser power density of ~0.35 GW/cm^2. A NIST SRM 610 glass was used for calibration and ablated with a laser power density of ~1 GW/cm^2 between every 5 or 10 sample analyses. Calibration of element/calcium ratios in calcium carbonate samples using a NIST glass standard has been demonstrated to be accurate for many elements when using a 193 nm laser (Hathorne et al., 2008). The precision of the technique is ~4% (1σ) for Mg/Ca and Sr/Ca based on many spot analyses of powder pellets of carbonate reference materials (e.g. Raitzsch et al., 2011a).

Time resolved signals were selected for integration, background subtracted, internally standardized to ^{43}Ca, and calibrated with the signals from the NIST SRM610 using the GeoPro software (Cetac). Despite the removal of organics with NaOCl it was clear from the time resolved laser signals that some cytoplasm, with elevated Mg and Zn, remained on the outside and inside of a few chambers. Zinc is known to be concentrated by phytoplankton (Ho et al., 2003), adding to the intracellular concentrations in the foraminifera when taken up as food. Parts of analyses, towards the outside or inside of the test wall, with elevated Mg and Zn were omitted from the integration (Fig. 2C). In some cases where the test wall was thin, the ablation was very short and the Mg and Zn levels remained high throughout. Such analyses were discarded and not considered further. Screening of time resolved signals for surface contamination is a standard practice to ensure that only contaminant-free data are considered (e.g. Reichart et al., 2003; Sadekov et al., 2008; Hathorne et al., 2009).

As a solid state laser system is not optimized for depth profiling, a number of cultured tests were also analyzed using a 193 nm ArF Excimer laser at Utrecht University (GeoLas 200Q) and at the GEOMAR in Kiel (New Wave) to acquire depth-profiles of the element/Ca ratios through the shell walls (Table 1). The analyses at Utrecht also used an Element2 (Thermo Scientific) sector field ICP-MS. The laser at the GEOMAR is equipped with a large format cell with a low volume (~1 cm^3) ablation chamber that is optimal for such depth profiling analyses and employed an Agilent 7500cs ICP-MS. Calibration and standardization also used the NIST SRM 610 glass (values from Jochum et al., 2011) that was ablated using a higher laser fluence of ~4 J/cm^2. The raw time resolved counts were blank subtracted, internally standardized to ^{43}Ca and calibrated using standard spreadsheet software to obtain depth profiles for Sr/Ca and Mg/Ca ratios. Data were further processed with a 2σ outlier rejection to remove outliers and smoothed with a 3-point running average to obtain the depth profile (data from Bremen were not treated in this way as only average values for each laser spot were obtained). Analyses of a powder pellet of the JCp-1 carbonate reference material agree with the recommended values in the literature (Okai et al., 2002, 2004) and indicate a within depth profile precision of <20% (1σ). A similar result was obtained by depth profiling through an Iceland spar calcite used in the Utrecht laboratory.

Using the obtained foraminiferal Mg/Ca and Sr/Ca and those of seawater, apparent partition coefficients for these elements in the calcite of *Ammonia tepida* are calculated as follows:

$$D_{Element} = (Element/Ca)_{calcite}/(Element/Ca)_{medium}$$

Table 1
Settings and details of the different laser systems employed in this study.

Laboratory	Bremen	Utrecht	Kiel
Manufacturer	NWR	Geolas 200Q	NWR
Laser	193 nm solid state	193 nm Excimer	193 nm Excimer
Energy density	~0.35 GW/cm^2	~1 J/cm^2	~1 J/cm^2
Laser spot size	35/75 μm	40 μm	25/50 μm
Ablation frequency	5 Hz	7 Hz	4/5 Hz
Results	Figs. 5 and 7	Fig. 4A, B	Fig. 4B, C

3. Results

3.1. Reproduction, growth rates and size-normalized weights

The number of juveniles that result from one reproductive event varied between the clone groups (Table 2). The maximum size (diameter) that was reached at the end of the culturing period also varied, resulting in analyses being performed on individuals with a range of sizes.

Table 2: Reproduction, growth and amount of calcite available for chemical analyses. Dextral coiling is clockwise addition of chambers on the spiral side: sinistral is anti-clockwise. 'n.d.' = not determined.

Growth rates (expressed here as number of chambers added per day) varied between clone groups, although the general pattern was similar between groups: as size increases, growth (chamber addition) rates decrease. Chamber-normalized weights as determined after the culturing experiments show that the amount of calcite precipitated per chamber increases with size (Fig. 3).

3.2. Test wall variability in Sr/Ca and Mg/Ca

Ablation profiles obtained with the excimer laser systems at Utrecht and Kiel from different chambers of one individual show that inner chambers are progressively thicker because of bilamellar calcification. This is visible from the length of profiles as they become longer when ablating chambers that were formed at earlier lifestages of the foraminifers.

Within the obtained profiles, Sr/Ca varies between 1.0 and 2.5 mmol/mol (Fig. 4C). On average, Sr/Ca of these profiles was 1.42 mmol/mol and the average standard deviation of a profile is 0.32 mmol/mol. Mg/Ca in profiles from the same measurements varies between 2 and 14 mmol/mol within the same chamber wall (Fig. 4B). Average Mg/Ca in these profiles varies between 1.8 and 6.1 mmol/mol, with an average standard deviation of 1.2 mmol/mol for one profile. The obtained average Mg/Ca for these profiles match the range in Mg/Ca from the larger dataset (Section 3.3; Fig. 5B). Variability in average Mg/Ca between laser ablation spots is caused by the occasional occurrence of calcite with high Mg/Ca (Fig. 4B, chamber F-6; Fig. 4A, chamber F-5). These parts with elevated Mg/Ca, however, are not present in all chambers and their position or number per chamber wall is not the same for different chambers within a single individual.

Average Sr/Ca and Mg/Ca and the variability in these profiles (Fig. 4) are similar for the different laser systems employed. This not only facilitates direct comparison between the data obtained by us, but also demonstrates the reproducibility of the Sr/Ca and Mg/Ca ratios despite differences in ablation cell design.

3.3. Interchamber and size-related variability in Sr/Ca and Mg/Ca

When combining the average values from the ablation profiles with the 173 spot analyses obtained at the University of Bremen, Sr/Ca of all ablations range between 1.2 and 2.0 mmol/mol (Fig. 5A), with an

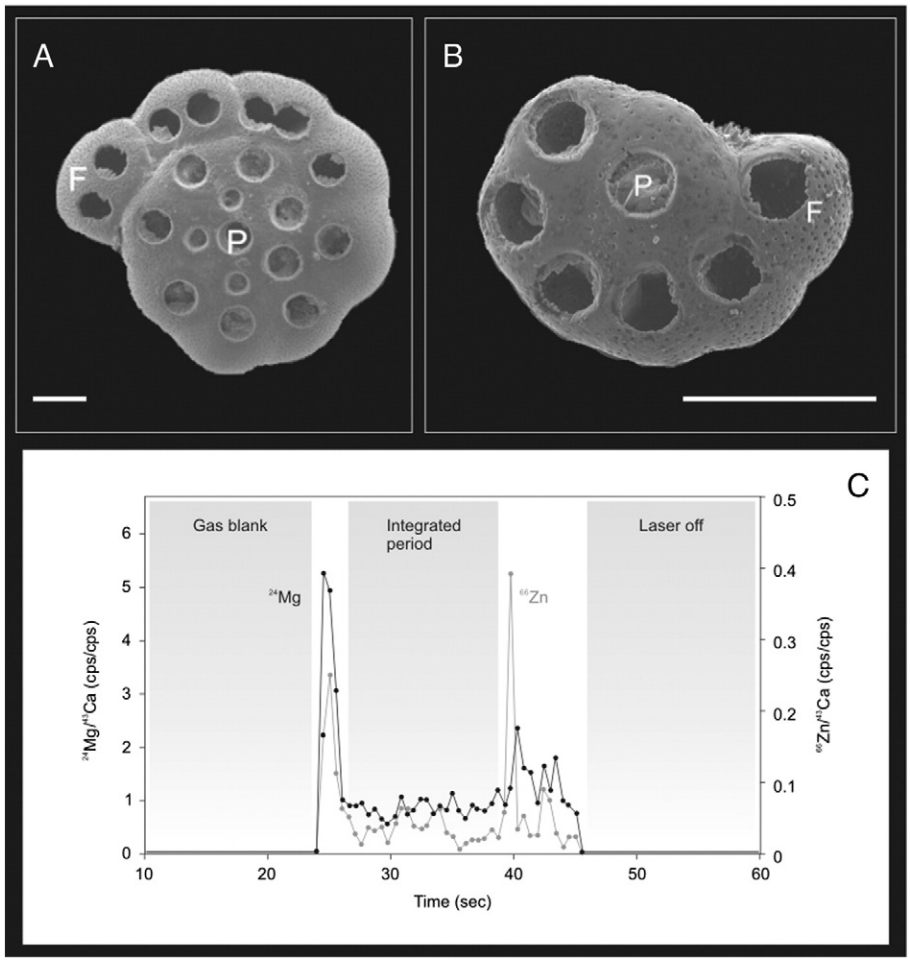

Fig. 2. Example of two individuals (A and B) after LA-ICP-MS. P = proloculus, F = final chamber. Scale bar = 100 μm. C: example of a laser ablation profile with high Mg/Ca and Zn/Ca indicative of residual cytoplasm on both sides of the chamber wall.

average of 1.6 mmol/mol (±0.13 mmol/mol standard deviation). No trend for Sr/Ca and chamber number is detectable (data of all clone groups combined, as well as for separate groups: regression analysis, $R^2 < 0.001$). In 15 cases, 2 measurements were performed on a single chamber (Fig. 2A). The average difference between these pairs of measurements is 0.084 mmol/mol (±0.072 standard deviation) and smaller than the overall variability in Sr/Ca (Fig. 5A).

Average Mg/Ca of single laser ablation spots range between 1 and 8 mmol/mol (Fig. 5B), with an average ratio of 3.6 mmol/mol (±1.2 standard deviation) and no ontogenetic trend (regression analysis, $R^2 < 0.001$). Nor was there a significant difference in Sr/Ca or Mg/Ca between coiling directions. For the 15 pairs of measurements on the same chamber, the average difference in Mg/Ca from these spots is 0.48 mmol/mol (±0.64 standard deviation), which equals 16% of the average Mg/Ca. This average difference is comparable to the average difference between two laser ablation measurements randomly taken from the complete dataset (see end of this section).

The variability (standard deviation) between single-chamber Mg/Ca (±33% of the average; Fig. 5B) is larger than for Sr/Ca (±8% of the average; Fig. 5A). The large number of measurements results in a small standard error of the mean (<1% and ~5% for Sr/Ca and Mg/Ca, respectively; Fig. 5A and B).

When comparing successive chambers counting from the proloculus onward, there is no trend in Sr/Ca (nor in Mg/Ca) with chamber number. The layering caused by so-called bilamellar calcification in Rotaliid species (Reiss, 1957; Erez, 2003) means that we prefer to compare chambers that have the same number of lamellae (thus comparing all F chambers, F-1, etc.; Fig. 5A and B).

Not all individuals had the same number of chambers at the end of the experiment, which might mask (subtle) ontogenetic trends in

Table 2
Reproduction, growth and amount of calcite available for chemical analyses. Dextral coiling is clockwise addition of chambers on the spiral side: sinistral is anti-clockwise. 'n.d.' = not determined.

	Clone Group 1	Clone Group 2	Clone Group 3
Number of juveniles	244	116	103
Incubation time (days)	21	17	17
Chambers after incubation	14.7 ± 2.0 (n = 94)	12.2 ± 2.1 (n = 96)	5–7 (n = 50)
Mean growth rate (chambers added/day)	0.70	0.72	0.35
Dextral coiling	52% (n = 94)	35% (n = 55)	n.d.
Sinistral coiling	48% (n = 94)	65% (n = 55)	n.d.
Individuals analyzed for element/Ca	10	5	10
Chambers analyzed for element/Ca	111	42	32

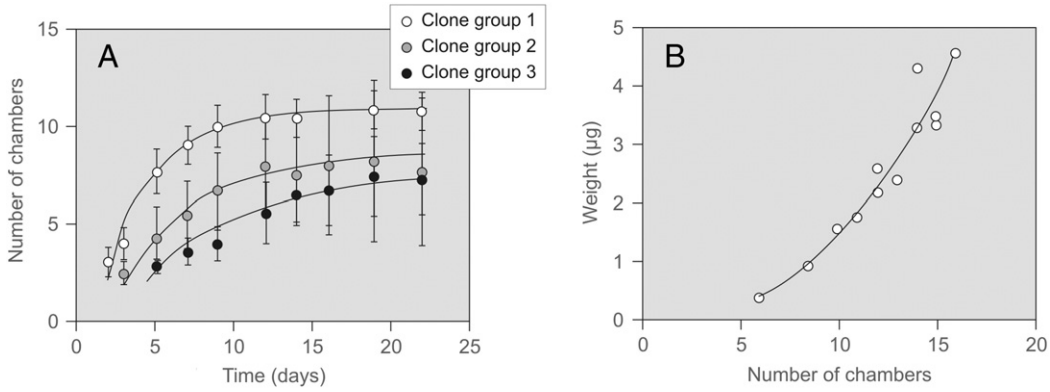

Fig. 3. Growth rates (A, ± 1 standard deviation) for each of the three clone groups and chamber-normalized weights (B) of cultured *A. tepida*. The weight of tests increases exponentially with every chamber being added ($R^2 = 0.934$; compared to 0.888 for a linear fit) and is described by: $w = 0.138e^{0.225n}$, where w is the $CaCO_3$ weight of an individual test in µg and n is the chamber number (1 = proloculus).

element/Ca ratios. Therefore we also tested for changes in Sr/Ca and Mg/Ca with chamber number within individuals. For the 22 individuals that were ablated 3 or more times, no significant intra-individual trend was observed in Sr/Ca or Mg/Ca (Student's *t*-test using residual sum of squares from a linear regression, $p < 0.05$). Since some individuals have the same final number of chambers, these tests were repeated on results combined for individuals with 18, 17, 16, 15, 8 and 7 chambers. None of the resulting regression analyses and *t*-tests indicated a significant increase or decrease of Sr/Ca or Mg/Ca with chamber number. Finally, we compared all F-chambers measured (n = 16) and conducted a regression analysis for Sr/Ca and Mg/Ca as a function of final number of chambers. This too revealed no significant trend with chamber number.

To evaluate the relation between the number of observations (i.e. laser ablation spots) and the representativeness of the resulting average Mg/Ca of all measurements, a Monte Carlo Permutation test was executed. From all 207 laser ablation-determined Mg/Ca ratios, a randomly selected ratio was taken to calculate the deviation from the average Mg/Ca (=3.6 mmol/mol). This was repeated 50 times to calculate the average deviation from the data set's mean Mg/Ca (based on 207 laser ablation measurements). This value approximates the uncertainty in Mg/Ca when using only one laser spot to determine the average Mg/Ca in a dataset like ours. This procedure was repeated by taking 50 sets of two randomly selected Mg/Ca to calculate the average deviation from the dataset's mean Mg/Ca, then taking 50 sets of three randomly selected Mg/Ca, etc. (Fig. 6). The relationship between the number of laser ablation spots and the deviation from the dataset's average resembles $1/\sqrt{n}$.

3.4. Interindividual variability in Sr/Ca and Mg/Ca

Combining the results from laser ablation spots on the same individual (on average 7.7 spots) provides an estimate of variability in Sr/Ca and Mg/Ca between the 25 analyzed individuals (Fig. 7). The three individuals with less than 3 laser ablation spots/individual are not discussed further in this section.

To compare the Sr/Ca and Mg/Ca between individuals, a one-way ANOVA test was performed for every possible pair of individuals, 231 in total. Of all these pairs, the Mg/Ca of 80 pairs of individuals (35%) was significantly different ($p < 0.05$). Of these 80 pairs, only four individuals are involved in 51 pairs. This means that, with the exception of these four individuals (two at the far left and two at the far right side in Fig. 7A), the average Mg/Ca of 87% of all possible combinations of two individuals is not significantly different from each other. Interindividual differences for Sr/Ca are similar with 67 out of 231 pairs (29%) that are being significantly different. Of these 67 pairs, three individuals (one at the left side and two at the far right side in Fig. 7B) are involved in 31 significantly different average individual's Sr/Ca. This means that excluding these three individuals, the average Sr/Ca of 84% of all possible combinations of two individuals are not significantly different from each other.

3.5. Inter-clone group variability and summary

When separating all single chamber Sr/Ca and Mg/Ca values into the three groups of clones, the resulting averages are very similar. Average Sr/Ca of each of the three groups is 1.56 mmol/mol, with variability (standard deviation) within groups of 0.11, 0.15 and 0.16 mmol/mol. Average Mg/Ca for the three groups is 3.68 mmol/mol (±1.21, n = 110), 3.51 mmol/mol (±0.99, n = 31) and 3.33 mmol/mol (±0.80, n = 32). Differences in single-chamber Sr/Ca and Mg/Ca between any combination of clone groups are not significant (two-tailed Student's *t*-test, assuming unequal variances, $p < 0.95$), although the limited number of clone groups that are compared here hampers generalization of the calculated variability between them.

Average Mg/Ca and Sr/Ca and the variability of different hierarchical levels are summarized in Table 3.

Table 3: different levels of variability in Sr/Ca and Mg/Ca. The variability within test walls was determined on 12 individuals, displaying relatively high within-wall variability in Mg/Ca. The associated average standard deviation for these ablation profiles is ~40% of the average Mg/Ca. Calculated standard deviation for the inter-individual level is based on averages for the 22 individuals and the range in standard deviations for the clone groups represent the variability within these three groups.

4. Discussion

4.1. Reproduction, growth rates and size-normalized weights

Using the offspring of reproducing foraminifera provides a number of advantages for studying minor and trace element incorporation in foraminiferal calcite. In a number of culture experiments growth is monitored by incorporation of a fluorescent marker (Bernhard et al., 2004) after which newly formed chambers (either stained or recognized after pre-incubation with the label) can be analyzed individually. Although the effect of such markers on calcite Mg/Ca and Sr/Ca may be limited (Dissard et al., 2009), its complexation potential dictates the need to be accounted for in culturing studies (De Nooijer et al., 2007).

When culture-grown foraminifera with chambers formed before incubation are used for geochemical analysis, isotope- and element composition of calcite added under experimental conditions have to be corrected for the initial calcite weight of the test when whole individuals are analyzed (e.g. Kisakürek et al., 2011). Alternatively, newly

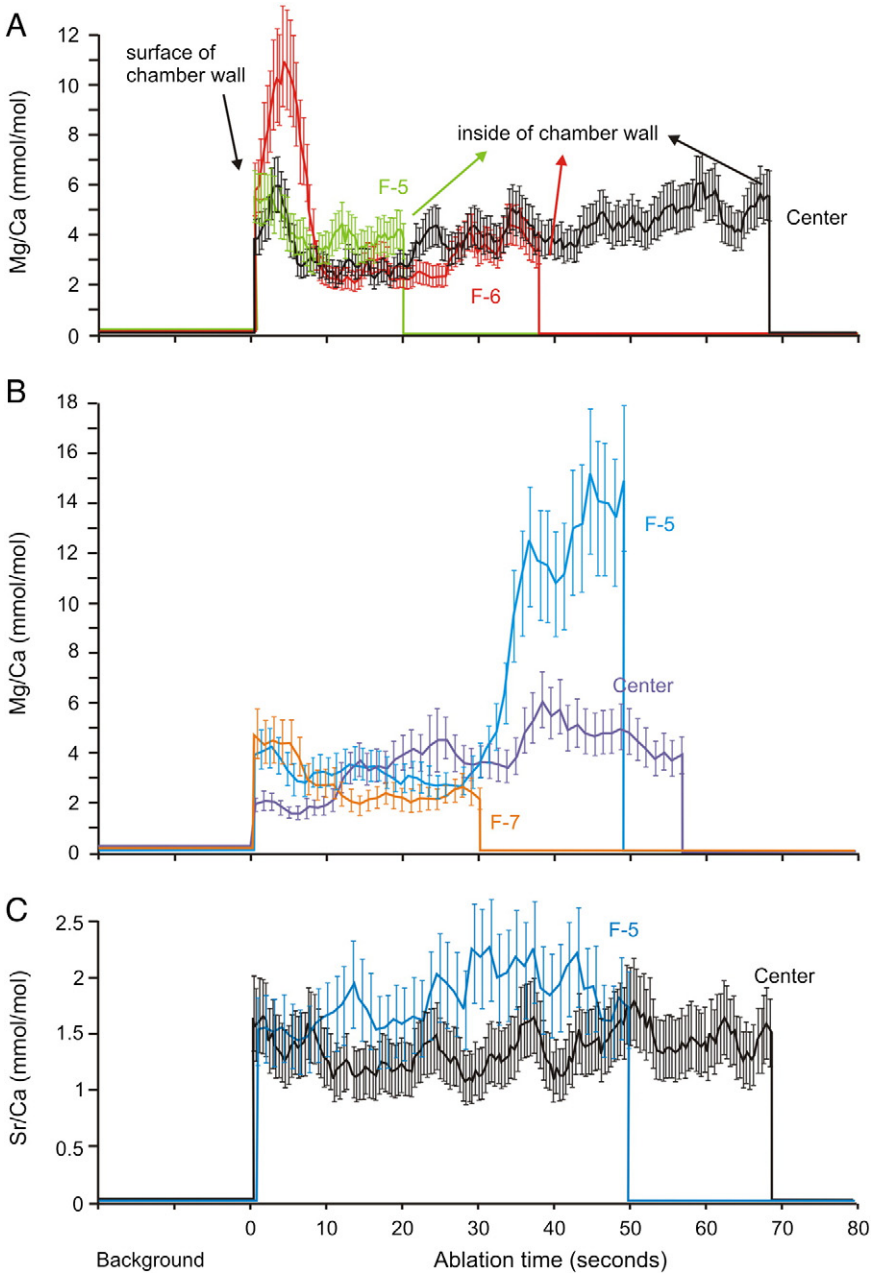

Fig. 4. Sr/Ca and Mg/Ca ablation profiles from cultured *Ammonia tepida*. A: Mg/Ca of three different chambers obtained at GEOMAR, B: Mg/Ca of three different chambers obtained at Utrecht University and C: Sr/Ca of one chamber obtained at Utrecht University (in black) and one obtained at GEOMAR (in blue). Error bars are based on within-profile variability of a powder pellet of the JCp-1 carbonate standard (Okai et al., 2002, 2004).

formed chambers can be dissected from pre-existing chambers in planktonic species and pooled for analysis (e.g. Spero and Lea, 1996; Bijma et al., 1998). Using newborn clones (Section 2.1; Hintz et al., 2006; McCorkle et al., 2008; Filipsson et al., 2010; Barras et al., 2010; Diz et al., 2012) circumvents the inaccuracies associated with such manipulations and allows analysis of the smallest foraminifer size fractions. Moreover, using LA-ICP-MS, the full range of chamber sizes can be analyzed for elements with sufficiently high concentrations (e.g. Reichart et al., 2003).

In our experiment, growth rates progressively decreased from approximately 1 chamber/day to 1 chamber/week. The time period between two chamber additions is relatively short in juveniles and increases as the individual matures (Fig. 3A). Since mass increases exponentially with every chamber added in this species (Fig. 3B), this results in a relatively constant rate of $CaCO_3$ addition over time (from approximately 0.70 to 0.15 μg/day for clone groups that grew slowest and fastest, respectively). The addition of calcite in foraminifera is however, concentrated into short time-intervals during which chambers are formed (~hours; Keul et al., 2013).

Calcite precipitation rates are known to affect Sr/Ca, more than Mg/Ca (e.g. Lorens, 1981; Morse and Bender, 1990; Tesoriero and Pankow, 1996). A similar rate of calcite addition (in μg/day) over time therefore fits the absence of an ontogenetic trend and limited variability of calcite Sr/Ca (and to a lesser extent Mg/Ca; Fig. 5A and B, Section 3.3). A caveat here is that overall calcite addition of an individual provides no information about crystal growth rate, which is essentially unknown. Moreover, element partitioning in inorganically precipitated calcites may not be directly comparable to that in foraminifera, since the

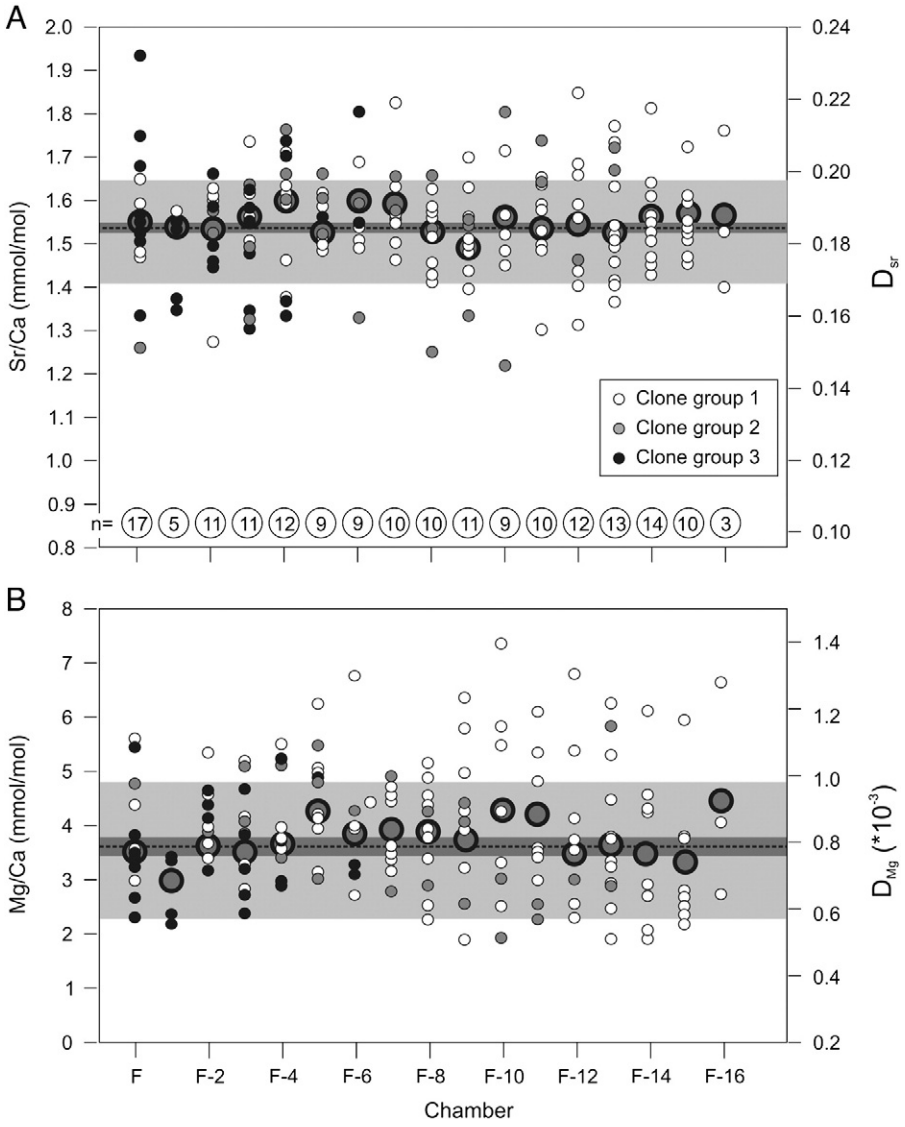

Fig. 5. Average Sr/Ca (panel A), Mg/Ca (panel B) and partition coefficients (D_{Sr} and D_{Mg}) from single-chamber analyses of 30 individuals of cultured *A. tepida* as a function of the position within the foraminifer. Every point represents one laser ablation spot. On the left side, analyses of the final (F) chamber are plotted, while measurements towards the right side represent Sr/Ca and Mg/Ca from older chambers. Black, gray and white symbols represent the three different clone groups. Larger circles represent average Sr/Ca and Mg/Ca for each chamber position. The dotted line and surrounding gray box represent the average ±1 standard error of the mean. The lighter gray box represents ± 1 standard deviation. Number of laser ablation spots per chamber position is indicated in circles at the lower side of panel A.

microenvironment in which foraminifera precipitate calcite is under biological control (e.g. Erez, 2003; De Nooijer et al., 2009b) where element concentrations, pH, and the presence of organic compounds can all differ from inorganic precipitation experiments.

4.2. Test wall variability in Mg/Ca

Magnesium is known to be heterogeneously distributed through chamber walls of a number of species (Eggins et al., 2003; Erez, 2003; Hathorne et al., 2003; Eggins et al., 2004; Anand and Elderfield, 2005; Sadekov et al., 2005; Toyofuku and Kitazato, 2005; Kunioka et al., 2006; Sadekov et al., 2008; Hathorne et al., 2009; Wit et al., 2010). The laser ablation profiles from our cultured individuals also show a large variability in Mg/Ca within a chamber wall and between chamber walls despite constant culturing conditions (Fig. 4). Early formed chambers positioned near the center of the individual, contain relatively more layers of calcite produced during consecutive chamber formation events. The absence of an increase or decrease in Mg/Ca within these inner chambers fits with the absence of an interchamber trend of Mg/Ca with size (Fig. 5B). This is important to note, since the lamellar structure of the ontogenetic calcite in Rotaliids (Erez, 2003) may mask (subtle) ontogenetic trends in chamber-to-chamber element distribution. The irregular position of the Mg/Ca peaks in the profiles (Fig. 4) furthermore suggests that the location of high-Mg calcite is not related to the location of organic layers that separate the layers of lamellar calcite (e.g. Hemleben et al., 1977).

Part of the variability in Mg- and Sr-incorporation observed in our dataset may be caused by variability in the microenvironment between individuals. Respiration (e.g. Rink et al., 1998) and proton pumping (Glas et al., 2012) during calcification alter the carbonate chemistry in the direct surrounding of the test and thus may have an effect on the chemical speciation of ions like Mg and Sr, thereby possibly affecting their uptake and eventually the calcitic Sr/Ca and Mg/Ca. In *Ammonia*, ion pumping during calcification decreases the surrounding pH by up to 1 unit (Glas et al., 2012). Since this decrease in pH is size-dependent, and the uptake of Ca^{2+} (and possibly other cations like Mg and Sr too) takes place during calcification in *Ammonia* (Nehrke et al., 2013), there may be a size-related change in Mg/Ca in our cultured specimens. Since this is not the case (Fig. 5 and accompanying text), it is unlikely that pH in the foraminiferal microenvironment significantly

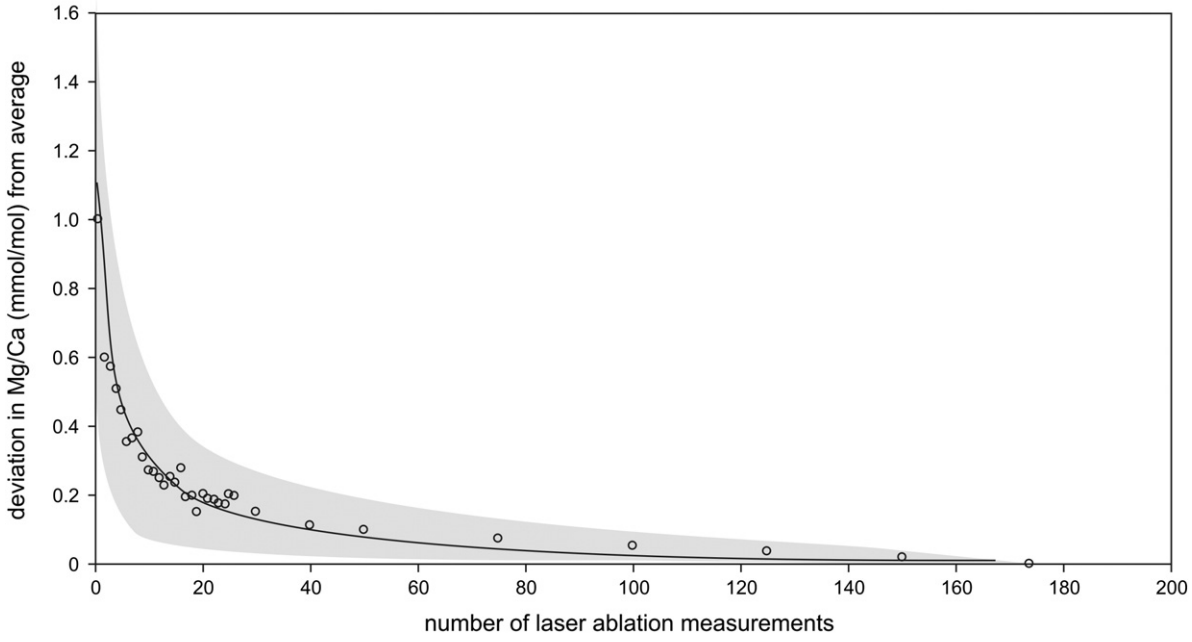

Fig. 6. Relation between number of laser ablation spots and deviation from the set average Mg/Ca (n = 50, see text for explanation) from the average Mg/Ca of the complete dataset (=3.6 mmol/mol). With ~6 laser ablation measurements on different chambers (or positions on the test) the deviation is approximately 10% of the average of the dataset, with ~20 measurements, the estimated Mg/Ca is within 5% of the average of the complete dataset.

impacts Mg/Ca. Since respiration rates are likely to have a relatively small impact on ambient (pH) gradients, it is unlikely that these processes can account for a large portion of the variability in Mg/Ca reported here.

4.3. Interchamber and size-related variability in Sr/Ca and Mg/Ca

In the *Ammonia tepida* samples from this study, there is no detectable control of coiling direction or ontogeny (i.e. size-related) on Mg/Ca and Sr/Ca as the average ratios do not change with size (number of chambers: Fig. 5). This is in contrast with a number of reports on size-specific Mg/Ca ratios in other species of benthic foraminifera from culturing experiments (Hintz et al., 2006; Filipsson et al., 2010; Diz et al., 2012). Discrepancies between studies could stem from species-specific differences in controls on element incorporation, sample size, or both. Field studies of planktonic species show Mg/Ca increases with size in some species and decreases with size in other species (Elderfield et al., 2002; Anand and Elderfield, 2005; Friedrich et al., 2012), while under controlled constant conditions, Mg/Ca of the planktonic *Globigerinoides sacculifer* decreases with size (Dueñas-Bohórquez et al., 2011a). This implies that part of the relation between planktonic foraminiferal shell size and Mg/Ca is determined by calcification at different water depths (and hence different temperatures), and part of the ontogenetic controls on Mg/Ca are not environment-induced. Raitzsch et al. (2011a, 2011b) show the variability of Mg/Ca and B/Ca ratios are related within single tests of the benthic *Planulina wuellerstorfi* suggesting that changes in carbonate chemistry within the sediment pore waters could be responsible for some of the Mg/Ca variability. Interchamber variability may thus be explained by migration within the sediment (for benthic species) or calcification at different ambient temperatures (for planktonic species). Still, variability in Mg/Ca is often too large to be explained by vertical migration (e.g. Hathorne et al., 2009).

Based on the interchamber variability of Mg/Ca in our dataset (Fig. 5), we calculate that the average Mg/Ca of the *A. tepida* populations can be estimated with a precision of 10% using 6 laser ablation measurements on different chambers (Fig. 6). Under the controlled conditions used here the number of individuals on which these 6 measurements are performed, is irrelevant for the precision obtained. However, the interchamber (and interindividual) variability in Mg/Ca may be different between species and depend on the absolute Mg/Ca ratios. This means that the representativeness of 6 laser ablation measurements may be better or worse for samples with other foraminiferal species.

4.4. Interindividual and inter-clone group variability of Sr/Ca and Mg/Ca in *Ammonia* spp

A number of previous culturing experiments and field surveys using *Ammonia* spp. resulted in similar Sr/Ca and Mg/Ca values as those presented here. In those studies calcitic Mg/Ca was shown to depend on temperature (Toyofuku et al., 2011) and seawater [Ca^{2+}] (Raitzsch et al., 2010). Studies of the dependence of calcitic Mg/Ca in benthic foraminifera on salinity have produced contradictory results (Dissard et al., 2010a; Toyofuku et al., 2011; Diz et al., 2012), while Mg/Ca in the calcite of cultured individuals of *Ammonia tepida* is not influenced by seawater carbonate ion concentration (Dissard et al., 2010b; Dueñas-Bohórquez et al., 2011b). Sr/Ca ratios of *A. tepida* are known to depend on seawater salinity (Dissard et al., 2010a), whereas an effect of carbonate ion concentration is absent (Raitzsch et al., 2010; Dueñas-Bohórquez et al., 2011b) or slightly positive (Dissard et al., 2010b).

Intra- and inter-individual variability in Mg/Ca is usually larger than that for Sr/Ca (e.g. Allison and Austin, 2003). The large variability in Mg/Ca is attributed to a number of factors including variability in environmental conditions (Wit et al., 2012), genetic differences between individuals (Numberger et al., 2009), and ontogenetic effects (Elderfield et al., 2002). Small fluctuations in experimental conditions cannot be responsible for the variability in Mg/Ca, since the dependency of Mg/Ca on temperature and salinity is too small in *Ammonia* spp. to account for the observed variability (e.g. Toyofuku et al., 2011; this study). Our results show that the small sample size afforded by LA-ICP-MS allows the detection of interindividual (and intrachamber) variability in the Mg distribution. To account for this small-scale variability, the average Mg/Ca of one or more complete individual tests can be determined by combining multiple measurements on one individual (Fig. 7).

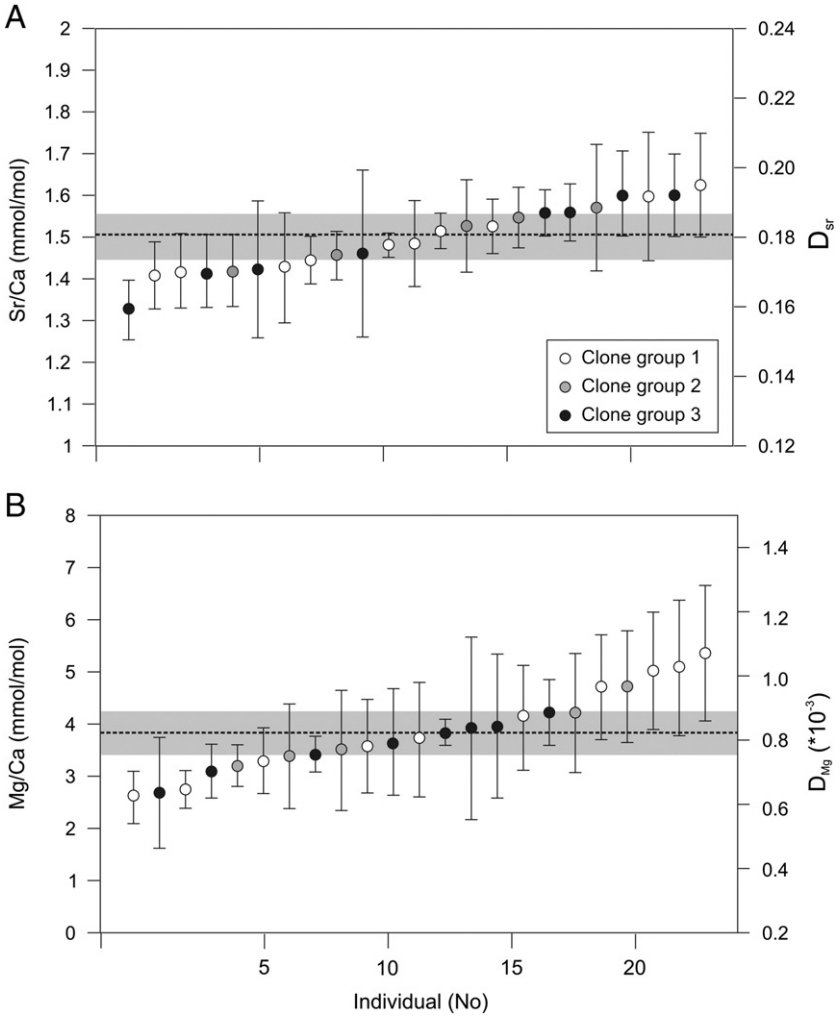

Fig. 7. A: Variability of single individual Sr/Ca in cultured *A. tepida*. Results from all laser spots (Fig. 5A) are combined to display the inter-individual variability in Sr/Ca (average per individual ± 1 standard deviation). These data have been ranked according to their Sr/Ca ratio (note that the ranking for inter-individual Mg/Ca is different). B: Variability of Mg/Ca in cultured individuals. Results from single-chamber measurements (Fig. 5B) are combined to display the inter-individual variability in Mg/Ca (average per individual ± 1 standard deviation). For both panels, dotted horizontal line is the average element/Ca of all individuals and accompanying dark gray box represents 1 standard deviation.

4.5. Implications for paleo-environmental studies

The presence or absence of ontogenetic controls on element incorporation is important for the use of foraminifera in paleoceanography. The recognition of size-related controls in Mg/Ca (e.g. Dueñas-Bohórquez et al., 2011a) has lead to the proposal of using correction factors when applying Mg/Ca-based temperature reconstructions. If the absence of an ontogenetic trend (as observed here) is representative for foraminifera in general, ontogenetic trends found in natural samples then most likely result from environmental changes (e.g. migration through the water column for planktonic species). This changes the view of parts of the vital effect from being 'biological noise' to being 'environmental information', the later potentially providing a useful paleoclimate proxy.

Furthermore, our results show that despite substantial intra-test variability, the average Sr/Ca of individual tests of *Ammonia tepida* is reproducible to ±0.043 mmol/mol and Mg/Ca to 0.40 mmol/mol. These uncertainties are based on the variability between the average laser spot-derived Sr/Ca and Mg/Ca when combining data from one individual (n = 23; Fig. 7). Variability between single measurements is considerably larger (Fig. 5). To translate the Mg/Ca reproducibility into an error for temperature reconstructions using Mg/Ca data based on single individuals, we have combined our results with those from

Table 3
Different levels of variability in Sr/Ca and Mg/Ca. The variability within test walls was determined on 12 individuals, displaying relatively high within-wall variability in Mg/Ca. The associated average standard deviation for these ablation profiles is ~40% of the average Mg/Ca. Calculated standard deviation for the inter-individual level is based on averages for the 22 individuals and the range in standard deviations for the clone groups represent the variability within these three groups.

	Sr/Ca		Mg/Ca	
	Range (min–max in mmol/mol)	SD	Range (min–max in mmol/mol)	SD
Within test walls (n = 12)	1.0–2.5	0.39/Ablation profile	1.1–14	1.9/Ablation profile
Inter-chamber (n = 173)	1.2–2.0	0.13	1.7–7.0	1.2
Inter-individual (n = 22)	1.4–1.7	0.084	2.5–5.0	0.72
Within clone group (n = 3)	1.56	0.11–0.16	3.33–3.68	0.80–1.2

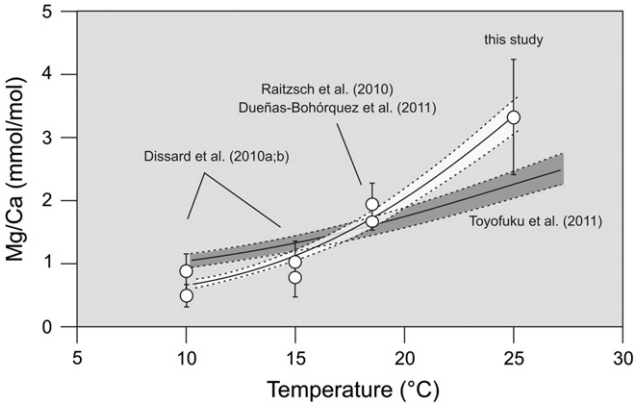

Fig. 8. Mg/Ca-T relationship for cultured *A. tepida*. All culture data (Raitzsch et al., 2010; Dissard et al., 2010a, 2010b; Dueñas-Bohórquez et al., 2011b; this study) are from individuals grown at similar salinity (32–35) and inorganic carbon chemistry (e.g. pH 8.1–8.4 and $[CO_3^{2-}]$ of 160–260 μmol/kg). Symbols represent average Mg/Ca from all laser ablation data from these studies.

previous culturing studies (Fig. 8). The *Ammonia* cultured by Dissard et al. (2010a, 2010b) and Dueñas-Bohórquez et al. (2011b) were all collected from the Wadden Sea and cultured using similar culturing set-ups. Together with our new data, these foraminifera were cultured at a range of temperatures from 10 to 25 °C. The obtained exponential relationship between Mg/Ca and temperature ($R^2 = 0.86$) is described by:

$$Mg/Ca = 0.167(\pm\ 0.064) * \exp^{0.121\ \ (\pm 0.019) * T} \quad (1)$$

According to the exponential factor, a change in Mg/Ca of 0.40 mmol/mol in *Ammonia tepida* (Fig. 7) corresponds to a temperature change of 0.9 °C at 25 °C. It should be stressed that this uncertainty is based on the calculated inter-individual variability in Mg/Ca and at 25 °C only. The recently published Mg/Ca-T relationship of Toyofuku et al. (2011) produces a Mg/Ca for *Ammonia beccarii* at 25 °C (2 mmol/mol ± 0.3), approximately two times lower than that of *A. tepida* (Eq. (1)). The exponential factor of the Mg/Ca-T relationship for *A. beccarii* is also approximately two times lower ($Mg/Ca = 0.575 * e^{0.0531 * T}$) than found here. Mg/Ca from cultured *A. tepida* reported by Diz et al. (2012) fit the Mg/Ca-T calibration from Toyofuku et al. (2011) better than the one presented here, suggesting that even within a single genus, there may be (small) differences in the control on Mg-incorporation. Taxonomy for the genus *Ammonia* is notoriously unreliable (e.g. Holzmann and Pawlowski, 2000; Hayward et al., 2004), and specimens commonly used for laboratory studies span a wide genetic range. Those employed by Toyofuku et al. (2011) are *Ammonias* of molecular type T4, those of Diz et al. (2012) of type T3 and those lumped for our calibration (Fig. 8) are of molecular type T6 (Hayward et al., 2004), which may account for the variability in Mg/Ca-T calibrations reported so far. Differences in Mg/Ca ratios of the closely related genotypes, or even within one species underscores the need for species-specific calibrations before applying foraminiferal Mg/Ca in paleoceanographic reconstructions (e.g. Anand et al., 2003).

The error in a Mg/Ca-based reconstructed seawater temperature is a combination of the error arising from the inherent, biological variability in Mg/Ca (Fig. 6) and that associated with the uncertainty in the Mg/Ca-T regression (Eq. (1)). For a number of planktonic species, uncertainties in the Mg/Ca-temperature calibration are ~0.06 for the pre-exponential constant and ~0.02 for the exponential one (e.g. Dekens et al., 2002; Anand et al., 2003) and are similar to those reported here (Eq. (1)). The uncertainty in the pre-exponential constant results in a temperature offset of 1.1–1.4 °C. Error propagation using partial derivatives of this uncertainty and the one resulting from biological noise reported here (Fig. 6), shows that the total error in seawater temperature reconstruction is 2.1 °C at 25 °C and <1 °C at 10 °C, assuming a 5% error when using 20 laser ablation-derived Mg/Ca values. With only 6 laser ablation measurements (resulting in a ~10% error), the uncertainty in temperature increases to 3.1 °C at 25 °C and 1.2 °C at 10 °C.

The inherent, biological variability in Mg/Ca found here may be different at other temperatures. If, however, the relative variability in Mg/Ca is similar (i.e. ~10%) across temperatures, this would result in an error of ~0.75 °C at 1.0 °C and ~0.85 °C at 10 °C. If the absolute variability in Mg/Ca (~0.40 mmol/mol) would be constant across temperatures, absolute temperature estimates would be much more uncertain at lower temperatures. Reported variability in Mg/Ca at different temperatures (e.g. Nürnberg et al., 1996; Sadekov et al., 2008) seem to suggest that relative variability in Mg/Ca is similar across temperatures.

5. Conclusions

Our results show that Mg/Ca and Sr/Ca in the calcite of *Ammonia tepida* is not influenced by ontogeny as there is no clear trend in the variability with size in the absence of environmental change with ontogeny. The intra-chamber, inter-chamber and inter-individual variability of Mg/Ca is larger than that of Sr/Ca, in line with previous studies of within shell element/Ca ratios. The variability in Mg/Ca within and between individuals is not related to environmental conditions and is not correlated to genetic variability or similarity. With the variability in calcitic Mg/Ca in our dataset, 6 laser ablation spots per individual *A. tepida* are sufficient to estimate the average with an uncertainty of 10%, thereby accounting for the biological noise on Mg/Ca-based temperature reconstructions.

Acknowledgments

We kindly acknowledge H. Kuhnert from the University of Bremen for his assistance with the analyses in Bremen. Eight anonymous reviewers are thanked for their comments on earlier versions of this manuscript. This work was supported by the European Commission through grant 211384 (EU FP7 "EPOCA"). Financial support for BIOACID was provided by the German Federal Ministry of Education and Research (BMBF, FKZ 03 F0608). The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement 265103 (Project MedSeA). This work was funded in part by The European Research Council (ERC grant 2010-NEWLOG ADG-267931 HE) and in part by the Darwin Center for Biogeosciences.

References

Allison, N., Austin, W.E.N., 2003. The potential of ion microprobe analysis in detecting geochemical variations across individual foraminifera tests. Geochem. Geophys. Geosyst. 4, GC000430.
Anand, P., Elderfield, H., 2005. Variability of Mg/Ca and Sr/Ca between and within the planktonic foraminifers *Globigerina bulloides* and *Globorotalia truncatulinoides*. Geochem. Geophys. Geosyst. 6, Q11D15.
Anand, P., Elderfield, H., Conpte, M.H., 2003. Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series. Paleoceanography 18, PA000846.
Barras, C., Duplessy, J.-C., Geslin, E., Michel, E., Jorissen, F.J., 2010. Calibration of $\delta^{18}O$ of cultured benthic foraminiferal calcite as a function of temperature. Biogeosciences 7, 1349–1356.
Beer, C.J., Schiebel, R., Wilson, P.A., 2010. Testing planktonic foraminiferal shell weight as a surface water $[CO_3^{2-}]$ proxy using plankton net samples. Geology 38, 103–106.
Bentov, S., Erez, J., 2006. Impact of biomineralization processes on the Mg content of foraminiferal shells: a biological perspective. Geochem. Geophys. Geosyst. 7, GC001015.
Bernhard, J.M., Blanks, J.K., Hintz, C.J., Chandler, G.T., 2004. Use of fluorescent calcite marker calcein to label foraminiferal tests. J. Foramin. Res. 34, 96–101.
Bijma, J., Hemleben, C., Huber, B.T., Erlenkeuser, H., Kroon, D., 1998. Experimental determination of the ontogenetic stable isotope variability in two morphotypes of *Globigerinella siphoniphera* (d'Orbigny). Mar. Micropaleontol. 35, 141–160.
Blackmon, P.D., Todd, R., 1959. Mineralogy of some foraminifera as related to their classification and ecology. J. Paleontol. 33, 1–15.
De Moel, H., Ganssen, G.M., Peeters, F.J.C., Jung, S.J.A., Kroon, D., Brummer, G.J.A., Zeebe, R.E., 2009. Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification? Biogeosciences 6, 1917–1925.

De Nooijer, L.J., Reichart, G.J., Dueñas-Bohórquez, A., Wolthers, M., Ernst, S.R., Mason, P.R.D., Van der Zwaan, G.J., 2007. Copper incorporation in foraminiferal calcite: results from culturing experiments. Biogeosciences 4, 493–504.
De Nooijer, L.J., Toyofuku, T., Kitazato, H., 2009a. Foraminifera promote calcification by elevating their intracellular pH. Proc. Natl. Acad. Sci. U. S. A. 106, 15374–15378.
De Nooijer, L.J., Langer, G., Nehrke, G., Bijma, J., 2009b. Physiological controls on the seawater uptake and calcification in the benthic foraminifer *Ammonia tepida*. Biogeosciences 6, 2669–2675.
Debenay, J.P., Bénéteau, E., Zhang, J., Stouff, V., Geslin, E., Redois, F., Fernandez-Gonzalez, M., 1998. *Ammonia beccarii* and *Ammonia tepida* (Foraminifera): morphofunctional arguments for their distinction. Mar. Micropaleontol. 34, 235–244.
Dekens, P.S., Lea, D.W., Pak, D.K., Spero, H.J., 2002. Core top calibration of Mg/Ca in tropical foraminifera: refining paleotemperature estimation. Geochem. Geophys. Geosyst. 3, 1022. http://dx.doi.org/10.1029/2001GC000200.
Delaney, M.L., Bé, A.W.H., Boyle, E.A., 1985. Li, Sr, Mg, and Na in foraminiferal calcite shells from laboratory culture, sediment traps, and sediment cores. Geochim. Cosmochim. Acta 49, 1327–1341.
Dissard, D., Nehrke, G., Reichart, G.J., Bijma, J., 2009. Effect of the fluorescent indicator calcein on Mg and Sr incorporation in foraminiferal calcite. Geochem. Geophys. Geosyst. 10, Q11001.
Dissard, D., Nehrke, G., Reichart, G.J., Bijma, J., 2010a. The impact of salinity on the Mg/Ca and Sr/Ca ratio in the benthic foraminifera *Ammonia tepida*: results from culture experiments. Geochim. Cosmochim. Acta 74, 928–940.
Dissard, D., Nehrke, G., Reichart, G.J., Bijma, J., 2010b. Impact of seawater pCO_2 on calcification and Mg/Ca and Sr/Ca ratios in benthic foraminifera calcite: results from culturing experiments with *Ammonia tepida*. Biogeosciences 7, 81–93.
Diz, P., Jorissen, F.J., Reichart, G.J., Poulain, C., Dehairs, F., Leorri, E., Paulet, Y.-M., 2012. Interpretation of benthic foraminiferal stable isotopes in subtidal estuarine environments. Biogeosciences 6, 2549–2560.
Dueñas-Bohórquez, A., Da Rocha, R.E., Kuroyanagi, A., Bijma, J., Reichart, G.J., 2009. effect of salinity and seawater calcite saturation state on Mg and Sr incorporation in cultured planktonic foraminifera. Mar. Micropaleontol. 73, 178–189.
Dueñas-Bohórquez, A., Da Rocha, R.E., Kuroyanagi, A., De Nooijer, L.J., Bijma, J., Reichart, G.J., 2011a. Interindividual variability and ontogenetic effects on Mg and Sr incorporation in the planktonic foraminifer *Globigerinoides sacculifer*. Geochim. Cosmochim. Acta 75, 520–532.
Dueñas-Bohórquez, A., Raitzsch, M., De Nooijer, L.J., Reichart, G.J., 2011b. Independent impacts of calcium and carbonate ion concentration on Mg and Sr incorporation in cultured benthic foraminifera. Mar. Micropaleontol. 81, 122–130.
Eggins, S.M., De Deckker, P., Marshall, J., 2003. Mg/Ca variation in planktonic foraminifera tests: implications for reconstructing palaeo-seawater temperature and habitat migration. Earth Planet. Sci. Lett. 212, 291–306.
Eggins, S.M., Sadekov, A., De Deckker, P., 2004. Modulation and daily banding of Mg/Ca in *Orbulina universa* tests by symbiont photosynthesis and respiration: a complication for sea water thermometry. Earth Planet. Sci. Lett. 225, 411–419.
Elderfield, H., Ganssen, G.M., 2000. Past temperature and $\delta^{18}O$ of surface ocean waters inferred from foraminiferal Mg/Ca ratios. Nature 405, 442–445.
Elderfield, H., Cooper, M., Ganssen, G., 2000. Sr/Ca in multiple species of planktonic foraminifera: Implications for reconstructions of seawater Sr/Ca. Geochem. Geophys. Geosyst. 1 (11). http://dx.doi.org/10.1029/1999GC000031.
Elderfield, H., Vautravers, M., Cooper, M., 2002. The relationship between shell size and Mg/Ca, Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ of species of planktonic foraminifera. Geochem. Geophys. Geosyst. 3. http://dx.doi.org/10.1029/2001GC000194.
Erez, J., 2003. The source of ions for biomineralization in foraminifera and their implications for paleoceanographic proxies. In: Dove, P.M., De Yoreo, J.J. (Eds.), Reviews in Mineralogy and Geochemistry. Mineralogical Society of America, Geochemical Society, vol. 54, pp. 115–149.
Filipsson, H., Bernhard, J.M., Lincoln, S.A., McCorkle, D.C., 2010. A culture-based calibration of benthic foraminiferal paleotemperature proxies: $\delta^{18}O$ and Mg/Ca results. Biogeosciences 7, 1335–1347.
Friedrich, O., Schiebel, R., Wilson, P.A., Weldeab, S., Beer, C.J., Cooper, M.J., Fiebig, J., 2012. Influence of test size, water depth, and ecology on Mg/Ca, Sr/Ca, delta-O18 and delta-C13 in nine modern species of planktonic foraminifera. Earth Planet. Sci. Lett. 319, 133–145.
Ganssen, G.M., Peeters, F.J.C., Metcalfe, B., Anand, P., Jung, S.J.A., Kroon, D., Brummer, G.J.A., 2011. Quantifying sea surface temperature ranges of the Arabian Sea for the past 20,000 years. Clim. Past 7, 1337–1349.
Glas, M., Langer, G., Keul, N., 2012. Calcification acidifies the microenvironment of a benthic foraminifer (*Ammonia* sp.). J. Exp. Mar. Biol. Ecol. 424–425, 53–58.
Goldstein, S.T., Moodley, L.M., 1993. Gametogenesis and the life cycle of the foraminifer *Ammonia beccarii* (Linné) forma tepida (Cushman). J. Foraminifer. Res. 23, 213–220.
Haarmann, T., Hathorne, E.C., Mohtadi, M., Groeneveld, J., Kölling, M., Bickert, T., 2011. Mg/Ca ratios of single planktonic foraminifer shells and the potential to reconstruct the thermal seasonality of the water column. Paleoceanography 26, PA3218.
Hathorne, E.C., Alard, O., James, R.H., Rogers, N.W., 2003. Determination of intratest variability of trace elements in foraminifera by laser ablation inductively coupled mass spectrometry. Geochem. Geophys. Geosyst. 4, GC000539.
Hathorne, E.C., James, R.H., Savage, P., Alard, O., 2008. Physical and chemical characteristics of particles produced by laser ablation of biogenic calcium carbonate. J. Anal. Atom. Spectrom. 23, 240–243.
Hathorne, E.C., James, R.H., Lampitt, R.S., 2009. Environmental versus biomineralization controls on the intratest variation in the trace element composition of the planktonic foraminifera *G. inflata* and *G. scitula*. Paleoceanography 24, PA4204.
Hayward, B.W., Holzmann, M., Grenfell, H.R., Pawlowski, J., Triggs, C.M., 2004. Morphological distinction of molecular types in *Ammonia*—towards a taxonomic revision of the world's most commonly misidentified foraminifera. Mar. Micropaleontol. 50, 237–271.
Hemleben, C., Bé, A.W.H., Anderson, O.R., Tuntivate, S., 1977. Test morphology, organic layers and chamber formation of the planktonic foraminifer *Globorotalia menardii* (D'Orbigny). J. Foramin. Res. 7, 1–25.
Hintz, C.J., Shaw, T.J., Chandler, G.T., Bernhard, J.M., McCorkle, D.C., Blanks, J.K., 2006. Trace/minor element: calcium ratios in cultured benthic foraminifera. Part II: ontogenetic variation. Geochim. Cosmochim. Acta 70, 1964–1976.
Ho, T.Y., Quigg, A., Finkel, Z.V., Milligan, A.J., Wyman, K., Falkowski, P.G., Morel, F.M.M., 2003. The elemental composition of some marine phytoplankton. J. Phycol. 39, 1145–1159.
Holzmann, M., Pawlowski, J., 1997. Molecular, morphological and ecological evidence for species recognition in *Ammonia* (Foraminifera). J. Foraminifer. Res. 27, 311–318.
Holzmann, M., Pawlowski, J., 2000. Taxonomic relationships in the genus *Ammonia* (Foraminifera) based on ribosomal DNA sequences. J. Micropaleontol. 19, 85–95.
Jochum, K.P., Weis, U., Stoll, B., Kuzmin, D., Yang, Q., Raczek, I., Jacob, D.E., Stracke, A., Birbaum, K., Frick, D.A., Günther, D., Enzweiler, J., 2011. Determination of reference values for NIST SRM 610–617 glasses following ISO guidelines. Geostand. Geoanal. Res. 35, 397–429.
Keul, N., Langer, G., De Nooijer, L.J., Bijma, J., 2013. Effect of ocean acidification on the benthic foraminifera *Ammonia* sp. is caused by a decrease in carbonate ion concentration. Biogeosci. Discuss. 10, 1147–1176.
Khider, D., Stott, L.D., Emile-Gray, J., Thunell, R., Hammond, D.E., 2011. Assessing El Niño southern oscillation variability during the past millennium. Paleoceanography 26, PA3222.
Kisakürek, B., Eisenhauer, A., Böhm, F., Hathorne, E.C., Erez, J., 2011. Controls on calcium isotope fractionation in cultured planktonic foraminifera, *Globigerinoides ruber* and *Globigerinella siphonifera*. Geochim. Cosmochim. Acta 75, 427–443.
Kunioka, D., Shirai, K., Takahata, N., Sano, Y., Toyofuku, T., Ujiie, Y., 2006. Microdistribution of Mg/Ca, Sr/Ca, and Ba/Ca ratios in *Pulleniantina obliquilloculata* test by using a NanoSIMS: implication for the vital effect mechanism. Geochem. Geophys. Geosyst. 7, Q12P20.
Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca ratios in benthic foraminiferal calcite. Science 287, 269–272.
Lorens, R.B., 1981. Sr, Cs, Mn and Co distribution coefficients in calcite as a function of calcite precipitation rate. Geochim. Cosmochim. Acta 45, 553–561.
McCorkle, D.C., Bernhard, J.M., Hintz, C.J., Blanks, J.K., Chandler, G.T., Shaw, T.J., 2008. The carbon and oxygen stable isotopic composition of cultured benthic foraminifera. In: Austin, W.E.N., James, R.H. (Eds.), Biogeochemical controls on paleoceanographic environmental proxies, pp. 135–154.
Morse, J.W., Bender, M.L., 1990. Partition coefficients in calcite: examination of factors influencing the validity of experimental results and their application to natural systems. Chem. Geol. 82, 265–277.
Mortyn, P.G., Elderfield, H., Anand, P., Greaves, M., 2005. An evaluation of controls on planktonic foraminiferal Sr/Ca: comparison of water column and core-top data from a North Atlantic transect. Geochem. Geophys. Geosyst. 6, Q12007.
Mucci, A., 1987. Influence of temperature on the composition of magnesian calcite overgrowths precipitated from seawater. Geochim. Cosmochim. Acta 51, 1977–1984.
Nehrke, G., Keul, N., Langer, G., De Nooijer, L.J., Bijma, J., Meibom, A., 2013. A new model for biomineralization and trace-element signatures of foraminiferal tests. Biogeosciences 10, 6759–6767.
Numberger, L., Hemleben, C., Hoffmann, R., Mackensen, A., Schultz, H., Wunderlich, J.-M., Kucera, M., 2009. Habitats, abundance patterns and isotopic signals of morphotypes of the planktonic foraminifer *Globigerinoides ruber* (d'Orbigny) in the eastern Mediterranean Sea since the Marine Isotopic Stage 12. Mar. Micropaleontol. 73, 90–104.
Nürnberg, D., Bijma, J., Hemleben, C., 1996. Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures. Geochim. Cosmochim. Acta 60, 803–814.
Okai, T., Suzuki, A., Kawahata, H., Terashima, S., Imai, N., 2002. Preparation of a new Geological Survey of Japan geochemical reference material: coral JCp-1. Geostand. Newslett. 26, 95–99.
Okai, T., Suzuki, A., Terashima, S., Inoue, M., Nohara, M., Kawahata, H., Imai, N., 2004. Collaborative analysis of GSJ/AIST geochemical reference materials JCp-1 (Coral) and JCt-1 (Giant Clam). Chikyukagaku (Geochemistry) 38, 281–286.
Oomori, T., Kaneshima, H., Maezato, Y., 1987. Distribution coefficient of Mg^{2+} ions between calcite and solution at 10–50 °C. Mar. Chem. 20, 327–336.
Raitzsch, M., Dueñas-Bohorquez, A., Reichart, G.J., De Nooijer, L.J., Bijma, J., 2010. Incorporation of Mg and Sr in calcite of cultured benthic foraminifera: impact of calcium concentration and associated calcite saturation state. Biogeosciences 7, 869–881.
Raitzsch, M., Hathorne, E.C., Kuhnert, H., Groeneveld, J., Bickert, T., 2011a. Modern and Late Pleistocene B/Ca ratios of the benthic foraminifer *Planulina wuellerstorfi* determined with Laser Ablation ICP-MS. Geology 39, 1039–1042.
Raitzsch, M., Kuhnert, H., Hathorne, E.C., Groeneveld, J., Bickert, T., 2011b. U/Ca in benthic foraminifers: a proxy for the deep-sea carbonate saturation. Geochem. Geophys. Geosyst. 12, Q06019.
Rathburn, A.E., De Deckker, P., 1997. Magnesium and strontium compositions of recent benthic foraminifera from the Coral Sea, Australia and Prydz Bay, Antarct. Mar. Micropaleontol. 32, 231–248.
Reichart, G.J., Jorissen, F.J., Anschutz, P., Mason, P.R.D., 2003. Single foraminiferal test chemistry records the marine environment. Geology 31, 355–358.
Reiss, Z., 1957. The Bilamellidae, nov. superfam. and remarks on Cretaceous Globorotaliids. Contrib. Cushman Found Foram. Res. 8, 127–145.
Rink, S., Kühl, M., Bijma, J., Spero, H.J., 1998. Microsensor studies of photosynthesis and respiration in the symbiotic foraminifer *Orbulina universa*. Mar. Biol. 131, 583–595.
Rosenthal, Y., Boyle, E.A., Slowley, N., 1997. Temperature control on the incorporation of magnesium, strontium, fluorine, and cadmium into benthic foraminiferal shells

from Little Bahama Bank: prospects for thermocline paleoceanography. Geochim. Cosmochim. Acta 61, 3633–3643.
Rosenthal, Y., Lear, C.H., Oppo, D.W., Linsley, B.K., 2006. Temperature and carbonate ion effects on Mg/Ca and Sr/Ca ratios in benthic foraminifera: aragonitic species *Hoeglundina elegans*. Paleoceanography 21, PA1007.
Sadekov, A.Y., Eggins, S.M., De Deckker, P., 2005. Characterization of Mg/Ca distributions in planktonic foraminifera species by electron microprobe mapping. Geochem. Geophys. Geosyst. 6, Q12P06.
Sadekov, A.Y., Eggins, S.M., De Deckker, P., Kroon, D., 2008. Uncertainties in seawater thermometry deriving from intratest and intertest Mg/Ca variability in *Globigerinoides ruber*. Paleoceanography 23, PA1215.
Spero, H.J., Lea, D.W., 1996. Experimental determination of stable isotope variability in *Globigerina bulloides*: implications for paleocanographic reconstructions. Mar. Micropaleontol. 28, 231–246.
Stouff, V., Lesourd, M., Debenay, J.P., 1999. Laboratory observations on asexual reproduction (schizogony) and ontogeny of *Ammonia tepida* with comment on the life cycle. J. Foraminifer. Res. 29, 75–84.
Tesoriero, A.J., Pankow, J.F., 1996. Solid solution partitioning of Sr^{2+}, Ba^{2+}, and Cd^{2+} to calcite. Geochim. Cosmochim. Acta 60, 1053–1063.
Toyofuku, T., Kitazato, H., 2005. Micromapping of Mg/Ca values in cultured specimens of the high magnesium benthic foraminifera. Geochem. Geophys. Geosyst. 6, GC000961.
Toyofuku, T., Suzuki, M., Suga, H., Sakai, S., Suzuki, A., Ishikawa, T., De Nooijer, L.J., Schiebel, R., Kawahata, H., Kitazato, H., 2011. Mg/Ca and $\delta^{18}O$ in the brackish shallow-water benthic foraminifer *Ammonia beccarii*. Mar. Micropaleontol. 78, 113–120.
Van Aken, H.M., 2008. Variability of the water temperature in the Western Wadden Sea on tidal to centennial time scales. J. Sea Res. 60, 227–234.
Wit, J.C., Reichart, G.J., Jung, S.J.A., Kroon, D., 2010. Approaches to unravel seasonality in sea surface temperatures using paired single-specimen foraminiferal $\delta^{18}O$ and Mg/Ca analyses. Paleoceanography 25, PA4220.
Wit, J.C., De Nooijer, L.J., Barras, C., Jorissen, F.J., Reichart, G.J., 2012. A reappraisal of the vital effect in cultured benthic foraminifer *Bulimina marginata* on Mg/Ca values: assessing temperature uncertainty relationships. Biogeosciences 9, 3693–3704.