Mg/Ca ratios of two *Globigerinoides ruber* (white) morphotypes: Implications for reconstructing past tropical/subtropical surface water conditions

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[1] Tests of the planktonic foraminifer *Globigerinoides ruber* (white; d'Orbigny) have become a standard tool for reconstructing past oceanic environments. Paleoceanographers often utilize the Mg/Ca ratios of the foraminiferal tests for reconstructing low-latitude ocean glacial-interglacial changes in sea surface temperatures (SST). We report herein a comparison of Mg/Ca measurements on sample pairs (n = 20) of two *G. ruber* (white) morphotypes (*G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato (s.l.)) from surface and downcore samples of the western Pacific and Indian Oceans. *G. ruber* s.s. refers to specimens with spherical chambers sitting symmetrically over previous sutures with a wide, high arched aperture, whereas *G. ruber* s.l. refers to a more compact test with a diminutive final chamber and small aperture. The *G. ruber* s.s. specimens generally show significantly higher Mg/Ca ratios compared to *G. ruber* s.l. Our results from the Mg/Ca ratio analysis suggest that *G. ruber* s.l. specimens precipitated their shells in slightly colder surface waters than *G. ruber* s.s. specimens. This conclusion is supported by the differences in $\delta^{18}O$ and $\delta^{13}C$ values between the two morphotypes. Although it is still unclear if these two morphotypes represent phenotypic variants or sibling species, our findings seem to support the hypothesis of depth and/or seasonal allopatry within a single morphospecies.

1. Introduction

[2] A major part of the current knowledge of past oceanographic systems is based on information derived from planktonic foraminifera. For this, the ecological preferences of individual planktonic foraminifera species and assemblages as well as the chemical compositions and stable isotopic ratios (e.g., Mg/Ca, δ^{13}C, or δ^{18}O) are used under the assumption that each morphospecies of planktonic foraminifera represents a genetically continuous species with a unique life habitat throughout ontogeny [*Hemleben and Bijma*, 1994; *Kucera and Darling*, 2002]. Recent molecular-genetic studies have demonstrated that many traditionally identified planktonic foraminifera species consist of complexes of genetically distinct types (see *de Vargas et al.* [2004] for a review). Through a morpho-chemical approach, e.g., test porosity, outline and geochemistry (stable isotopes, Mg/Ca ratios) on a few genetically sequenced morphospecies (e.g., *Globigerinella siphonifera*), it has been shown that newly discovered sibling species of a single morphospecies are probably adapted to different environmental conditions or depth habitats [*Huber et al.*, 1997; *Bijma et al.*, 1998; *Darling et al.*, 1999; *de Vargas et al.*, 2002], challenging the widely held view of a cosmopolitan species distribution. In addition to the taxonomic issue, this leads to an important conclusion concerning the interpretation of fossil planktonic foraminifera records: Slight morphological differences within classical species groups may reflect highly different environmental conditions and/or different life habitats. Although *G. ruber* (white; d'Orbigny) exhibits considerable morphological variations, its tests have become a standard tool for reconstructing past oceanic environments. Mg/Ca ratios, for example, are used for reconstructions of ancient SSTs in the tropics and subtropics where this morphospecies is most abundant. To date, four different *G. ruber* genotypes have been identified [*Kucera and Darling*, 2002, and references therein]. However, the genetic diversity of *G. ruber* has not yet been translated into distinguishable morphological features in order to differentiate them in the fossil record. *G. ruber* has both color (pink and white) and morphological variants, both of which have distinctive stable isotope signatures [*Williams et al.*, 1981; *Deuser and Ross*, 1989]. A number of morphotype variants of *G. ruber* have been recognized [e.g., *Parker*, 1962] and stable isotope analyses of different morphotypes from the same samples reveal statistically significant differences [*Berger*, 1970; *Hecht and Savin*, 1970, 1972; *Weiner*, 1975; *Robbins and Healy-Williams*, 1991; *Wang*, 2000; *Löwemark et al.*, 2005]. The differences in the isotopic signatures of recognized morphotype variants are interpreted to reflect a different depth habitat [*Hecht and Savin*, 1970, 1972; *Robbins and Healy-Williams*, 1991; *Wang*, 2000]. On the basis of these studies it seems that morphotype variants of single morphospecies are utilizing certain ecological niches.

[3] We report herein a first comparison of Mg/Ca measurements of two morphotype variants of *G. ruber* (white), namely *G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato (s.l.) [following *Wang*, 2000] that are common in the western Pacific (including South China Sea (SCS)) and Indian Oceans. The main purpose of this study is to test whether Mg/Ca analysis will reciprocate the previously observed distinct isotopic differences in different morphotypes as well as to offer better constraints on the use of different *G. ruber* morphotype variants for reconstructing past SSTs and the oxygen isotopic composition of seawater.

2. Material and Methods

2.1. Sediment Samples and Sample Preparation

[4] The core-top samples used in this study were taken from box cores and gravity cores obtained during R/V *SONNE* cruise 140 to the SCS and WEPAMA IMAGES VII/2001 cruise to the western Pacific and NE Indian Oceans (*Wiesner et al.* [1999] and *Houlborn et al.* [2002], respectively)
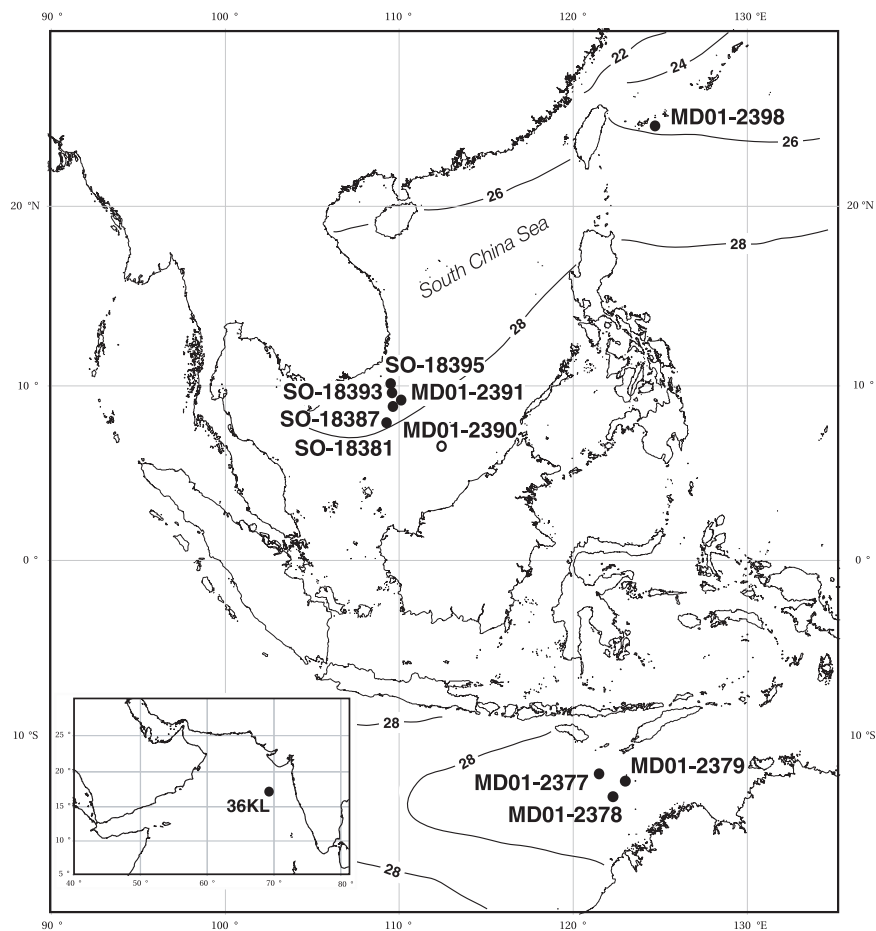
Figure 1. Site locations of sediment samples in the western Pacific and Indian Oceans. Thin isotherms represent the modern annual sea surface temperatures (in °C) at 0 m water depth (according to *Levitus and Boyer* [1994]).

(Figure 1). In addition, *G. ruber* morphotypes were picked from a core-top sample from the Arabian Sea (core 36KL, 17.1°N, 69.0°E, water depth 2055 m; see *Barker et al.* [2003] for details). A first downcore sample set was taken from gravity core MD01-2390 (06°38,12 N; 113°24,56 E; water depth of 1545 m; IMAGES VII cruise WEPAMA). The sample preparation followed standard procedures: The dried bulk samples were washed over a 63-μm sieve and dried at 40°C in an oven and subsequently dry sieved into subfractions. Prior to the geochemical analysis, foraminiferal census counts were performed on the >150 μm size fraction of downcore samples from core MD01-2390 in order to investigate variations in the *G. ruber* morphotype abundance. The samples were split into suitable aliquots of at least 300 specimens of planktonic foraminifera. The size fraction of 250–350 μm commonly used for Mg/Ca studies on *G. ruber* in low latitude oceanic settings [e.g., *Lea et al.*, 2000; *Visser et al.*, 2003] was used for picking specimens for Mg/Ca and stable isotope analysis.

2.2. Mg/Ca and Stable Isotope Analysis

[5] Core-top sample Mg/Ca analyses were performed on a Varian Vista ICP-AES at the Department of Earth Sciences, University of Cambridge. Precision and accuracy for Mg/Ca ratios are <0.5% (see *de Villiers et al.* [2002] for details). Downcore samples were analyzed using a Quadrupole-ICP-MS, Agilent 7500s, housed at the Department of Geosciences, National Taiwan University. The accuracy of Q-ICP-MS techniques was calibrated with primary standard solutions, which were prepared gravimetrically with ultrapure chemicals [*Shen et al.*, 2004]. The precision and external uncertainty are 0.1–0.2% and 0.4%, respectively [*Shen et al.*, 2004]. Mg/Ca were measured on samples composed of approximately 30–40 specimens (ca. 330–420 μg) of either of the two morphotypes of *G. ruber* (white) and cleaned using the cleaning
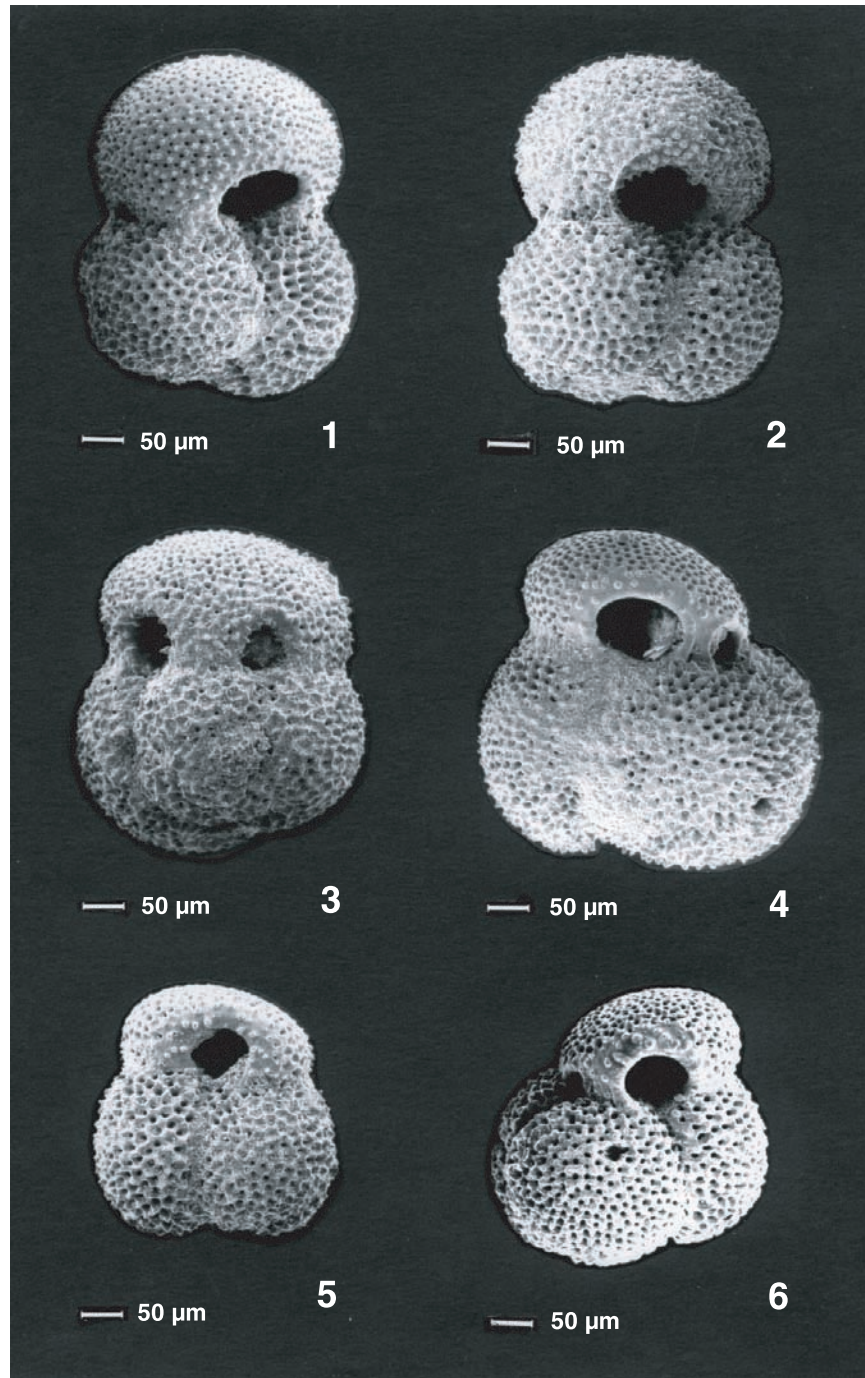
Figure 2. Representatives of the two morphotypes of *Globigerinoides ruber* (white): 1–2, *Globigerinoides ruber* sensu stricto (s.s.); 3–6, *Globigerinoides ruber* sensu lato (s.l.).

protocol developed by *Barker et al.* [2003]. Mg/Ca-based SST temperatures were calculated by means of the species-specific calibration for *G. ruber* (white; size fraction 250–350 μm) from the SCS surface sediment samples given by *Hastings et al.* [2001]: Mg/Ca (mmol mol^{-1}) = 0.38 exp [0.089 SST (°C)]. The standard errors for various temperature equations derived from core top and trap

calibrations are typically in the range of 0.5–1.0°C [*Lea et al.*, 2000; *Elderfield and Ganssen*, 2000; *Hastings et al.*, 2001; *Dekens et al.*, 2002; *Anand et al.*, 2003].

[6] Corresponding isotopic analyses of the core top samples were made with a Micromass IsoPrime mass spectrometer equipped with a Multicarb

automatic system at the National Taiwan Normal University. Average precisions based on NBS-19 carbonate standard are 0.03‰ for $\delta^{13}C$ and 0.06‰ for $\delta^{18}O$ (N = 177). Three to six repetitive measurements on each core top sample consisting of six individuals of each of the two morphotypes were performed. Isotopic analyses of downcore *G. ruber* s.s. and *G. ruber* s.l. samples were analyzed using a Finnigan MAT 251 mass spectrometer with an automated carbonate preparation device at the Leibniz Laboratory (University of Kiel) and Department of Geosciences (University of Bremen), respectively. The external standard errors of the stable oxygen and carbon isotope analyses at the Kiel and Bremen MAT 251 is <0.08‰ and <0.06‰, respectively. Oxygen and carbon isotope ratios were determined on samples composed of 15–20 specimens of either of the two morphotypes of *G. ruber* (white).

3. Definition of *Globigerinoides ruber* (white) Morphotype Variants

[7] Our morphotype concept follows that of *Wang* [2000]. *G. ruber* sensu stricto (s.s.) refers to specimens with spherical chambers sitting symmetrically over previous sutures with a wide, high-arched aperture (Figure 2: 1–2). Compared with the classification of *Hecht and Savin* [1970, 1972] and *Hecht* [1974], *G. ruber* s.s. basically corresponds to the normalform group. The normalform population represents specimens that construct their tests such that each new added chamber is larger than the previous ones (normalform growth [*Berger*, 1969]). *G. ruber* sensu lato (s.l.) refers to forms with more compact tests with compressed, flattened chambers sitting asymmetrically over the previous sutures and with a relatively small aperture over the suture (Figure 2: 3–6). These specimens, if compared to earlier studies [e.g., *Hecht*, 1974] basically represent the kummerform, where the final chamber is equal to or smaller than previous chambers (diminutive, flattened final chambers; kummerform growth [*Berger*, 1970; *Hecht and Savin*, 1970, 1972; *Hecht*, 1974]).

4. Results and Discussion

4.1. *G. ruber* Morphotype-Specific Variability in Mg/Ca Ratios and Stable Isotopes

[8] Mg/Ca analyses have been performed on sample pairs of *G. ruber* s.s. and *G. ruber* s.l. in 20 surface and downcore samples of the western Pacific (including SCS) and the Indian Oceans (Table 1). Generally, *G. ruber* s.s. shows higher Mg/Ca ratios than *G. ruber* s.l. (Figure 3). The mean difference between *G. ruber* s.s. and *G. ruber* s.l. of the entire data set is 0.37 ± 0.30 mmol/mol. The mean difference of the core top data and downcore sample set is 0.38 ± 0.30 mmol/mol and 0.35 ± 0.32 mmol/mol, respectively. A Student's t-test was performed on the entire data set in order to test if the difference in mean Mg/Ca ratios between the two different morphotypes is significant. The Student's t-test resulted in a t-value of 2.78. The calculated t-value exceeds the critical t-value of 2.02 for 38 degrees of freedom (p = 0.05). Although the standard deviation of the mean value is relatively large, the means in Mg/Ca between the two different morphotypes of *G. ruber* (white) show a statistically significant difference. Using the relationship of *Hastings et al.* [2001] and assuming that both morphotypes have the same temperature dependence, the difference between *G. ruber* s.s. and *G. ruber* s.l. would indicate an average 0.91 ± 0.75°C colder precipitation temperature for *G. ruber* s.l. than for *G. ruber* s.s. However, the application of the *Hastings et al.* [2001] calibration equation, and probably other *G. ruber* calibrations, to morphotype-specific instead of samples that contain the entire *G. ruber* population have some implications for SST reconstructions: The reconstructed Mg/Ca SSTs are 1–2°C higher for *G. ruber* s.s. and around 0.5–1°C lower for *G. ruber* s.l. than the modern annual SST at 0 m water depth in the SCS as indicated by the isotherms (Figure 1). As stated above, the Mg/Ca-based temperatures were calculated by means of the species-specific calibration for *G. ruber* developed by *Hastings et al.* [2001] for the SCS that used a mixture of both morphotypes. Consequently, using morphotype-specific samples, the application of the *Hastings et al.* [2001] equation would lead to higher SSTs when only using *G. ruber* s.s. morphotypes and vice versa somewhat colder SSTs than the modern average when using only *G. ruber* s.l. morphotypes (Table 1). Thus the higher *G. ruber* s.s. Mg/Ca based temperatures compared to the modern annual average SSTs is due to the sorting out of the two morphotypes (Figure 1). Consistently higher Mg/Ca-temperatures of both morphotypes outside the SCS may indicate that the SCS Mg/Ca-temperature relationship is not valid for sample locations outside the SCS.

[9] Several studies of Mg/Ca in core top-foraminifera suggest that post-depositional, partial disso-

Table 1. Measured Mg/Ca Ratios, Calculated Temperatures, and Temperature Differences Between the Two *Globigerinoides ruber* Morphotypes From Sediment Samples of the Western Pacific and Indian Oceans

| Station | Latitude, ° | Longitude, °E | Water Depth, m | Source | Size Fraction, μm | *Globigerinoides ruber* s.s. | | *Globigerinoides ruber* s.l. | | ΔT*G.rub.* s.s. − s.l., °C |
						Mg/Ca, mmol/mol	Mg/Ca-SST[a], °C	Mg/Ca, mmol/mol	Mg/Ca-SST[a], °C	
SO-18381	07.29N	109.07	214	core top	250–350	4.98	28.9	4.22	27.1	1.8
SO-18387	08.06N	110.38	381	core top	250–350	5.00	29.0	4.96	28.9	0.1
SO-18393	09.45N	109.07	155	core top	250–350	5.22	29.5	4.31	27.3	2.2
SO-18395	09.59N	109.28	280	core top	250–350	5.09	29.2	4.58	28.0	1.2
MD01-2377	12.43 S	121.26	2306	core top	250–350	5.42	29.9	5.06	29.1	0.8
MD01-2378	13.04 S	121.47	1783	core top	250–350	5.23	29.5	5.24	29.5	0.0
MD01-2379	12.53 S	122.45	560	core top	250–350	5.17	29.3	4.82	28.6	0.7
MD01-2391	08.32N	110.20	1312	core top	250–350	4.44	27.6	4.34	27.4	0.2
MD01-2398	23.59N	124.24	2416	core top	250–350	4.74	28.3	4.33	27.3	1.0
MD01-2390	06.38N	113.24	1545	downcore (12.5 cm)	250–350	4.45	27.7	4.63	28.1	−0.4
MD01-2390	06.38N	113.24	1545	downcore (52.5 cm)	250–350	4.84	28.6	4.26	27.2	1.4
MD01-2390	06.38N	113.24	1545	downcore (72.5 cm)	250–350	4.81	28.5	4.43	27.6	0.9
MD01-2390	06.38N	113.24	1545	downcore (287.5 cm)	250–350	4.97	28.9	4.10	26.7	2.2
MD01-2390	06.38N	113.24	1545	downcore (307.5 cm)	250–350	4.53	27.8	4.37	27.5	0.3
MD01-2390	06.38N	113.24	1545	downcore (372.5 cm)	250–350	4.07	26.7	4.02	26.5	0.2
MD01-2390	06.38N	113.24	1545	downcore (382.5 cm)	250–350	4.20	27.0	4.09	26.7	0.3
MD01-2390	06.38N	113.24	1545	downcore (392.5 cm)	250–350	4.29	27.2	3.63	25.4	1.8
MD01-2390	06.38N	113.24	1545	downcore (402.5 cm)	250–350	4.15	26.9	3.61	25.3	1.6
MD01-2390	06.38N	113.24	1545	downcore (412.5 cm)	250–350	4.42	27.6	4.05	26.6	1.0
36KL	17.10N	69,00	2055	core top	300–355	4.96[b]	28.9	4.57[b]	27.9	1.0

[a] Calculated using the equation of *Hastings et al.* [2001]; Mg/Ca (mmol/mol) = 0.38exp [0.089 SST (°C)].
[b] Mean (n = 5) Mg/Ca ratio of each morphotype.
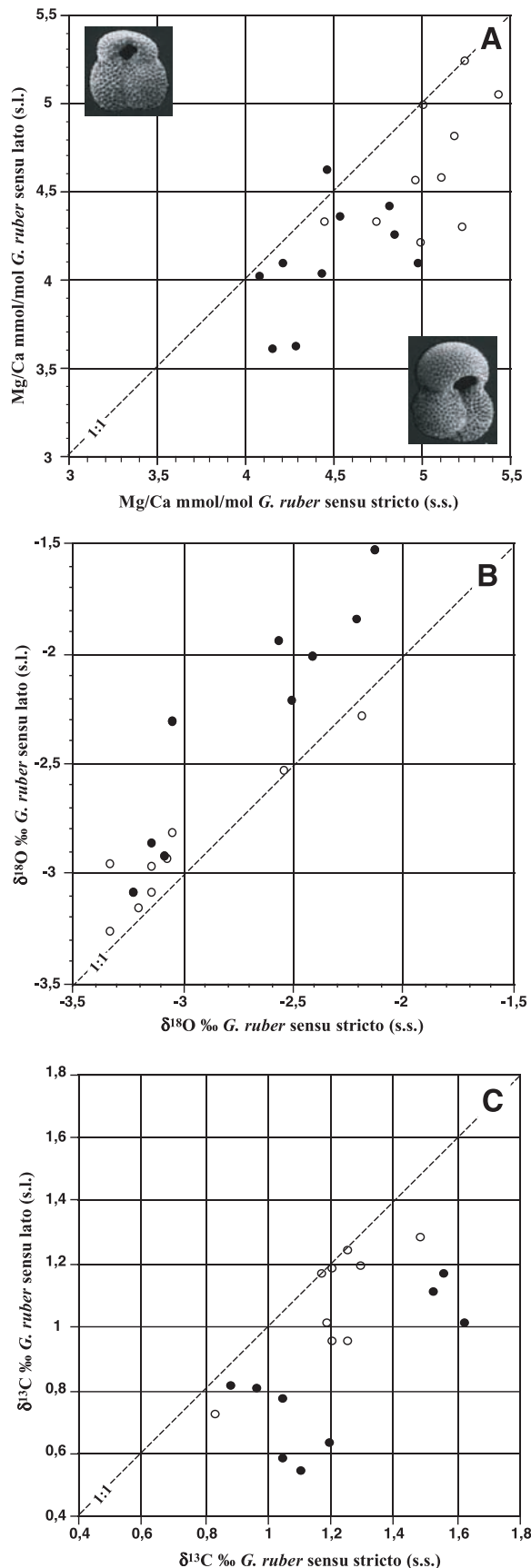
lution can exert an important control on the Mg/Ca ratios [e.g., *Brown and Elderfield*, 1996; *Rosenthal et al.*, 2000]. However, all core top and down-core foraminiferal samples are from water depths well above the present calcite lysocline that is located approximately at 3000 m and 2400 m in the SCS [*Rottman*, 1979; *Miao et al.*, 1994] and the eastern Indian Ocean [*Martinez et al.*, 1998], respectively. Therefore we believe that the foraminiferal Mg/Ca ratios are unaffected by dissolution.

[10] The Mg/Ca ratio data presented above suggests that *G. ruber* s.l. calcifies at a greater depth in the surface waters than *G. ruber* s.s. Alternatively, discrepancies in the Mg/Ca signature display a seasonal preference of the two morphotypes. It seems that the differences in the Mg/Ca data do not represent a ''marginal sea'' versus ''open ocean'' phenomenon, because our sample set includes specimens both from marginal and open ocean settings. Rather, the Mg/Ca ratios of both *G. ruber* morphotypes seem to record a consistent and significant difference without any local or regional preferences.

[11] Earlier studies show that specimens of *G. ruber* with a diminutive, flattened last chamber that equals our ''sensu lato''-specimens have isotopic temperatures 1–4.5°C colder than specimens with a normal last chamber (equaling our ''sensu stricto''-specimens) from the same sample sets [*Hecht and Savin*, 1972]. *Hecht and Savin* [1972] interpreted this to reflect a preferred depth habitat with kummerform specimens living consistently at deeper depth than normal specimens [*Hecht and Savin*, 1972]. *Berger* [1970] also reported that *G. ruber* populations are depth stratified. Further support for a preferred depth habitat of different morphotypes comes from a more recent study by *Wang* [2000] that compared stable isotopic signals of two *G. ruber* morphotypes obtained from surface samples of the SCS with modern oceanographic data. *Wang* [2000] interpreted differences in the oxygen stable isotopes of two *G. ruber* morphotypes (*G. ruber* s.s. and *G. ruber* s.l.) to reflect a different depth habitat with *G. ruber* s.s.

Figure 3. Comparison of the Mg/Ca ratios and stable isotopic composition of the two *Globigerinoides ruber* (white) morphotypes, *G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato, in surface (open dots) and downcore sediment samples (solid dots). (a) Mg/Ca ratios; (b) oxygen isotopes; (c) carbon isotopes. The 1:1 correlation line is added for reference.

Table 2. Isotopic Composition of *Globigerinoides ruber* Morphotypes From Sediment Samples of the Western Pacific and Indian Ocean[a]

Station	Latitude, °	Longitude, °E	Water Depth, m	Source	Size Fraction, μm	*Globigerinoides ruber* s.s.		*Globigerinoides ruber* s.l.	
						$\delta^{18}O$, ‰	$\delta^{13}C$, ‰	$\delta^{18}O$, ‰	$\delta^{13}C$, ‰
SO-18381	07.29N	109.07	214	core top	250–350	−3.15	1.17	−2.96	1.17
SO-18387	08.06N	110.38	381	core top	250–350	−3.21	1.25	−3.14	0.95
SO-18393	09.45N	109.07	155	core top	250–350	−3.05	1.18	−2.80	1.01
SO-18395	09.59N	109.28	280	core top	250–350	−3.34	1.20	−2.95	1.19
MD01-2377	12.43 S	121.26	2306	core top	250–350	−3.15	0.83	−3.08	0.73
MD01-2378	13.04 S	121.47	1783	core top	250–350	−3.08	1.20	−2.92	0.95
MD01-2379	12.53 S	122.45	560	core top	250–350	−2.19	1.48	−2.27	1.28
MD01-2391	08.32N	110.20	1312	core top	250–350	−3.34	1.25	−3.25	1.24
MD01-2398	23.59N	124.24	2416	core top	250–350	−2.54	1.28	−2.52	1.20
MD01-2390	06.38N	113.24	1545	downcore (12.5 cm)	250–350	−3.23	1.52	−3.08	1.12
MD01-2390	06.38N	113.24	1545	downcore (52.5 cm)	250–350	−3.15	1.62	−2.86	1.02
MD01-2390	06.38N	113.24	1545	downcore (72.5 cm)	250–350	−3.09	1.55	−2.91	1.17
MD01-2390	06.38N	113.24	1545	downcore (287.5 cm)	250–350	−3.05	1.1	−2.3	0.55
MD01-2390	06.38N	113.24	1545	downcore (307.5 cm)	250–350	−2.89	0.7	n.d.	n.d.
MD01-2390	06.38N	113.24	1545	downcore (372.5 cm)	250–350	−2.13	0.88	−1.52	0.82
MD01-2390	06.38N	113.24	1545	downcore (382.5 cm)	250–350	−2.22	0.96	−1.84	0.81
MD01-2390	06.38N	113.24	1545	downcore (392.5 cm)	250–350	−2.57	1.04	−1.94	0.78
MD01-2390	06.38N	113.24	1545	downcore (402.5 cm)	250–350	−2.42	1.04	−2.01	0.59
MD01-2390	06.38N	113.24	1545	downcore (412.5 cm)	250–350	−2.51	1.19	−2.2	0.64
36KL	17.10N	69,00	2055	core top	300–355	n.d.	n.d.	n.d.	n.d.

[a] n.d., no data.

inhabiting the upper 30 m of the water column and *G. ruber* s.l. inhabiting depths below 30 m. Differences in the isotopic signals of *G. ruber* morphotypes from the SCS are corroborated by the study of *Löwemark et al.* [2005]: This work corroborates the view of *Wang* [2000] that *G. ruber* s.l. lives at a larger depth than *G. ruber* s.s. On the basis of plankton tow and pumping samples from the seas around Japan, *Kuroyanagi and Kawahata* [2004] found that *G. ruber* s.s. is predominant in the surface waters while *G. ruber* s.l. is predominant in deeper waters. Our corresponding stable isotope analyses on the same sample pairs reveal that most of the *G. ruber* s.s. show lighter $\delta^{18}O$ values than *G. ruber* s.l. In $\delta^{13}C$, however, most of the *G. ruber* s.l. show lighter values than *G. ruber* s.s. (Table 2, Figure 3). The mean differences between *G. ruber* s.s. and *G. ruber* s.l. of the core top samples are only 0.13 ± 0.13‰ and -0.12 ± 0.11‰ for $\delta^{18}O$ and $\delta^{13}C$. For the downcore samples, the mean differences are 0.41 ± 0.2‰ and -0.37‰ $\pm$ 0.18‰, respectively, resulting in mean differences of the entire data set of 0.27 ± 0.22‰ for $\delta^{18}O$ and -0.25 ± 0.19‰ for $\delta^{13}C$. Thus our stable isotope and accompanying Mg/Ca data seem to corroborate the view of different dwelling depths of both *G. ruber* morphotypes as suggested by *Wang* [2000]. This is further supported by sediment trap studies from the northern SCS that show no difference in seasonal preference between the two morphotypes in the investigated collection period [*Lin et al.*, 2004]. According to *Lin et al.* [2004], however, the data do not allow any definitive conclusions concerning the seasonal preference or different dwelling depths of the two *G. ruber* morphotypes.

[12] Studies on morphological or phenotypic variations within planktonic populations (such as diminutive, flattened last chambers or kummerform growth) have interpreted these variations as growth in a stressed environment, e.g., changes in temperature, salinity or food availability [*Berger*, 1969; *Hecht and Savin*, 1970, 1972; *Hecht*, 1974]. On the basis of oxygen isotopes, *Hecht and Savin* [1970] concluded that kummerform morphotypes are produced when they leave the optimum water depth to which the species is adapted. In contrast to these studies, *Bijma et al.* [1990a] observed that a "normal" morphology is found more often under extreme conditions, questioning that kummerform morphotypes are indicative of non-optimum conditions. Elsewhere, diminutive, peculiar final chambers also have been linked to reproductive processes [*Bé and Hemleben*, 1970; *Hemleben and Spindler*, 1983; *Hemleben et al.*, 1988]. *Bijma et*

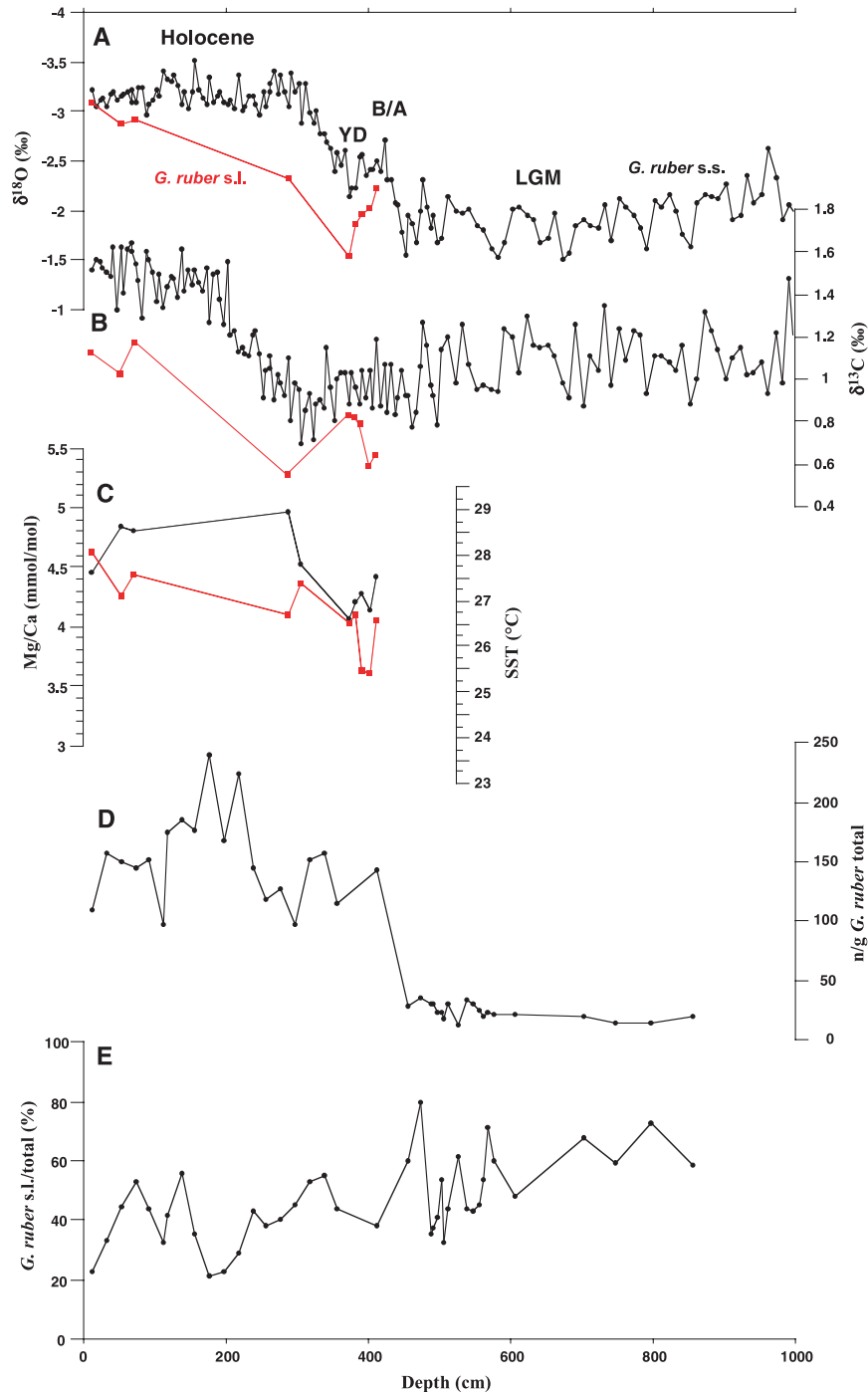**Figure 4.** Downcore Mg/Ca and stable isotope records of core MD01-2390 from the southern South China Sea. (a) δ^{18}O records of *G. ruber* s.s. (black circles) and *G. ruber* s.l. (red squares); (b) δ^{13}C records of *G. ruber* s.s. (black circles) and *G. ruber* s.l. (red squares); (C) Mg/Ca ratios and Mg/Ca-SST estimates of *G. ruber* s.s. (black circles) and *G. ruber* s.l. (red squares); (d) abundance of the entire *G. ruber* population in the size fraction > 150 μm (n/g); (e) ratios of *G. ruber* s.l. in the total population of *G. ruber* from the >150 μm size fraction. YD, Younger Dryas; B/A, Bølling/Allerød; LGM, Last Glacial Maximum. Stratigraphy is based on the oxygen isotope curve that has been compared to previous published AMS-^{14}C dated oxygen isotope records form the southern SCS [*Kienast et al.*, 2001; *Steinke et al.*, 2001].

al. [1990b] found the highest proportions of kummerform morphotypes during reproduction, concluding that this phenomenon is associated with the reproductive processes. We speculate that *G. ruber* s.l. may represent "terminal stages of the reproductive cycle" as suggested by *Bijma et al.* [1990b] which are produced in colder (deeper) water. However, more detailed studies on *G. ruber* morphotypes through tow and trap samples are needed to fully understand their ecology as well as the discrepancies in the geochemical signatures of the different morphotypes. Although sediment trap studies from the northern SCS display no seasonal preference of the two morphotypes, *Spero et al.* [1987] have shown that *G. ruber* has a seasonal component in its morphology. They suggested that seasonal changes in temperature and salinity of the upper water column may be responsible for the observed morphological changes in living *G. ruber*.

4.2. Implications for Paleoceanographic Studies

[13] Our data indicate that differences in Mg/Ca ratios between *G. ruber* s.s. and *G. ruber* s.l. indicate a colder precipitation temperature for *G. ruber* s.l. than for *G. ruber* s.s. This is particularly important for paleotemperature studies because temperature determined on entire *G. ruber* populations may tend to be somewhat colder than those determined when only *G. ruber* s.s. specimens are used. This may be of further importance when the *G. ruber* morphotype ratio is not constant over the time period investigated. In the case of the southern SCS (core MD01-2390; Figure 4), the abundance of *G. ruber* s.l. increased relative to the *G. ruber* s.s. morphotype during the last glaciation. The generally low absolute abundances of *G. ruber* specimens during the last glaciation are due to dilution by increased siliciclastic material delivery. Therefore we suggest that supplementing *G. ruber* s.s. records with specimens of the sensu lato morphotype may slightly decrease the apparent average temperatures of the last glacial period. In addition, the use of the entire *G. ruber* population instead of "morpho-specific" samples may have some implications to $\delta^{18}O$ seawater reconstructions in this region, when the foraminiferal calcite $\delta^{18}O$ is corrected for temperature-related fractionation of seawater $\delta^{18}O$. A higher contribution of *G. ruber* s.l. morphotype may give the impression of a larger average cooling during the LGM. This would imply a stronger temperature-related control on the foraminiferal $\delta^{18}O$ and consequently a shift in $\delta^{18}O$ to lower average glacial $\delta^{18}O_{seawater}$.

5. Conclusions

[14] Pairs of two morphotype variants of *G. ruber* (white) from surface and downcore sediments of the western Pacific and Indian Oceans record statistically different Mg/Ca ratios. The differences in Mg/Ca between *G. ruber* s.s. and *G. ruber* s.l. indicate a colder precipitation temperature for *G. ruber* s.l. than for *G. ruber* s.s., suggesting that *G. ruber* s.l. calcifies at a greater depth in the surface waters than *G. ruber* s.s. The differences in Mg/Ca ratios between *G. ruber* s.s. and *G. ruber* s.l. are particularly important for paleotemperature studies because temperature determined on entire *G. ruber* populations may tend to be colder than those determined when only *G. ruber* s.s. specimens are used. Differences in the Mg/Ca ratio and corresponding stable isotopes of the two *G. ruber* morphotypes may be related to different depth habitats. However, further studies on sediment tow and trap material are needed to confirm our results, particularly to unravel contrasting findings regarding the potential seasonal occurrences of different morphotypes.

Acknowledgments

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