# Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series

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Paired Mg/Ca and $\delta^{18}O$ measurements on planktonic foraminiferal species (*G. ruber* white, *G. ruber* pink, *G. sacculifer*, *G. conglobatus*, *G. aequilateralis, O. universa*, *N. dutertrei*, *P. obliquiloculata*, *G. inflata*, *G. truncatulinoides*, *G. hirsuta*, *G. crassiformis*) from a six-year sediment trap time series in the Sargasso Sea were used to define the sensitivity of foraminiferal Mg/Ca to calcification temperature. Habitat depths and calcification temperatures were estimated from comparison of $\delta^{18}O$ of foraminifera with equilibrium calcite, based on historical temperature and salinity data. When considered together, Mg/Ca (mmol/mol) of all species, except two, show a significant (r =0.93) relationship with temperature (T $^{o}$C) of the form Mg/Ca = 0.38 (±0.02) exp 0.090 (±0.003)T, equivalent to a 9.0 ± 0.3 % change in Mg/Ca for a 1$^{o}$C change in temperature. Small differences exist in calibrations between species and between different size fractions of the same species. *O. universa* and *G. aequilateralis* have higher Mg/Ca than other species and, in general, data can be best described with the same temperature sensitivity for all species and pre-exponential constants in the sequence *O. universa* > *G. aequilateralis* ≈ *G. bulloides* > *G. ruber* ≈ *G. sacculifer* ≈ other species. This approach gives an accuracy of ± 1.2 $^{o}$C in the estimation of calcification temperature. The ~9% sensitivity to temperature is similar to published studies from culture and core-top calibrations but differences exist from some

literature values of pre-exponential constants. Different cleaning methodologies and artefacts of core-top dissolution are probably implicated, and perhaps environmental factors not yet understood. Planktonic foraminiferal Mg/Ca-temperature estimates can be used for reconstructing surface temperatures, mixed and thermocline temperatures (using *G. ruber* pink, *G. ruber* white, *G. sacculifer, N. dutertrei, P. obliquiloculata*, etc., respectively). The existence of a single Mg thermometry equation is valuable for extinct species although use of species-specific equations will, where statistically significant, provide more accurate evaluation of Mg/Ca paleotemperature.

# 1. Introduction

Mg/Ca in foraminiferal calcite is becoming an established palaeotemperature proxy. The advantage of foraminiferal Mg/Ca thermometry over other marine palaeotemperature proxy methods is that temperature estimates can be obtained from the same foraminiferal sample upon which data on oxygen isotopes, also sensitive to temperature, are obtained. The oxygen isotope composition of foraminiferal calcite is additionally controlled by the oxygen isotopic composition of sea water. Thus, the approach of measuring Mg/Ca and $\delta^{18}O$ in single species of foraminiferal calcite is potentially of great value in estimating both temperature and sea water $\delta^{18}O$ from the same sample and associated with the same parcel of sea water.

Early studies, e.g., *Emiliani* [1955], *Delaney et al*. [1985], on planktonic foraminifera showed no correlation between temperature and Mg/Ca because of complicating factors not appreciated at that time. Since then, a dependence of Mg on temperature has been established in foraminifera from core tops [*Nuernberg,* 1995; *Rosenthal et al.*, 1997; *Elderfield and Ganssen*, 2000; *Lea et al.,* 2000; *Rosenthal et al.,* 2000; *Rosenthal and Lohman*, 2002; *Dekens et al*., 2002; *Lear et al.*, 2002] and in cultures of three species: *G. sacculifer*, *G. bulloides* and *O. universa* [*Nuernberg*, *et al.,* 1996; *Lea et al.,* 1999; *Mashiotto et al.,* 1999]. Calibrations based on culture and core-tops are invaluable but both have disadvantages. Culture calibrations have the great advantage that foraminifera calcify under prescribed and accurately known temperatures but the disadvantage that the controlled environment may not reproduce natural growth fully and that a limited number of species can be studied. Core-top calibrations have the great advantage that they reflect the material that is buried to form the paleoceanographic record but the disadvantage of potential artefacts, specifically from dissolution, and of difficulties in establishing the link with SST, although use of $\delta^{18}O$-derived calcification temperature circumvents the latter problem. All the previous calibration studies

show similar exponential constants within error (0.09 ± 0.01). However, there are differences in pre-exponential constants, which is due to dissolution and some other factors e.g., different cleaning method, inter laboratory differences etc.

The third way to establish a calibration is through the use of foraminifera from the water column, with collection either by net (with the advantage of regional coverage) or by sediment trap (the advantage of seasonal and inter-annual records). Here, we report the results of a calibration based on six years of bimonthly trap samples from the Sargasso Sea. The work allowed us to define Mg incorporation into several species of planktonic foraminifera during changing seasonal cycles of hydrological conditions in the surface and near-surface waters at a site where information on seasonality and ecology of planktonic foraminifera was available [*Deuser et al.,* 1981; *Deuser*, 1987; *Deuser and Ross*, 1989; *Hemleben et al*., 1985].

Paired Mg/Ca and $\delta^{18}O$ measurements were made on seasonally abundant planktonic foraminifera from the sediment traps and were used to evaluate: (i) seasonal and inter-annual variations in Mg/Ca and $\delta^{18}O$, (ii) agreement between observed and predicted foraminiferal $\delta^{18}O$ as a function of seasonal temperature and salinity variations in the water column so as to evaluate the habitat depths of foraminiferal species at the site, (iii) the temperature dependence of Mg/Ca in twelve species of planktonic foraminifera, including inter-specific differences, differences between calibrations based on calcification temperature and SST, the influence of size fraction, and comparisons with literature data.

## 2. Methodology

### 2.1. Sediment trap deployment

A six-year programme of continuous sediment trap collection, "Seasonal Change in Isotopes and Flux of Foraminifera" (SCIFF), was carried out between 6th April 1978 and 17th May 1984 in the Sargasso Sea. The SCIFF site was located at 32° 05.4' N, 64° 15.4' W, 45 km south east of Bermuda. A long time series of temperature and salinity measurements (0 to 2600 m) was available from nearby station 'S' (32° 10' N, 64° 30' W) (Fig. 1). Thirty one of the trap deployments yielded a complete set of samples (Table 1), providing quantitative material for 83 % of the elapsed time [*Deuser*, 1987]. Average deployment length was 60 ± 7 (1σ) days. No poisons or preservatives were used in the collection cup. In-situ oxidation of organic matter was below the level at which pH changes can cause calcite dissolution [*Deuser*, 1987]. Some evidence of slight dissolution in pteropod shells (aragonite) was observed in two spring samples [*Deuser*, 1987].

### 2.2. Foraminiferal sampling and analysis

Twelve planktonic foraminiferal species present in the bimonthly sediment trap samples were analysed (Table 2). *G. ruber* white and pink were distinguished, and also *G. sacculifer*, with and without a sac-like final chamber, and *O. universa* with both thin and thick test. Foraminifera from the archive at Woods Hole Oceanographic Institution were picked from the >125 μm size-fraction and three sub-fractions (250-350, 350-500, 500-1000 μm) separated. The size fractions used here are unusually large for Mg/Ca work but this is a constraint of working with trap samples of limited foraminiferal numbers. Each paired analysis of foraminiferal $\delta^{18}O$ and Mg/Ca was performed using a split of the same homogenised crushed samples to minimise error arising from sample heterogeneity. Foraminiferal samples were first gently crushed, using glass plates, to open chambers, homogenised and then divided. One part (~ 2/3rd) was used for Mg/Ca and the second part

(~1/3$^{rd}$) was used for $\delta^{18}O$ measurements. The number of individuals used for each sample was variable, limited by availability, but typically was ~5-15 for Mg/Ca. Sub-samples for Mg/Ca were cleaned to remove clays (water and methanol wash) and organic matter (hydrogen peroxide treatment) followed by a dilute acid polish prior to analysis. The cleaning method has evolved since *Elderfield and Ganssen* [2000] (a copy of the current method is available on request to he101@esc.cam.ac.uk). Additionally, for sediment trap samples, the organic matter removal step was extended (50 % buffered $H_2O_2$ for 45 minutes) as a precaution to eliminate the likelihood of higher organic matter contents than found in typical core material [also shown by *Pak et al*. 1999].

Elemental analyses were performed with a Varian Vista AX simultaneous inductively coupled plasma atomic-emission spectrometer [*de Villiers et al.,* 2002]. At the time of analysis, precision of measured Mg/Ca ratios was < 0.02 mmol/mol (1 $\sigma$ s.d.) for a standard solution of Mg/Ca=5.13 mmol/mol. The second sub-sample was analysed for $\delta^{18}O$ (0.08 ‰; 1 $\sigma$ s.d.) at the Godwin Institute, University of Cambridge.

### 2.3. Estimation of $\delta^{18}O$ of sea water and equilibrium calcite, and isotopic calcification temperature

Temperature and salinity data from Bermuda Biological Station "S" (e.g. Fig. 1) were used to calculate $\delta^{18}O$ of seawater ($\delta^{18}O_w$) and to predict $\delta^{18}O$ of calcite ($\delta^{18}O_c$) formed in equilibrium with seawater, seasonally and over 0-800m, during the period for which the sediment trap was deployed. The reason for calculating equilibrium calcite $\delta^{18}O$ was to compare with measured $\delta^{18}O$ to estimate depth habitats. The isotopic temperatures based on the $\delta^{18}O_w$ at different water depths and measured $\delta^{18}O$ in foraminiferal calcite are used for the Mg calibration.

$\delta^{18}O_w$, expressed as ‰ deviation from the standard mean ocean water (SMOW) scale, was calculated from the Station "S" salinity data using the equation of *Duplessy et al.* [1991], itself obtained from $\delta^{18}O_w$ and salinity for water samples collected in the upper 250 m of the Atlantic Ocean during the GEOSECS expedition:

$$\delta^{18}O_w = -19.264 + 0.558 \times \text{Salinity} \quad (1)$$

Other relationships exist in the literature but values for $\delta^{18}O_w$ obtained using eqn. 1 were the closest to measured $\delta^{18}O_w$ available for 32° N 64° W [*Schmidt et al*., 1999]. *Equilibrium* $\delta^{18}O_c$ was calculated from $\delta^{18}O_w$, together with Station "S" temperature data (T $^oC$), using a rearrangement of the palaeotemperature equation of *O'Neil et al.* [1969] and *Shackleton* [1974]:

$$\delta^{18}O_c = (\delta^{18}O_w - 0.27) + [4.38 - (4.38^2 - 4 \times 0.1(16.9 - T))^{0.5}]/2 \times 0.1 \quad (2)$$

The factor 0.27 was used to convert from water on the SMOW scale to calcite on the Pee Dee Belemnite (PDB) scale.

Isotopic calcification temperatures of the foraminifera were calculated, using the paleotemperature equation, from *measured* $\delta^{18}O_c$ (from the planktonic foraminifera) and estimates of $\delta^{18}O_w$ (as described above) based on their habitat depths defined as in Section 3.3 and 3.4:

$$T = 16.9 - 4.38(\delta^{18}O_c - (\delta^{18}O_w - 0.27)) + 0.1(\delta^{18}O_c - (\delta^{18}O_w - 0.27))^2 \quad (3)$$

The abbreviation T is used for '$\delta^{18}O$ calcification temperature' in equations in this study. We

have also used 'monthly mean temperature' in figure 10b that was obtained from Bermuda Biological Station 'S' data set.

## 3. Results

Results (Appendix I) obtained from the sediment trap samples represent averages over the trap deployment periods. The results show: (i) a small inter-annual variability in Mg/Ca and $\delta^{18}O$ of planktonic foraminifera (Fig. 2); (ii) large intra-annual (seasonal) variations in Mg/Ca and $\delta^{18}O$ of the surface dwelling planktonic foraminiferal species e.g., *G. ruber* (white and pink), over a ~7 °C change in isotopic temperature (Fig. 3); (iii) variable depth habitats of planktonic foraminiferal species estimated from calcite isotopic equilibrium with sea water (Fig. 4); (iv) an exponential relationship between Mg/Ca and isotopic temperature showing a ~10 % change in Mg/Ca per °C change in temperature for all except two species (Fig. 6a); and (v) exceptionally high Mg/Ca in *O. universa* and *G. aequilateralis* (Fig. 6c).

### 3.1. Inter-annual variations

Mg/Ca and $\delta^{18}O$ data for the species *G. ruber* white, *G. ruber* pink, *G. aequilateralis,* and possibly *G. truncatulinoides*, showed a seasonally cyclic variation with little inter-annual variation over the six year period (Fig. 2). For example, peak value for *G. ruber* white are Mg/Ca = 4.74±0.26 mmol/mol, $\delta^{18}O$ = -1.45±0.1 ‰ and lows are Mg/Ca = 2.99±0.14 mmol/mol, $\delta^{18}O$ = -0.28±0.02 ‰. There were not enough data for other species from the time series to fully evaluate inter-annual chemical variations but some evidence of seasonal cyclicity was also observed (Appendix I).

### 3.2. Seasonal variations

Intra-annual (seasonal) changes in planktonic foraminiferal Mg/Ca and $\delta^{18}O$ were identified for nine species (Fig, 3; the standard deviation is plotted as a vertical bar representing inter-annual variation for a particular month). Data from the same months over the six-year period were averaged and show large seasonal changes in all surface-dwelling planktonic species. Two size-fractions of *G. ruber,* white and pink, (250-350 and 350-500 μm) showed clear variations in Mg/Ca and $\delta^{18}O$ (Fig, 3a, b). *G. sacculifer* without a sac-like final chamber showed a slightly higher Mg/Ca and a stronger trend in seasonal variation compared to without-sac individuals (Fig. 3c). *G. aequilateralis* (aka *G. siphonifera*) showed similar Mg/Ca but heavier $\delta^{18}O$ when compared to *G. ruber* in the same size fraction (350-500 μm). *G. aequilateralis* showed a higher Mg/Ca ratio in the 500-1000 μm size-fraction compared to 350-500 μm, with no significant offsets in $\delta^{18}O$ (Fig. 3d). *O. universa* showed greater scatter in Mg/Ca compared to $\delta^{18}O$ (Fig. 3e) with higher Mg/Ca in the larger size-fraction (500-1000 μm), for both thin and thick test, compared to the smaller size-fraction (350-500 μm, thin test). *N. dutertrei* and *P. obliquiloculata* showed a small annual variation (Fig. 3f,g). Samples belonging to the deeper-dwelling *Globorotaliid* genus (*G. truncatulinoides* and *G. hirsuta*) showed a small variation in Mg/Ca and $\delta^{18}O$ (Fig. 3h,i).

## 4. Planktonic foraminifera as recorders of near-surface hydrography

In order to place the foraminiferal data within the context of the near surface hydrography, measured $\delta^{18}O$ data of the various planktonic species were compared with predicted $\delta^{18}O_c$ values for equilibrium of calcium carbonate with $\delta^{18}O$ of seawater at depths from 0 to 800m at Station "S". Predicted $\delta^{18}O_c$ data were averaged for two successive months

in order to compare them with the measured bimonthly $\delta^{18}O$ data obtained from foraminifera. They were used to estimate the depth habitat of the different species in the Sargasso Sea and in defining calcification temperatures. It should be stressed that the habitat depths so calculated are based on the assumption of oxygen isotope equilibrium between seawater and foraminiferal calcite as outlined in Section 2.3.

Overall, average depth habitats extending from surface waters down to 500-800m were estimated (Table 2). *G. ruber* pink, *G. ruber* white and *G. sacculifer* calcified in near surface conditions (Fig. 4a-c). Measured $\delta^{18}O$ for these species are in good agreement with predicted $\delta^{18}O_c$ at 1-25 m, 25-50 m and 1-50 m depths, respectively. This is consistent with the depth habitat suggested for this area [*Deuser et al.,* 1981]. However, all of these species show lighter $\delta^{18}O$ than predicted $\delta^{18}O_c$ of surface water from November to April. *Deuser* [1987] also showed an offset, up to a maximum of ~1.0 ‰, in predicted and measured $\delta^{18}O$ in *G. ruber* white from these traps. There are several possible reasons for this offset. One is that, because *G. ruber* calcifies at warm temperatures, it may record temperatures higher than the six-year averaged winter temperature. For example, it may calcify only in warm pool ring temperatures not represented by the Station "S" averages. A second possibility is that there may be uncertainties in the representativity of sampling because winter-time fluxes of foraminiferal tests were much less than during the summer [*Deuser*, 1987; *Deuser and Ross*, 1989]. The winter flux of these species is very low, except for *G. ruber* white, and reaches fluxes close to zero. This leads to sampling limitations for such species during winter.

*G. aequilateralis* and *O. universa* calcified in equilibrium with 50-100 m water depth (Fig. 4d,e). *N. dutertrei* and *P. obliquiloculata* calcifed in relatively deeper water and follow predicted $\delta^{18}O_c$ values at 50-100 m water depth (Fig. 4f). Less data were available for *G. hirsuta*, *G. inflata*, *G. crassiformis* and *G. conglobatus* from different seasons and hence it is difficult to evaluate their exact depth habitats (Table 2). Of course, observed $\delta^{18}O$ for the

deeper dwelling species may represent an average, reflecting calcification over a range from surface to deeper waters, and do not imply that they were restricted to the estimated range.

## 5. Mg/Ca thermometry from foraminiferal calcite

A single palaeotemperature equation [*O'Neil et al.*, 1969; *Shackleton*, 1974] was used for calculating calcification temperature for all the species using $\delta^{18}O_w$ values for the seasonally-defined species habitat depths (Table 2, Fig. 4). There is some uncertainty in the habitat depths of the deeper dwelling species, reflected in their wide depth ranges in Table 2, but $\delta^{18}O_w$ varies little with depth over this range.

Mg/Ca has been assumed to show an exponential dependence on temperature:

$$Mg/Ca = B \exp(AT) \quad (4)$$

where the pre-exponential and exponential constants are designated B and A and T is $\delta^{18}O$ calcification temperature. There are two types of method that have been used for multispecies regression analysis. The least square regression method, is not the most appropriate for deriving calibration equations from Mg/Ca and isotopic temperature because both variables have significant errors and there is no independent variable. The reduced major axis (geometric mean) regression method, addresses this question and has been used for generating a single equation for the multi species data, after assuming that all species have same Mg/Ca temperature dependence but variable intercepts [*Rosenthal and Lohman,* 2002]. The advantage of geometric mean method is that it allows for normalising (reducing) a multispecies data set to a single regression line and the slopes of the variables are reciprocal to each other so the selection of a notional ndependent variable is unimportant. Because of

the different ranges in temperature of individual species of planktonic foraminifera, and the lack of a truly independent variable, the geometric mean method [*Laws*, 1977; *Rosenthal and Lohman*, 2002] has been used for linear regression analysis and applied to ln(Mg/Ca) vs T (an example of the approach is shown in Fig. 5).

### 5.1. All species

Initially, we consider all species together comparing Mg/Ca with calcification temperature but only in one size fraction (350-500 μm). We have taken this approach because $\delta^{18}O_c$ - $\delta^{18}O_w$ records calcification temperature for all species but does not record SST for many of the species examined. A comparison with SST is shown later.

When considered together, Mg/Ca for all the species, except two (*O. universa* and *G. aequilateralis*, which are considered later), show a significant correlation, r = 0.93, with temperature (Fig. 6a). *G. ruber* white, *G. ruber* pink and *G. sacculifer* (with and without sac) represent the warmer temperature end of the calibration curve. Deeper-dwelling species fall on the same curve towards the lower end of the correlation curve, representing colder temperatures. The temperature (T $^{o}$C) calibration for all species considered together is described by:

$$Mg/Ca = 0.38 \exp (0.090T) \quad (5)$$

with (Mg/Ca in mmol/mol). The pre-exponential and exponential constants have uncertainties of B ± 0.02 and A ± 0.003. The exponent is equivalent to a 9.0 ± 0.3 % change in Mg/Ca for a 1$^{o}$C change in temperature. This temperature sensitivity is similar to most literature estimates, including a core-top multi-species calibration (Table 3). The pre-exponential

constant is similar to calibration data from the literature for similar species. It is lower than for the published core-top multi-species calibration which includes *G. bulloides*, for which other literature data indicate a higher pre-exponential constant. The other possible reason for these differences could be due to the different Mg/Ca cleaning method applied in the two studies.

### 5.2. Varieties and size-fractions of *G. ruber*

*G. ruber* white and pink have similar Mg/Ca at the lower-temperature end of the calibration but at higher temperatures Mg/Ca of *G. ruber* white are higher (Fig. 7a) resulting in small but significant differences in calibrations (Table 3). Correlations between Mg/Ca and calcification temperature for *G. ruber* pink are poorer than for the multi-species calibration and reveal no size-fraction dependence. Correlations for *G. ruber* white are similar to that of the multi-species calibration and reveal a small size-related dependence. The difference between the two size fractions is, however, a reflection of small differences in $\delta^{18}O$ between the two size fractions and not differences in Mg/Ca (Fig. 3).

### 5.3. Inter-specific differences

*O. universa* and *G. aequilateralis* have distinctly higher Mg/Ca ratios at a given temperature than the other species analysed (Fig. 7b). Data for *O. universa* show considerable scatter and although higher then for other species, are lower than seen in culture (which also show much scatter).

Small inter-specific differences in Mg/Ca versus temperature are apparent between some of the species which were used in the multi-species calibration. For example, Mg/Ca

data for *G. ruber* white over the temperature range are higher than, and those for *G. sacculifer* are lower than, values predicted by the the multi-species calibration (Fig. 6a).

It is not possible to construct statistically significant calibrations for all individual species simply because the ranges in calcification temperature are too narrow relative to the scatter in the data, and correlation coefficients (r) of 7 of the 15 individual species calibration equations are < 0.74 (see Appendix II). When the calibration curves for individual species are compared it can be seen that the constants B and A are correlated (Fig. 8a). A mechanistic significance is unlikely: the most likely explanation is that it is a consequence that correlation equation with larger gradients (A) when extrapolated to A=0 yield smaller intercept values (B) and *vice versa*. The species with low values for A are those for which the correlations are weaker (Fig. 8b) and strengthens the view that all planktonic species show a similar temperature sensitivity when assessed using reliable calibrations. The value for the exponential constant in Fig. 8b extrapolated to r = 1 is A = 0.09.

Given that some species have not yielded statistically significant calibrations, an alternative approach is shown, which is the one adopted for a core-top multi-species data set [*Elderfield and Ganssen*, 2000] and *assumes* that the temperature dependence of the multi-species calibration (i.e., A = 0.090 ±0.003) applies to all species and thus describe inter-specific differences via the pre-exponential constant (Fig. 6b, Table 4: values of B for *O. universa* and *G. aequilateralis* have been included for completeness). This is a satisfactory, although *ad hoc*, way to describe calibrations for individual species (see Section 5.6). But it should be emphasised that it does not constitute proof of a common temperature dependence for all species, although there is evidence (e.g., Fig. 8b) that this may be the case. Single temperature dependence is also suggested from benthic foraminiferal calibration studies [*Rosenthal et al.*, 1997; *Lear et al.*, 2002].

### 5.4. Spinose and non-spinose species

A good example in support of a common temperature dependence is a comparison of species within the spinose group of planktonic foraminifer with those from the non-spinose group (Fig. 9a). Grouping species in this way shows that the spinose group appear to have higher temperature sensitivity than the non-spinose group. It is interesting that the non-spinose foraminifera, mainly deeper dwelling species, have a temperature sensitivity closer to the thermodynamic value of ~ 0.03 [*Rosenthal et al.*, 1997; *Lea et al.*, 1999]. Although it is tempting, and logical, to advocate different extents of non-equilibrium fractionation between the two groups, calibrations of individual spinose species for which Mg/Ca and temperature are well correlated, as in this study and in culture work (Table 3), have much higher temperature sensitivities (~ 0.1). Therefore, in likelihood, this observation is an artefact of sparse data sets and scatter in the data, as shown when the geometric means are plotted (Fig. 9b), and emphasises the need for further work.

### 5.5. Calcification temperature and SST

It is obvious from the estimates of calcification depth (Table 2) that calibrations for some of the species considered here would never be employed to estimate sea surface temperature. However, the species *G. ruber* and *G. sacculifer* calcify at or close to the sea surface and represent mixed layer temperature. Whilst it is logical to link Mg/Ca to calcification temperature in their calibrations, nevertheless paleoceanographic data are used to define records of SST, and these species are the most promising for this purpose [*Dekens et al.,* 2002]. Therefore, it is useful to compare data with temperature derived from both approaches (Fig. 10). The calibration versus monthly mean temperature at calcification depth

for these species (see Table 2) is much weaker than with calcification temperature. This arises principally from ignoring depth habitat. As seen in Fig. 1, the strong summer thermocline results in a temperature gradient of about 8 $^{o}$C over the upper 100m which is equivalent in magnitude to all of the seasonal SST variation. The average calcification temperatures estimated from unweighted mean Mg/Ca data for each species are ~ 2 $^{o}$C warmer than average monthly mean temperatures. This is probably because the species, favouring warmer temperatures, calcify in somewhat warmer than monthly average sea surface temperatures (see Section 5; Fig. 12).

### 5.6. Accuracy of temperature calibrations

A comparison of calcification temperatures estimated from Mg/Ca thermometry with the calcification temperatures used in the construction of the calibrations gives a good indication of the uncertainty inherent in the calibration equations. Mg/Ca temperatures were obtained using the two approaches discussed in Section 5.3 (Tables 3). Both methods gave similar accuracy when applied to species for which the individual species-specific calibrations equations had correlation coefficients > 0.74 (see Appendix II). The species-specific equations obtained by geometric mean method for 7 species (where $r < 0.74$) gave much poorer estimates of temperature sensitivity than the *ad hoc* method this is because the *ad hoc* method assumes the same value for the exponential constant of all species (Table 3) for the remaining species.

Data obtained using the *ad hoc* method yield a slope of the linear regression of the data as a whole (Fig. 11a) which is not significantly different from unity but with a small positive intercept (data for *O. universa* and *G. aequilateralis* have been included although, as discussed earlier, the calibration data, especially for *O. universa*, show considerable scatter).

The scatter in Fig. 11a is equivalent to a standard deviation in Mg/Ca temperature estimate of ±1.13 $^{o}$C (Fig. 11b). *Dekens et al*. [2002] suggest a standard error of between ±1.2 and ± 1.4 $^{o}$C from core top studies in different oceans.

The scatter is not attributable to analytical error in measurement of Mg/Ca which makes a trivial (~ ±0.05 $^{o}$C) contribution. The foraminiferal cleaning procedure results in variability dependent on inferred temperature but typically of ~ ±0.2 $^{o}$C which is less than half of the natural variability in a population of 20 individuals [*Barker,* 2002]. Fewer individuals were used for analysis than is our normal practice as well as a wider size range than normal (there is a size effect [*Elderfield et al*., 2002], for example of up to about 0.2 $^{o}$C between *G. ruber* white in 300-350 and 425-500 μm fractions). Taken together, up to, perhaps, about ±0.5 $^{o}$C can be attributable to Mg/Ca temperature estimation. The remainder is most likely associated with $\delta^{18}O$ calcification temperature, resulting from calculation of $\delta^{18}O_w$ and thus assignment of habitat depth and temperature. It should also be remembered that $\delta^{18}O$ equilibrium between foraminiferal calcite and sea water has been assumed.

### 5.7. Estimation of thermocline structure from Mg/Ca

The average Mg/Ca-temperature and habitat depth derived from oxygen isotopes (Fig. 4; Table 2) for each species have been plotted along with measured average annual, December-January and July-August temperatures from Bermuda Biological Station 'S' (Fig. 12). The Mg/Ca-temperature was obtained using the *ad hoc* method after assuming a constant exponent value A=0.09.

Both estimates of depth habitat (from Mg/Ca-temperature and $\delta^{18}O$ of foraminifera) are in good agreement (Fig. 12). *G. ruber* pink calcifies near surface conditions and represents summer temperature based on Mg/Ca. *G. ruber* white and *G. sacculifer* with sac

records a temperature range of average annual to the warmest month (July-August) and lives in the mixed layer (Fig. 12). *G.* sacculifer with sac chamber calcifies at slightly deeper water depth compared to *G. ruber* white based on Mg/Ca-temperature. This is consistent with previous work based on Mg/Ca on the two species [*Rosenthal et al.*, 2000; *Dekens et al.,* 2002; *Rosenthal* and *Lohman*, 2002]. *P. obliquiloculata, N. dutertrei, G. aequilateralis, O. universa* and *G. conglobatus* calcifies on a range of temperatures extending from upper to lower thermocline position in the water column (Fig. 12). Globorotaliid species in this study show a deeper depth of calcification compared to other species although the depth estimates from Mg/Ca-temperature give a narrow depth range compared to the $\delta^{18}O$ approach except for *G. crassiformis* (Fig. 12).

Thus, estimation of Mg/Ca-temperature, along with $\delta^{18}O$, for multiple species of planktonic foraminifera from individual samples has potential for reconstructing the structure of the thermocline in the past.

### 5.8. Comparison of temperature estimates

The calibration data from this study have been added to a compilation of literature data (Table 3).

Three important issues should be considered in comparing these data:

(i) Different laboratories employ different pre-analysis cleaning procedures for Mg/Ca (some laboratories, including ours, have modified/refined procedures and therefore may have used different procedures for different publications). There has, as yet, been no inter-laboratory comparison.

(ii) The method of estimating temperature may be different between calibrations. Only the temperature fixed in culture experiments may be considered to be an independent

variable. In other calibrations (core tops and sediment traps) temperature is estimated from various measured parameters, sometimes using different equations, and is a dependent variable. This has a small effect on statistical procedures. As discussed above, the uncertainty in temperature estimate is probably greater than the uncertainty in Mg/Ca. In some cases calibration is made versus SST, although it is known that the species may not calcify at the sea surface, for the useful expedient of its paleoceanographic application to estimate past SST.

(iii) Mg/Ca is subject to dissolution effects, probably because of heterogeneous shell chemistry which results in preferential loss of calcite with higher than average Mg, and affects different species to different extents. This is a subject of active debate but it is safe to say that the effect should be considered in core top calibrations, even above the calcite lysocline. It is also possible that dissolution affects estimates of calcification temperature via $\delta^{18}O$.

Despite these constraints, some consensus appears to be developing as to appropriate calibration equations. The good fit of data from a number of different species to a single calibration is encouraging both because it implies that the temperature effect of Mg uptake is being properly described, and because the equation might be used for extinct planktonic species. In particular, a number of studies appear to be converging on the same calibrations, within error, for *G. ruber* white and *G. sacculifer*. This is important because of their suitability for charting SST or near-SST.

The effect of dissolution, and some complexities of detail, is illustrated from a comparison of the G. *ruber* data in Table 3. Core top data (250-350 μm) from the Equatorial Pacific [*Lea et al.,* 2000] gave Mg/Ca =0.30 exp(0.089T), which was subsequently corrected for dissolution [*Dekens et al.,* 2002] by increasing pre-exponential constants to yield a "zero water depth" equation: Mg/Ca = 0.38 exp(0.090T). This is similar to the sediment trap

equation: Mg/Ca = 0.34±0.08 exp(0.102T) (250-350 μm). It is safe to conclude that an upward correction (which is equivalent to 1.5 °C) is warranted, because of the known depth effect on dissolution [*Rosenthal and Boyle*, 1993; *Brown and Elderfield,* 1996; *Rosenthal et al.,* 2000] despite the correction being of the order of the uncertainty in the constant B. *Rosenthal and Lohman* [2002] has also suggested for correction on pre-exponential constant for dissolution effect in Mg/Ca calibration study.

As far as can be judged, calibrations for the other species considered here are consistent with a similar temperature dependence but further studies are needed, although these will be difficult because of the narrow temperature ranges for some species. Calibrations for *O. universa*, *G. aequilateralis* and *G. bulloides* appear to have higher pre-exponential constants than other species studied. These three species coincidentally fall towards the apex of the triangular plot based on amino acid compositions of foraminifera, constructed by *King and Hare* [1972]. Perhaps that there is a link between the amino acids in a protein template for foraminiferal calcification and Mg/Ca.

The use of a single oxygen isotope palaeotemperature equation for the calculation of calcification temperature should be borne in mind when applying the calibrations.

# 6. Summary and Conclusions

There is a small inter-annual variability in Mg/Ca and $\delta^{18}O$ in planktonic foraminiferal calcite from a sediment trap time series in the Sargasso Sea. However, a strong intra-annual variability occurs in the foraminiferal Mg/Ca and $\delta^{18}O$ of all the surface dwelling planktonic species with a lesser effect in deeper dwelling species. The $\delta^{18}O$ measurements and sea surface salinity and temperature data were used to evaluate the depth

habitat of the common planktonic foraminiferal species in the Sargasso Sea. Knowledge of foraminiferal depth habitat is important in order to estimate the $\delta^{18}O_w$ and calcification temperature for the foraminiferal species.

An empirical calibration between Mg/Ca (mmol/mol) and calcification temperature (T $^{O}$C) was obtained when all the species except two within 350-500 μm size fraction are considered together: Mg/Ca = 0.38 exp (0.090T), equivalent to a 9.0 ± 0.3 % change in Mg/Ca for a 1$^{o}$C change in temperature.

*G. aequilateralis* and *O. universa*, (and also *G. bulloides*) have significantly higher Mg/Ca values at a given temperature than the other species analysed. Only small differences exist in calibrations between the other species. The sediment trap calibrations for *G. ruber* and *G. sacculifer* are in agreement with literature data where dissolution effects can be excluded.

The Mg/Ca-temperature estimates can be used for reconstructing temperatures of near surface (using *G. ruber* pink), mixed layer (using *G. ruber* white and *G. sacculifer*) and thermocline temperatures (using *N. dutertrei*, *P. obliquiloculata, G. aequilateralis* etc.) at this site.

The single calibration equation will be useful especially for extinct species in the palaeoceanographic record but the use of species-specific equations will provide more accurate temperature estimates.

**Acknowledgements**. In particular we thank Werner Deuser whose foresight provided the important archive of sediment trap samples used in this study. We thank colleagues in Cambridge, especially Nick Shackleton for advice, and Linda Booth and Mervyn Greaves for help in the laboratory; and Yair Rosenthal for encouraging use of the geometric mean method (However, John Shepherd has recently pointed out to H.E. that the geometric mean estimate

for functional regression was shown by Copas in 1972 to be formally incorrect; but because this is a contentious issue, and the approach was recommended by Laws (1997), we have retained it here and shall consider his criticism elsewhere). We also thank Dorothy Pak and David Lea at UCSB for their advice on use of higher peroxide strength during Mg-cleaning. Research funded by a Cambridge Commonwealth Trust Studentship (to P.J.) and grants to H.E. from the Natural Environment Research Council (GR3/1310 and GR3/JIF/05a) and The European Commission (EVR1-CT-40018: CESOP).

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## Figure captions

**Figure 1**. Average annual cycles of temperature and salinity at station 'S' in the Sargasso Sea, during the sediment trap deployments, April 1978 to May 1984: **(a)** temperature (ºC) **(b)** salinity, 0-800m [*Deuser and Ross*, 1989]. Numbers on the plot are water depths in meter.

**Figure 2.** Interannual variation in Mg/Ca (mmol/mol) and $\delta^{18}O$ (‰ VPDB) in: **(a)** *G. ruber* white, **(b)** *G. ruber* pink, **(c)** *G. aequilateralis* and **(d)** *G. truncatulinoides*. Note the differences in scales for Mg/Ca and $\delta^{18}O$ between some species. (J=June and D=December).

**Figure 3.** Average intra-annual variation in Mg/Ca (mmol/mol) and $\delta^{18}O$ (‰ VPDB) of several planktonic species. Each point represents the mean of bimonthly samples from the six-year time series and the vertical bar is the standard deviation (interannual variation). Note the differences in scales for Mg/Ca and $\delta^{18}O$ between some species.

**Figure 4**. Determination of depth habitat of planktonic foraminiferal species in Sargasso Sea. Measured $\delta^{18}O$ (‰ VPDB) of foraminiferal calcite (thick curve) is plotted versus calendar month, together with predicted $\delta^{18}O$ (‰ VPDB) of calcite in equilibrium with seawater for various depths in the water column, using salinity and temperature profiles at time of the trap deployment. The predicted $\delta^{18}O$ of calcite was calculated for an average of six-years of temperature and salinity data on a calendar month scale and for various depths.

**Figure 5.** Data for multiple species plotted as geometric means. Plotted on each axis are (value - mean of value)/std deviation of mean (see *Laws* [1997]).

**Figure 6.** Mg/Ca versus $\delta^{18}O$ calcification temperature: **(a)** All species except *O. universa* and *G. aequilateralis* **(b)** Mg/Ca versus $\delta^{18}O$ calcification temperature showing individual

species calibrations assuming a constant exponential constant. Note that data are only for the size fraction 350-500 μm in both figure 6 a and b.

**Figure 7.** Mg/Ca versus $\delta^{18}O$ calcification temperature: **(a)** *G. ruber* white and pink in two size fractions **(b)** O. *universa* and *G. aequilateralis*; compared with culture data and equation for multiple species.

**Figure 8. (a)** Comparison of pre-exponential (B) and exponential (A) constants for species and they are related to each other: B=1.46±0.14 + (-10.94±1.86)*A (r=0.9). **(b)** Comparison of A and correlation coefficient (r) of calibration equation. Values for A, B and r were obtained using geometric mean method.

**Figure 9**. Comparison of spinose and non spinose species: **(a)** Mg/Ca versus $\delta^{18}O$ calcification temperature **(b)** geometric mean plot.

**Figure 10.** Mg/Ca versus temperature for *G. ruber* and *G. sacculifer:* **(a)** $\delta^{18}O$ calcification temperature **(b)** Monthly mean temperature. Monthly mean temperature is the average temperature based on habitat depth range of each species, obtained from measured hydrological data at Biological station 'S'. Black squares without error bar is the Mg/Ca-temperature and grey squares with error bars are mean monthly temperatures for these species.

**Figure 11.** Accuracy of temperature estimation: **(a)** Mg/Ca temperature versus $\delta^{18}O$ calcification temperature. The equation of the line is Mg/Ca temperature=1.003(±0.004) $\delta^{18}O$ calcification temperature (r=0.93). Mg/Ca temperature is calculated using ad-hoc method

after assuming A=0.090. **(b)** Mg/Ca temperature minus $\delta^{18}O$ calcification temperature versus $\delta^{18}O$ calcification temperature; the mean and standard deviations are shown.

**Figure 12.** Mg/Ca temperature versus habitat depth for species (Table 2). Mean annual temperature, mean temperatures for December and January (coldest) and mean temperatures for July and August (warmest) are also shown. Mg/Ca temperatures are calculated using ad-hoc method after assuming A=0.090. Error bars are standard deviations of Mg/Ca temperature and depth range for individual species.

## Table captions

**Table 1**. Dates and duration of 31 sediment trap deployments in the Sargasso Sea that provided samples used in study.

**Table 2**. Species of planktonic foraminifera in Sargasso Sea used in study and estimated of calcification depth from comparison of foraminiferal $\delta^{18}O$ with calcite in equilibrium with sea water.

**Table 3.** Calibration equations based on geometric mean method from this study compared with literature data (recalculated using geometric mean method except for *Dekens et al.,* 2002). Equations based on *ad hoc* method after assuming A=0.09 is also provided.

**Table 1** Dates and duration of 31 sediment trap deployments in the Sargasso Sea that provided samples used in study.

| Recovery | Start | End | Days |
|---|---|---|---|
| 1 | 78/04/06 | 78/06/07 | 62 |
| 2 | 78/06/07 | 78/08/08 | 62 |
| 3 | 78/08/09 | 78/10/10 | 62 |
| 5 | 78/12/12 | 79/02/14 | 64 |
| 6 | 79/03/24 | 79/05/31 | 68 |
| 7 | 79/05/31 | 79/07/30 | 60 |
| 9 | 79/10/12 | 79/12/03 | 52 |
| 10 | 79/12/05 | 80/02/04 | 61 |
| 11 | 80/02/06 | 80/04/07 | 61 |
| 12 | 80/04/15 | 80/06/17 | 63 |
| 13 | 80/06/20 | 80/08/11 | 52 |
| 14 | 80/08/11 | 80/10/14 | 64 |
| 15 | 80/10/17 | 80/12/09 | 53 |
| 17 | 81/02/05 | 81/04/07 | 61 |
| 18 | 81/04/08 | 81/05/26 | 48 |
| 19 | 81/05/27 | 81/07/21 | 55 |
| 20 | 81/07/21 | 81/09/15 | 56 |
| 21 | 81/09/17 | 81/12/02 | 76 |
| 22 | 81/12/02 | 82/02/02 | 62 |
| 23 | 82/02/02 | 82/04/06 | 63 |
| 24 | 82/04/13 | 82/06/08 | 56 |
| 25 | 82/06/11 | 82/08/17 | 67 |
| 27 | 82/10/18 | 82/12/07 | 50 |
| 28 | 83/01/17 | 83/03/16 | 58 |
| 29 | 83/03/16 | 83/05/25 | 70 |
| 30 | 83/05/25 | 83/07/12 | 48 |
| 31 | 83/0713 | 83/09/20 | 69 |
| 32 | 83/09/20 | 83/11/15 | 56 |
| 33 | 83/11/15 | 84/01/17 | 63 |
| 34 | 84/01/17 | 84/0313 | 56 |
| 35 | 84/03/28 | 84/05/17 | 50 |

**Table 2** Species of planktonic foraminifera in Sargasso Sea used in study and estimated of calcification depth from comparison of foraminiferal $\delta^{18}O$ with calcite in equilibrium with sea water.

| Species | Calcification depth (m) |
|---|---|
| *Globigerinoides ruber* pink | 0-25 |
| *Globigerinoides ruber* white | 0-50 |
| *Globigerinoides sacculifer* | 0-50 |
| *Globigerinoides sacculifer* with sac | 0-50 |
| *Globigerinella aequilateralis*, | 50-75 |
| *Orbulina universa* thin test | 50-100 |
| *Orbulina universa* thick test | 50-100 |
| *Globigerinoides conglobatus* | 50-100 |
| *Neogloboquadrina dutertrei* | 50-100 |
| *Pulleniatina obliquiloculata* | 50-100 |
| *Globorotalia inflata* | 100-400 |
| *Globorotalia truncatulinoides* | 200-500 |
| *Globorotalia crassiformis* | 500-800 |
| *Globorotalia hirsuta* | 500-800 |

**Table 3** Calibration equations based on geometric mean method from this study compared with literature data (recalculated using geometric mean method except for *Dekens et al.,* 2002). Equations based on *ad hoc* method after assuming A=0.09 is also provided.

| Species | source | Mg/Ca = B exp(AT) | | reference |
|---|---|---|---|---|
| | | B | A | |
| Ten planktonic species* (350-500 µm) | Sediment trap (N. Atl.) | 0.38 (±0.02) | 0.090 (±0.003) | This study (r=0.93) |
| *G. ruber* white (250-350 µm) | Sediment trap | 0.34 (±0.08) | 0.102 (±0.010) | This study (r=0.91) |
| *G. ruber* white (350-500 µm) | Sediment trap | 0.48 (±0.07) | 0.085 (±0.006) | This study (r=0.94) |
| *G. ruber* pink (250-350 µm) | Sediment trap | 0.88 (±0.20) | 0.058 (±0.009) | This study (r=0.81) |
| *G. ruber* pink (350-500 µm) | Sediment trap | 0.73 (±0.17) | 0.067 (±0.009) | This study (r=0.85) |
| *G. sacculifer* with sac (350-500 µm) | Sediment trap | 0.67 (±0.31) | 0.069 (±0.013) | This study (r=0.85) |
| *G. sacculifer* w/o sac (350-500 µm) | Sediment trap | 1.06 (±0.21) | 0.048 (±0.012) | This study (r=0.75) |
| *P. obliquiloculata* (350-500 µm) | Sediment trap | 0.18 (±0.1) | 0.12 (±0.03) | This study (r=0.79) |
| *G. inflata* (350-500 µm) | Sediment trap | 0.56 (±0.16) | 0.058 (±0.015) | This study (r=0.74) |
| *G. aequilateralis* (350-500 µm) | Sediment trap | 0.86 (±0.24) | 0.068 (±0.013) | This study (r=0.67) |
| Eight planktonic species** | Core tops (N. Atl.) | 0.65 (±0.04) | 0.085 (±0.005) | *Elderfield and Ganssen* [2000] |
| *G. ruber* white (250-350 µm) | Core tops (Eq. Pac.) | 0.3 (±0.06) | 0.089 (±0.007) | *Lea et al.* [2000] vs SST |
| *G. ruber* white (250-350 µm) | Core tops | 0.38 | 0.09 | *Dekens et al.* [2002] vs SST |
| *G. sacculifer* and *N. pachyderma* sinistral | Culture+core-tops | 0.47 (±0.03) | 0.082 (±0.006) | *Nuernberg et al.* [1996] |
| *G. sacculifer* | Culture | 0.39 (±0.06) | 0.089 (±0.008) | *Nuernberg et al.* [1996] |
| *G. sacculifer* w/o sac (250-350 µm) | Core tops | 0.37 | 0.09 | *Dekens et al*. [2002] vs SST |

| | | | | |
|---|---|---|---|---|
| *O. universa* | Culture | 1.38 (±0.05) | 0.085 (±0.002) | *Lea et al.* [1999] |
| *N. dutertrei* (250-350 µm) | Core tops | 0.60 | 0.08 | *Dekens et al*. [2002] vs SST |
| *G. bulloides* | Core tops (N. Atl.) | 0.81 (±0.04) | 0.081 (±0.005) | *Elderfield and Ganssen* [2000] |
| *G. bulloides* | Culture | 0.51 (±0.1) | 0.104 (±0.01) | *Lea et al*. [1999] |
| *G. bulloides* | Culture + core tops | 0.47 (±0.03) | 0.108 (±0.003) | *Mashiotta et al.* [1999] |
| *G. ruber* white (250-350 µm) | Sediment trap | 0.449 (±0.006) | 0.090 | This study (A assumed) |
| *G. ruber* white (350-500 µm) | Sediment trap | 0.395 (±0.009) | 0.090 | This study (A assumed) |
| *G. ruber* pink (250-350 µm) | Sediment trap | 0.381 (±0.01) | 0.090 | This study (A assumed) |
| *G. ruber* pink (350-500 µm) | Sediment trap | 0.383 (±0.008) | 0.090 | This study (A assumed) |
| *G. sacculifer* with sac (350-500 µm) | Sediment trap | 0.377 (±0.01) | 0.090 | This study (A assumed) |
| *G. sacculifer* w/o sac (350-500 µm) | Sediment trap | 0.347 (±0.011) | 0.090 | This study (A assumed) |
| *G. conglobatus* (350-500 µm) | Sediment trap | 0.347 (±0.024) | 0.090 | This study (A assumed) |
| *N. dutertrei* (350-500 µm) | Sediment trap | 0.342 (±0.012) | 0.090 | This study (A assumed) |
| *P. obliquiloculata* (350-500 µm) | Sediment trap | 0.328 (±0.007) | 0.090 | This study (A assumed) |
| *G. inflata* (350-500 µm) | Sediment trap | 0.299 (±0.005) | 0.090 | This study (A assumed) |
| *G. truncatulinoides* (350-500 µm) | Sediment trap | 0.359 (±0.008) | 0.090 | This study (A assumed) |
| *G. crassiformis* (350-500 µm) | Sediment trap | 0.339 (±0.029) | 0.090 | This study (A assumed) |
| *G. hirsuta* (350-500 µm) | Sediment trap | 0.409 (±0.015) | 0.090 | This study (A assumed) |
| *O. universa* (350-500 µm) | Sediment trap | 0.595 (±0.042) | 0.090 | This study (A assumed) |
| *G. aequilateralis* (350-500 µm) | Sediment trap | 0.532 (±0.008) | 0.090 | This study (A assumed) |

* *G. ruber* white, *G. ruber* pink, *G. sacculifer*, *G. conglobatus*, *G. aequilateralis, O. universa*, *N. dutertrei*, *P. obliquiloculata*, *G. inflata*, *G. truncatulinoides*, *G. hirsuta*, *G. crassiformis*

** *G. bulloides, G. ruber, G. sacculifer, G. siphonifera, N. pachyderma, G. hirsuta, G. inflata, G. truncatulinoide*

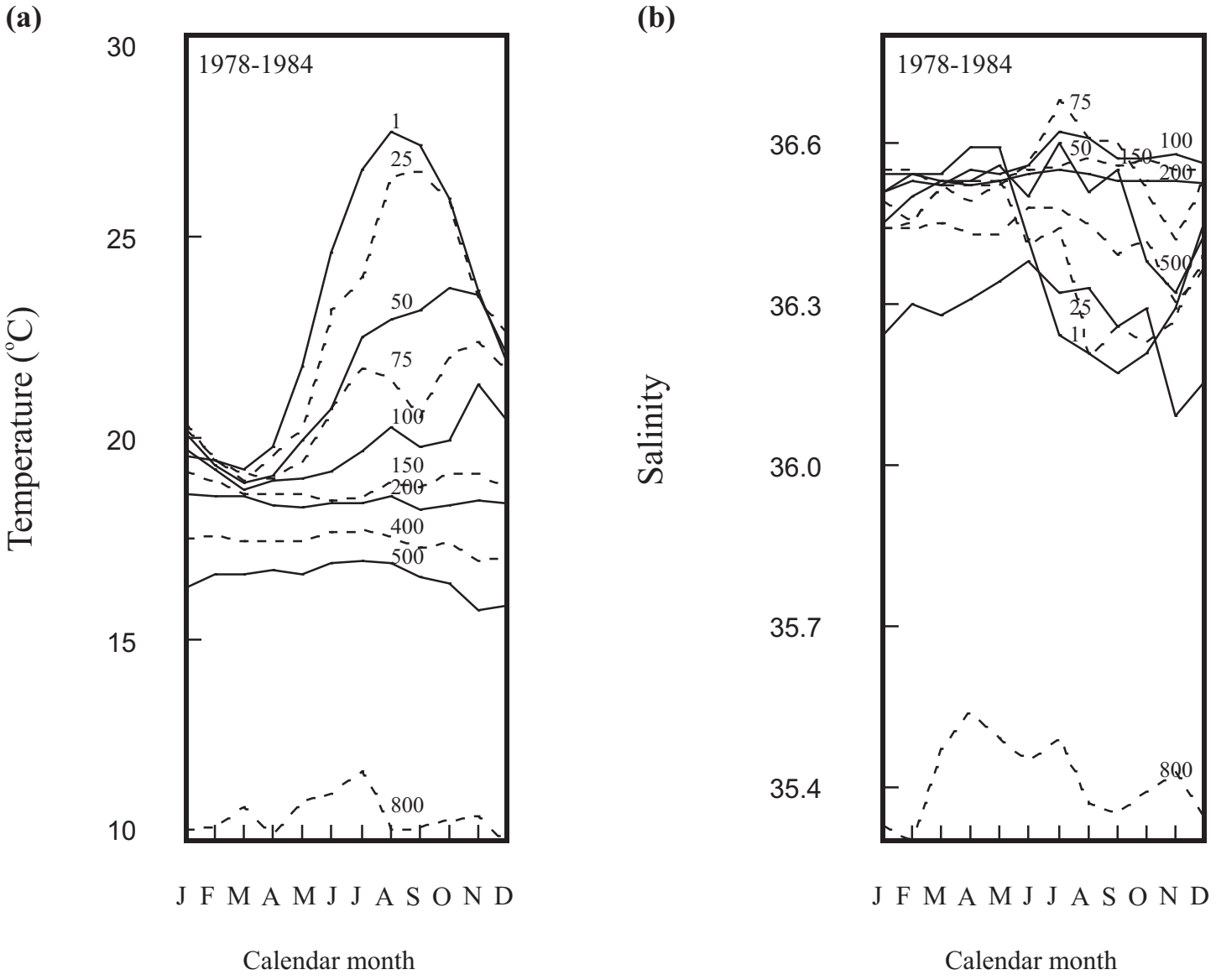

(a)
1978-1984
Temperature (°C)
30
25
20
15
10
1
25
50
75
100
150
200
400
500
800
J F M A M J J A S O N D
Calendar month
(b)
1978-1984
Salinity
36.6
36.3
36.0
35.7
35.4
75
50
100
150
200
500
25
1
800
J F M A M J J A S O N D
Calendar month

Fig 1

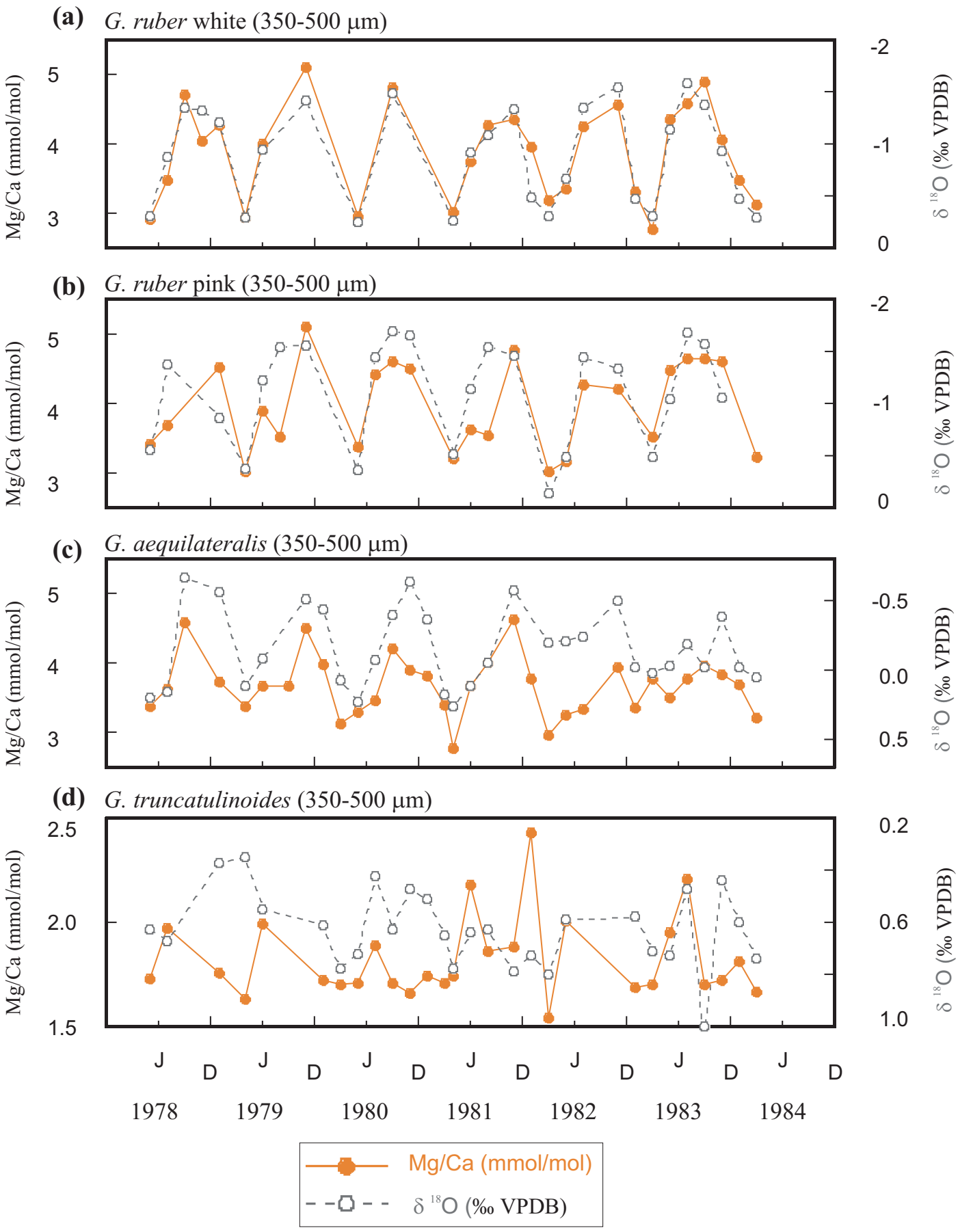

(a) G. ruber white (350-500 µm)
(b) G. ruber pink (350-500 µm)
(c) G. aequilateralis (350-500 µm)
(d) G. truncatulinoides (350-500 µm)
Mg/Ca (mmol/mol)
δ 18O (‰ VPDB)
J D J D J D J D J D J D J D
1978 1979 1980 1981 1982 1983 1984
Mg/Ca (mmol/mol)
δ 18O (‰ VPDB)

Fig 2

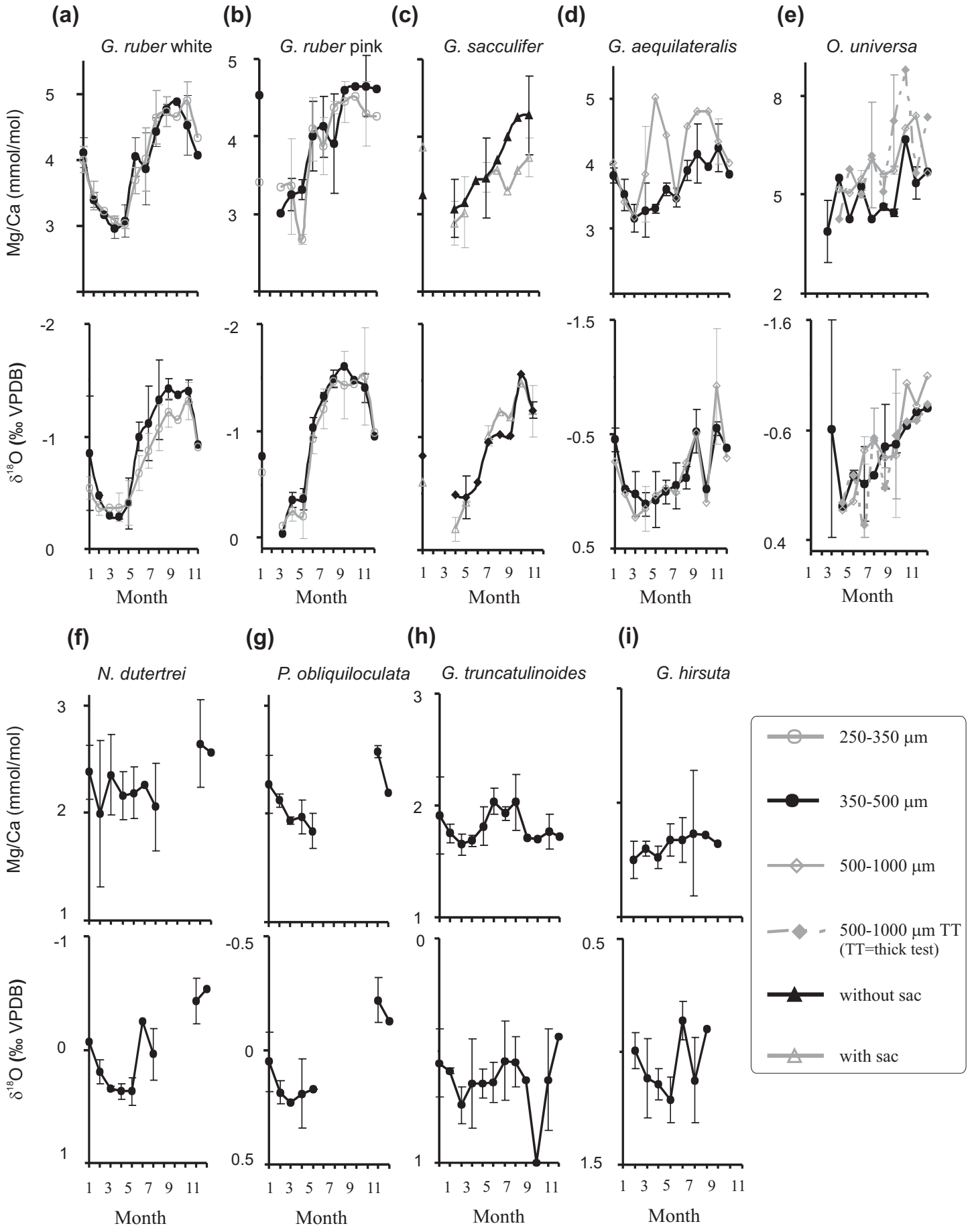

(a)
G. ruber white
(b)
G. ruber pink
(c)
G. sacculifer
(d)
G. aequilateralis
(e)
O. universa
Mg/Ca (mmol/mol)
δ18O (‰ VPDB)
Month
(f)
N. dutertrei
(g)
P. obliquiloculata
(h)
G. truncatulinoides
(i)
G. hirsuta
250-350 µm
350-500 µm
500-1000 µm
500-1000 µm TT
(TT=thick test)
without sac
with sac

Fig 3

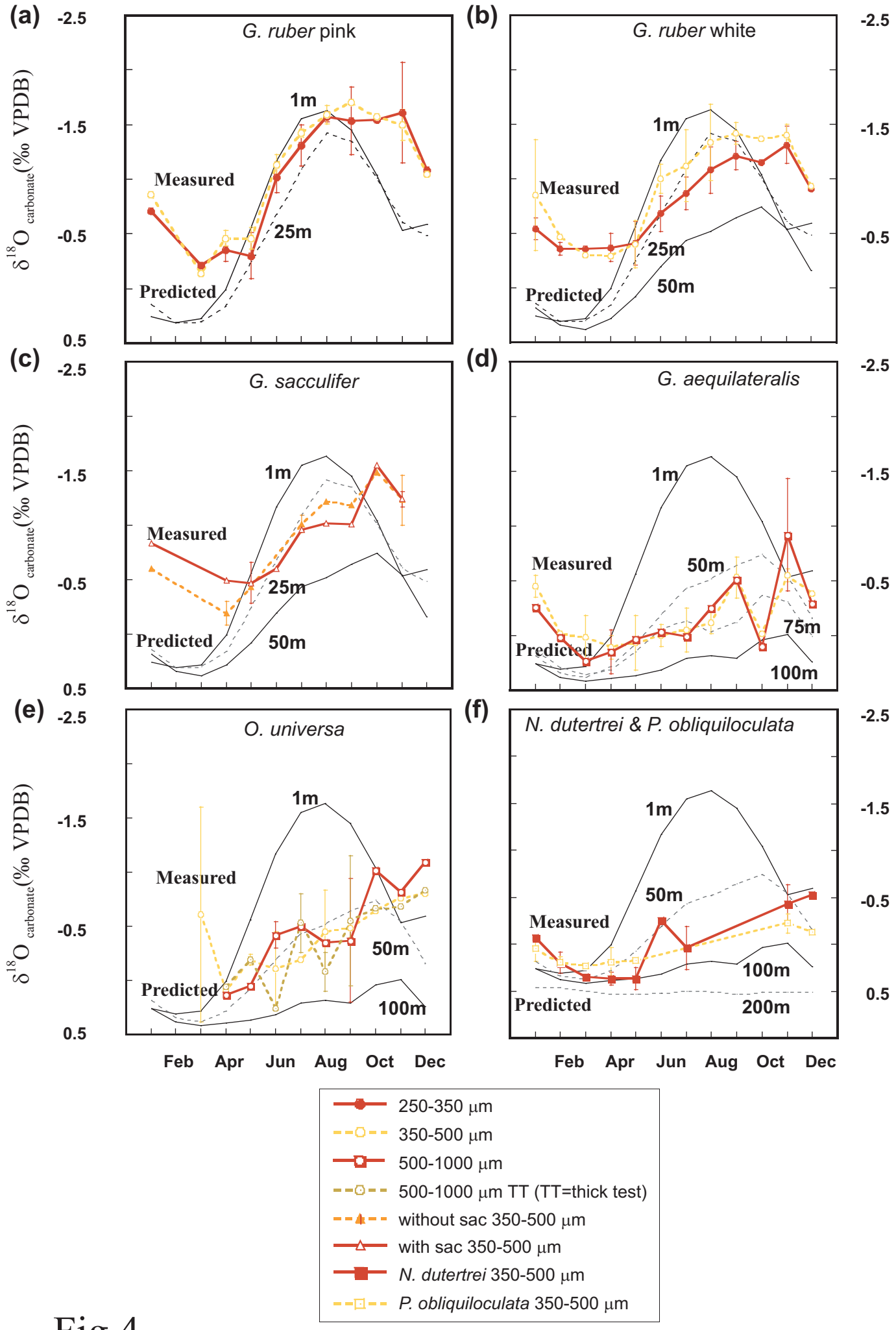

(a)
G. ruber pink
1m
Measured
25m
Predicted
(b)
G. ruber white
1m
Measured
25m
50m
Predicted
(c)
G. sacculifer
1m
Measured
25m
Predicted
50m
(d)
G. aequilateralis
1m
Measured
50m
75m
Predicted
100m
(e)
O. universa
1m
Measured
50m
Predicted
100m
(f)
N. dutertrei & P. obliquiloculata
1m
50m
Measured
100m
Predicted
200m
δ18O carbonate (‰ VPDB)
-2.5
-1.5
-0.5
0.5
Feb
Apr
Jun
Aug
Oct
Dec
250-350 µm
350-500 µm
500-1000 µm
500-1000 µm TT (TT=thick test)
without sac 350-500 µm
with sac 350-500 µm
N. dutertrei 350-500 µm
P. obliquiloculata 350-500 µm

Fig 4

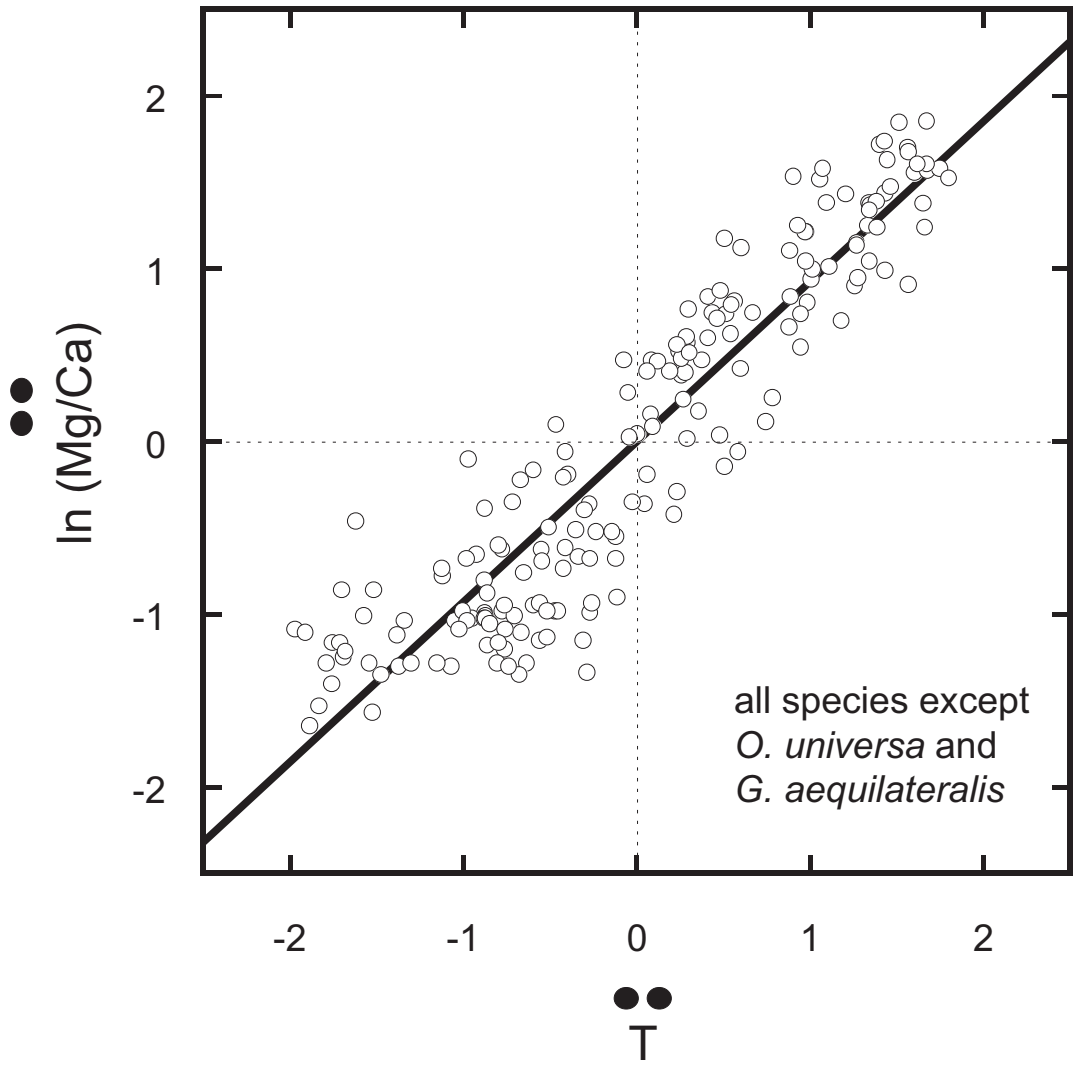

2
1
0
-1
-2
ln (Mg/Ca)
-2
-1
0
1
2
T
all species except
O. universa and
G. aequilateralis

Figure 5

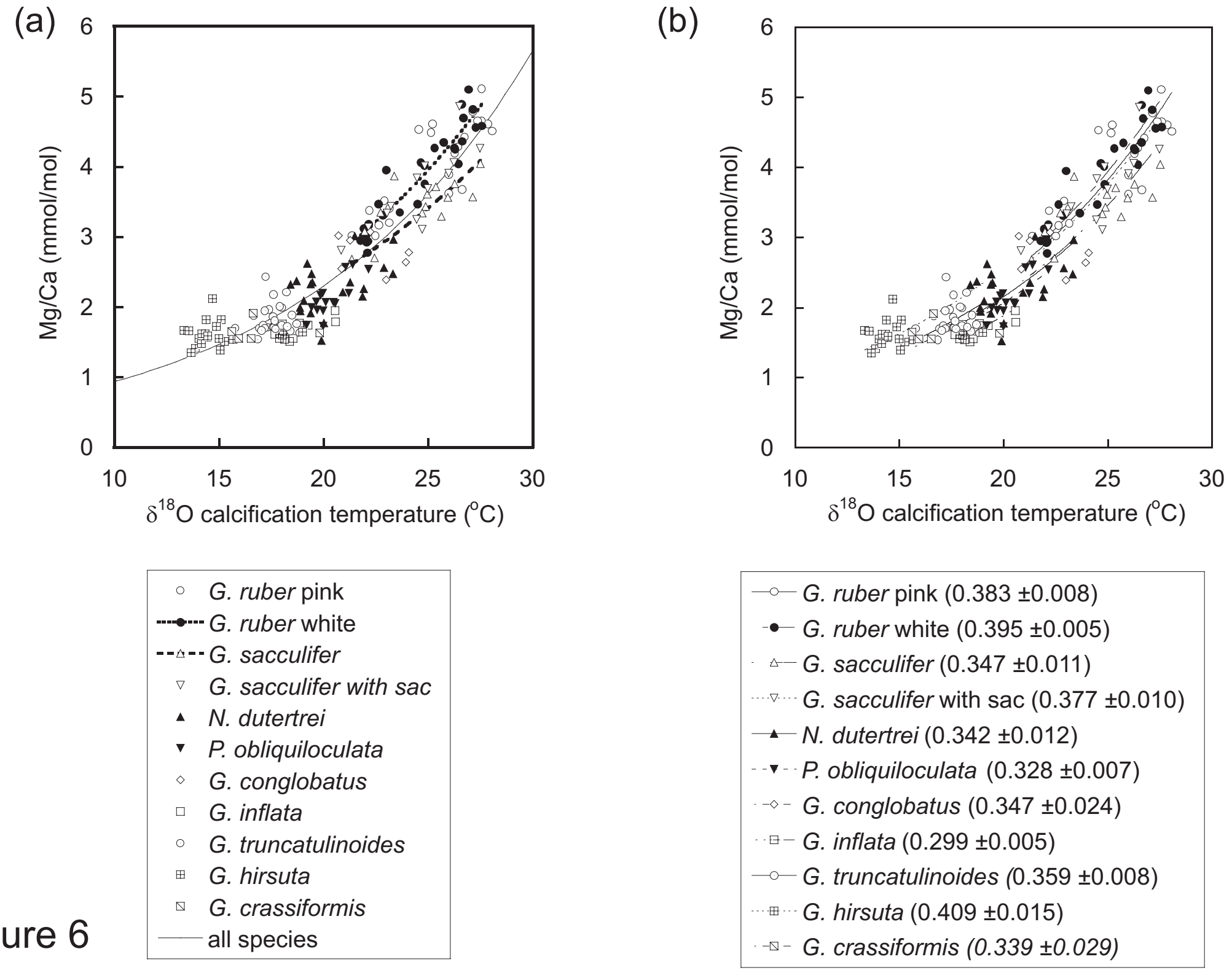

(a)
(b)
Mg/Ca (mmol/mol)
δ18O calcification temperature (°C)
0
1
2
3
4
5
6
10
15
20
25
30
G. ruber pink
G. ruber white
G. sacculifer
G. sacculifer with sac
N. dutertrei
P. obliquiloculata
G. conglobatus
G. inflata
G. truncatulinoides
G. hirsuta
G. crassiformis
all species
G. ruber pink (0.383 ±0.008)
G. ruber white (0.395 ±0.005)
G. sacculifer (0.347 ±0.011)
G. sacculifer with sac (0.377 ±0.010)
N. dutertrei (0.342 ±0.012)
P. obliquiloculata (0.328 ±0.007)
G. conglobatus (0.347 ±0.024)
G. inflata (0.299 ±0.005)
G. truncatulinoides (0.359 ±0.008)
G. hirsuta (0.409 ±0.015)
G. crassiformis (0.339 ±0.029)

Figure 6

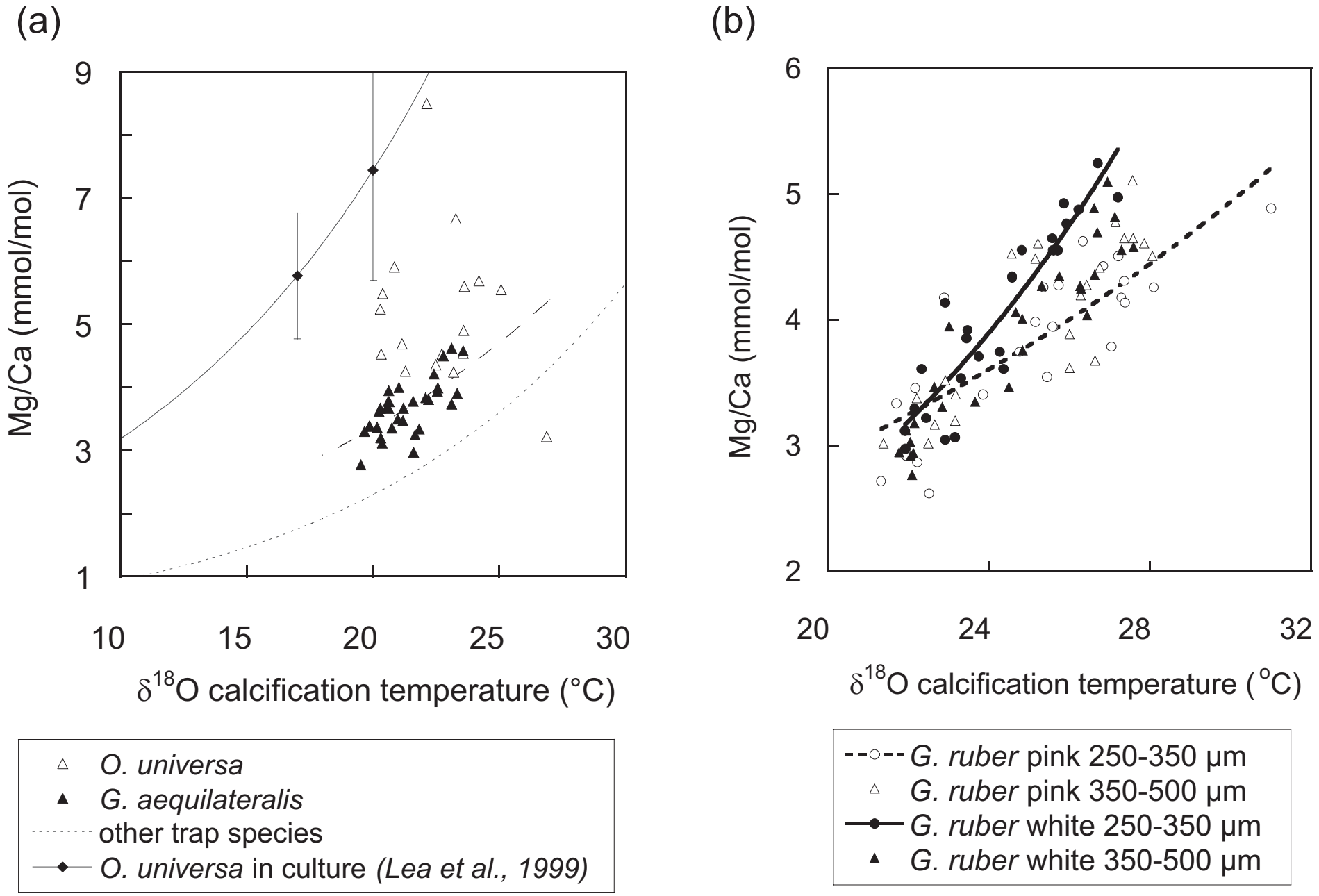

(a)
Mg/Ca (mmol/mol)
9
7
5
3
1
10
15
20
25
30
δ18O calcification temperature (°C)
O. universa
G. aequilateralis
other trap species
O. universa in culture (Lea et al., 1999)
(b)
Mg/Ca (mmol/mol)
6
5
4
3
2
20
24
28
32
δ18O calcification temperature (°C)
G. ruber pink 250-350 µm
G. ruber pink 350-500 µm
G. ruber white 250-350 µm
G. ruber white 350-500 µm

Figure 7

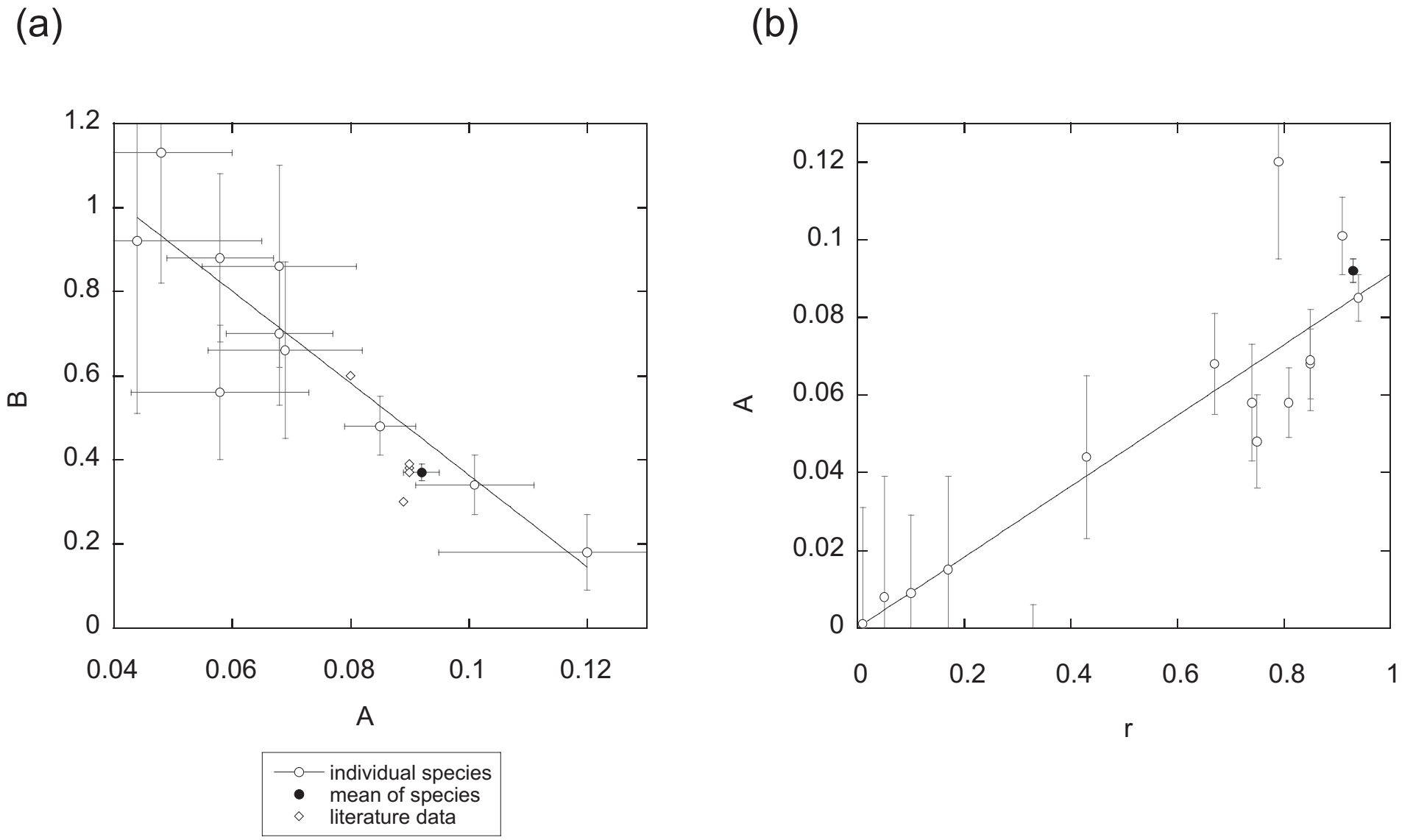

(a)
(b)
B
A
r
1.2
1
0.8
0.6
0.4
0.2
0
0.04
0.06
0.08
0.1
0.12
0.02
0.2
individual species
mean of species
literature data

Figure 8

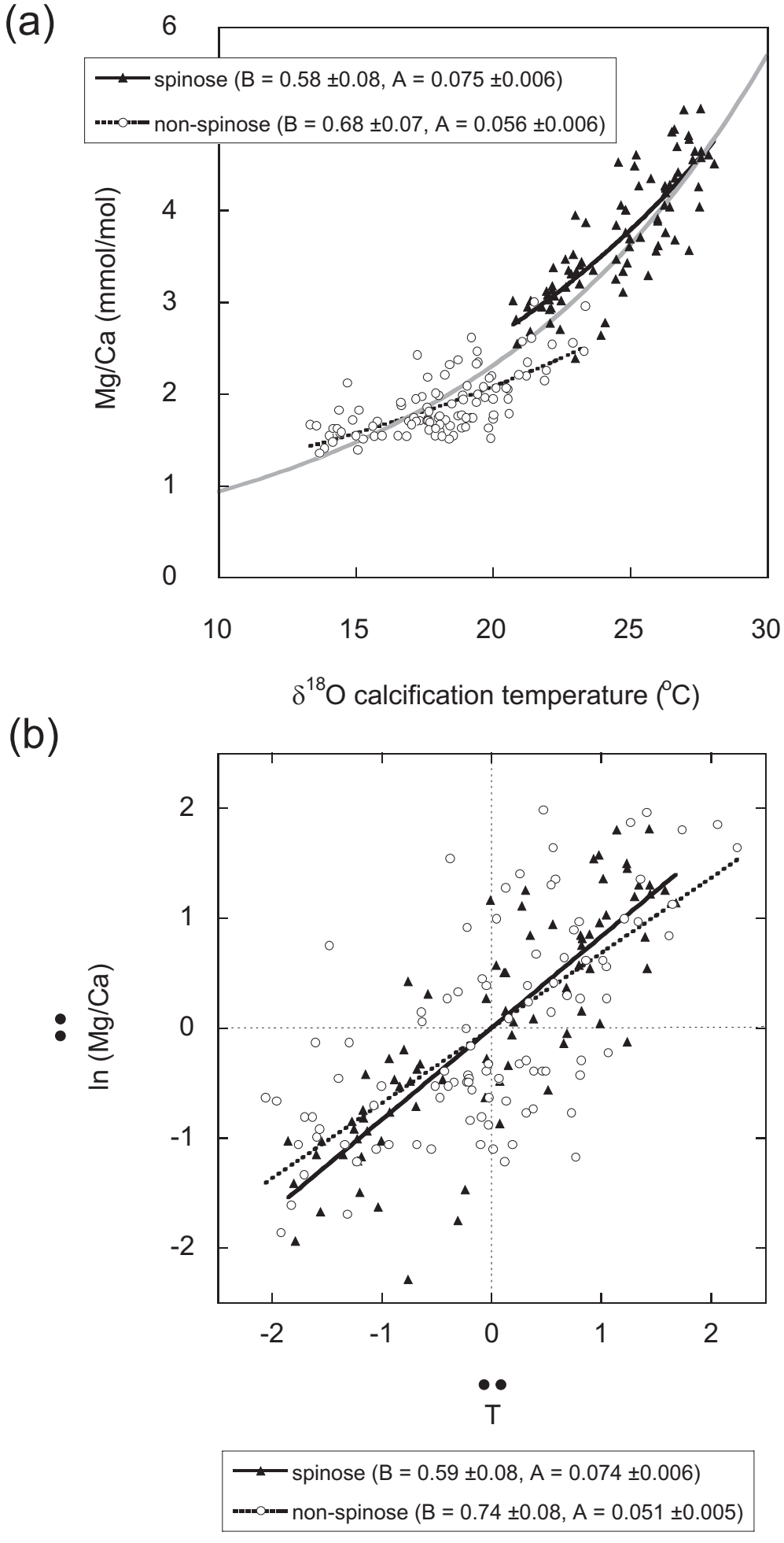

(a)
spinose (B = 0.58 ±0.08, A = 0.075 ±0.006)
non-spinose (B = 0.68 ±0.07, A = 0.056 ±0.006)
Mg/Ca (mmol/mol)
δ18O calcification temperature (°C)
(b)
ln (Mg/Ca)
T
spinose (B = 0.59 ±0.08, A = 0.074 ±0.006)
non-spinose (B = 0.74 ±0.08, A = 0.051 ±0.005)

Figure 9

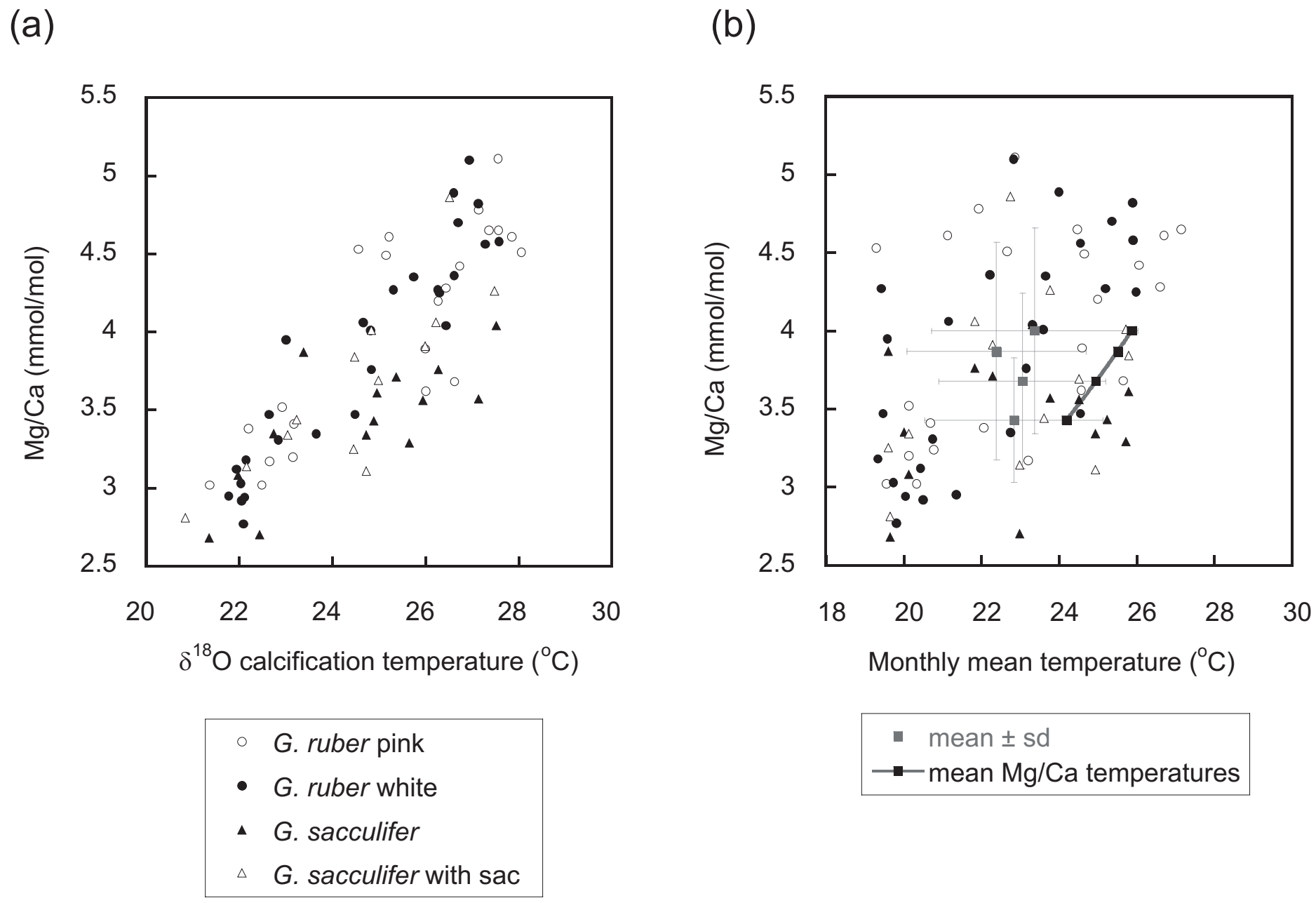
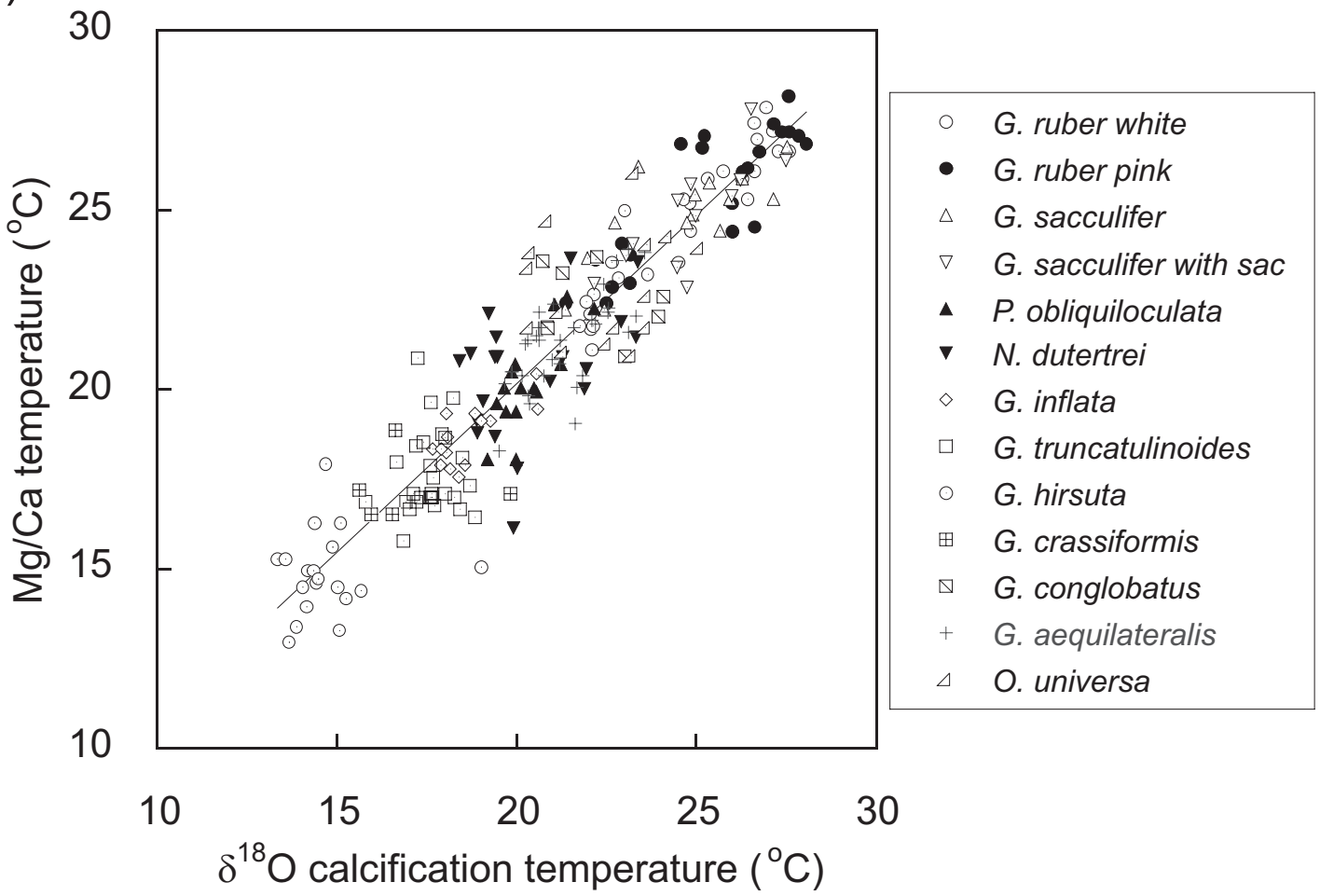

(a)
(b)
Mg/Ca (mmol/mol)
5.5
5
4.5
4
3.5
3
2.5
20
22
24
26
28
30
δ18O calcification temperature (°C)
18
Monthly mean temperature (°C)
G. ruber pink
G. ruber white
G. sacculifer
G. sacculifer with sac
mean ± sd
mean Mg/Ca temperatures

Figure 10

(a)


30
25
20
15
10
Mg/Ca temperature (°C)
10
15
20
25
30
δ18O calcification temperature (°C)
G. ruber white
G. ruber pink
G. sacculifer
G. sacculifer with sac
P. obliquiloculata
N. dutertrei
G. inflata
G. truncatulinoides
G. hirsuta
G. crassiformis
G. conglobatus
G. aequilateralis
O. universa

(b)

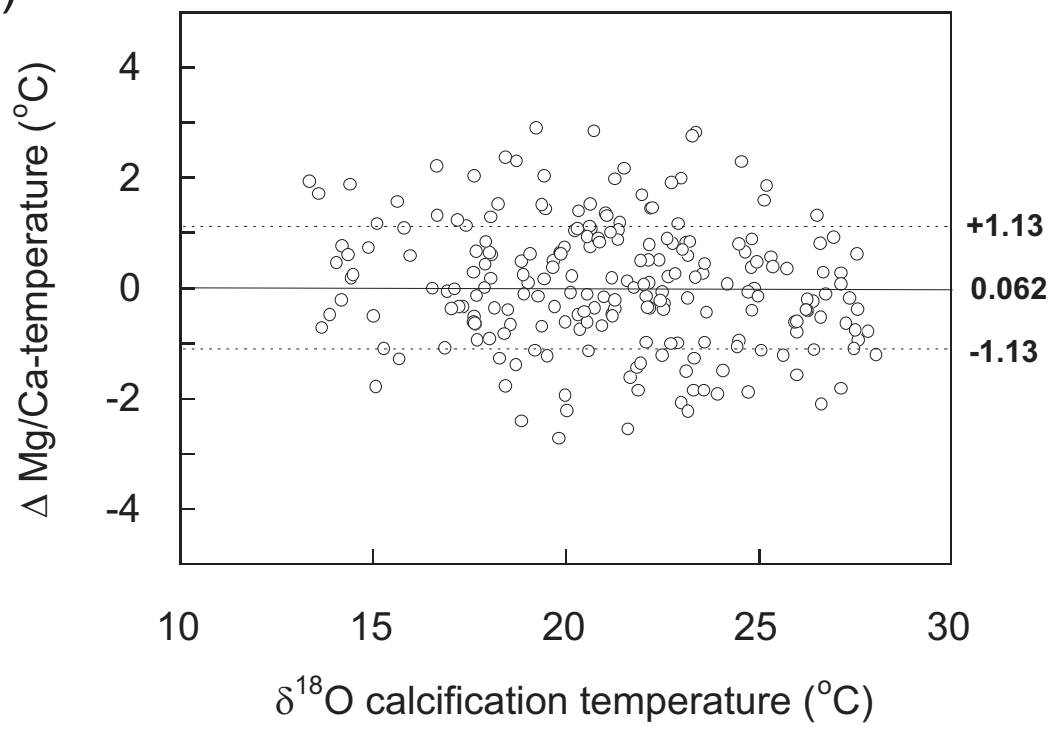
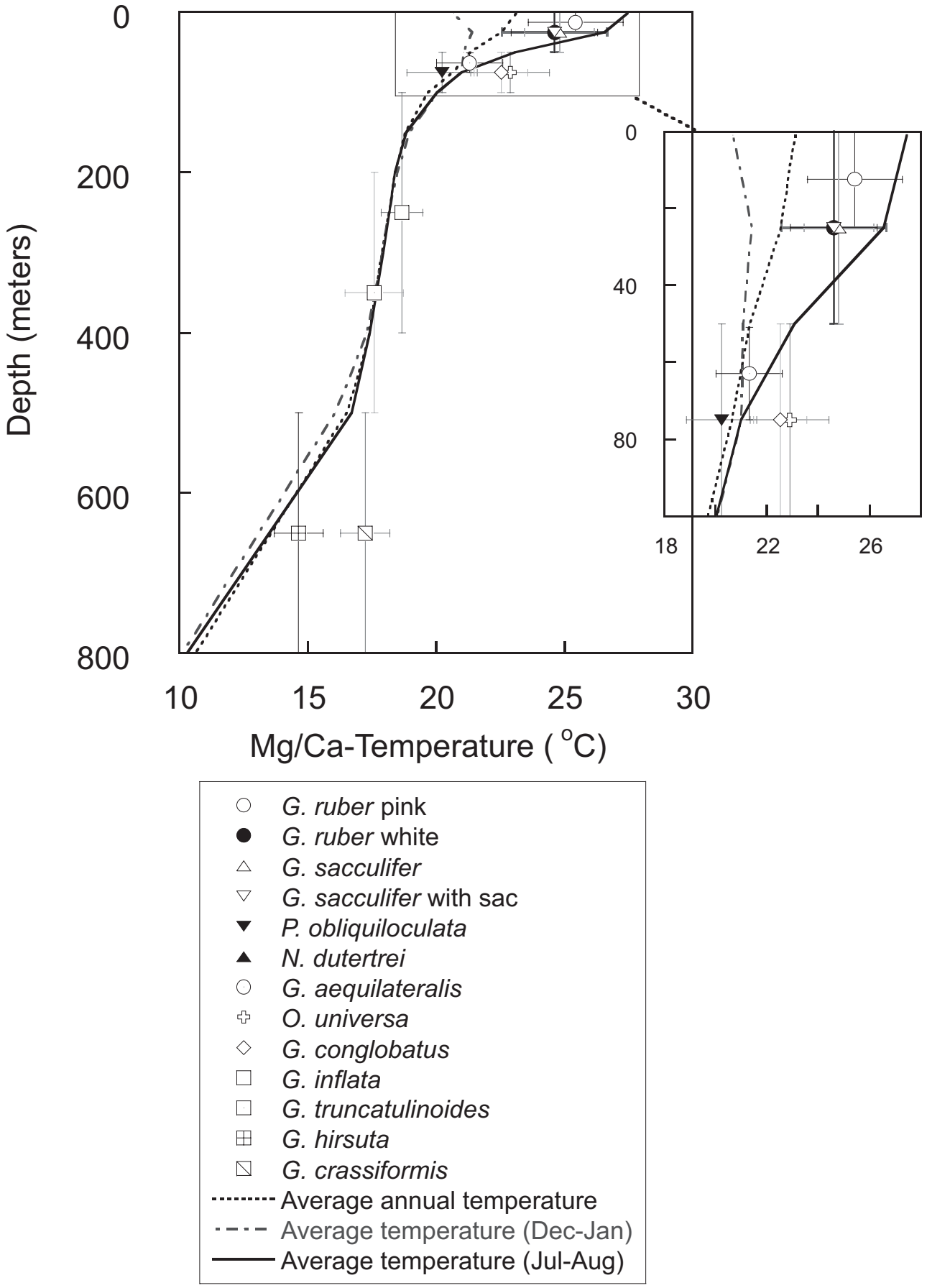

4
2
0
-2
-4
Δ Mg/Ca-temperature (°C)
+1.13
0.062
-1.13
10
15
20
25
30
δ18O calcification temperature (°C)

Figure 11


0
200
400
600
800
Depth (meters)
10
15
20
25
30
Mg/Ca-Temperature ( °C)
0
40
80
18
22
26
G. ruber pink
G. ruber white
G. sacculifer
G. sacculifer with sac
P. obliquiloculata
N. dutertrei
G. aequilateralis
O. universa
G. conglobatus
G. inflata
G. truncatulinoides
G. hirsuta
G. crassiformis
Average annual temperature
Average temperature (Dec-Jan)
Average temperature (Jul-Aug)

Figurre 12