



*Supplement of*

## **Seawater pH reconstruction using boron isotopes in multiple planktonic foraminifera species with different depth habitats and their potential to constrain pH and $p\text{CO}_2$ gradients**

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## **Supplemental Figures**

**Figure S1:** An example of the impact of seasonality on results. Based on data from GLODAP used for site FC13-a. Seasonality has less of an impact than a change in the depth habitats.

**Figure S2:** Figure showing the offset  $\Delta^{11}\text{B} = \delta^{11}\text{B}_{\text{carbonate}} - \delta^{11}\text{B}_{\text{borate}}$  versus calcification depth, red symbols are from Arabian Sea, green from Indian Ocean and Blue from the WEP, blue with black line symbols are data from site A14. This figure highlights a decrease of  $\delta^{11}\text{B}_{\text{carbonate}}$  for *T. sacculifer* and *G. ruber* with a deeper depth habitat.

**Figure S3:** Multi-panels figure showing the correlation between B/Ca and boron geochemistry and different variables. A to C show comparison of B/Ca and A)  $[\text{B(OH)}_4^-]/[\text{HCO}_3^-]$ , B)  $\delta^{11}\text{B}_{\text{carbonate}}$  and C) temperature. Panel D) shows the correlation between  $\delta^{11}\text{B}_{\text{carbonate}}$  and temperature. Symbol in brackets is high B/Ca; this point is included in the linear regressions. Linea regression (LR - black line) is when compiling *G. ruber* and *T. sacculifer*, LR of *G. ruber* (dotted line green), *T. sacculifer* (red line – p<0.05), *T. sacculifer* (w/o sacc – red dotted line).

**Figure S4:** Boron geochemistry against water depth. A)  $\delta^{11}\text{B}_{\text{carbonate}}$  versus water depth, B) B/Ca against water depth and C)  $\delta^{11}\text{B}_{\text{carbonate}}$  versus calcification depth and linear regressions for *G. ruber*, *T. sacculifer* (w/o sacc), *T. sacculifer* (sacc) and *O. universa*.

**Figure S5:** Figure evaluating the circularity of our reconstructions. It is showing in the y-axis the difference between reconstruction utilizing calibrations derive from the entire dataset and compare to *in-situ* values and in the x-axis the difference between the reconstruction utilizing the species-specific calibrations derived excluding the site of interest (no circularity) compared to *in-situ* values. Results show that difference is not significant between the two reconstruction methods (e.g. following the 1:1 line), validating the method and the calibrations.

## **Supplemental Tables**

**Table S1:** Elemental ratios of multi-elemental standards utilized in this study.

**Table S2:** Reproducibility of boron isotope standards.

**Table S3:** Reproducibility of elemental ratios for CamWuellestorfi standard.

**Table S4:** Seasonality of foraminifera utilized in this study.

**Table S5:** Mg/Ca-T calibrations used for reconstructions and  $\delta^{18}\text{O}_w$ -T calibrations used for calcification depth reconstructions.

**Table S6:** Calcification depth (CD) calculations from  $\delta^{18}\text{O}$  (CD1), Mg/Ca (CD2) and literature (CD3).

**Table S7:** Pre-industrial in-situ parameters estimated using calcification depths for each species and calculated parameters based on analytical results.

### **Trace element standards**

A series of multi-element standards (Table S1) with fixed Ca concentration and variable B, Mg, Sr, Mn, Ba, Zn, Cd, U, Li, Al and Fe concentrations were prepared for elemental ratios analysis in Brest following the method developed by Yu et al., (2005). Multi-element stock standard mixtures were prepared gravimetrically by spiking a 10,000 ppm Ca standard with appropriate amounts of Li, B, Al, Mn, Zn, Sr, Cd and U mono-elemental 1,000 ppm (SCP Science). They were diluted with OPTIMA grade HNO<sub>3</sub> acid and 18.2 MΩ.cm<sup>-1</sup> water to reach a 0.28M HNO<sub>3</sub> final solution. The stock standards (1500 ppm Ca) were prepared in 500mL cleaned PFA bottles. Working standards were made by diluting the stock solutions to a final concentration of 100 ppm Ca. The multi-element standards were calibrated at the University of Cambridge, elemental ratios are presented in Table S1. An external standard CamWuellestorfi (Misra et al., 2014a) was used in Brest for cross-calibration and reproducibility (Table S3).

### **Potential contaminations**

Possible contamination of samples due to presence of silicate minerals was monitored with the Fe/Mg ratio. Samples with Fe/Mg > 0.1 mol/mol would be rejected due to potential contamination by silicate minerals (Barker et al., 2003). Samples (site E035 excluded) have an average Fe/Mg of 0.03 ± 0.05 mol/mol (2SD, n=42), meaning that silicate minerals have been efficiently removed during our cleaning.

Contribution of Mn-Fe-oxide coatings to Mg/Ca ratio has been calculated to be 0.5 μmol/mol Mg/Ca (change for 5 μmol/mol Mn/Ca ratio Barker et al., 2003). The maximum Mn/Ca ratio in our samples is 89 μmol/mol which can lead to a potential contribution of ~9 μmol/mol Mg/Ca or in other words a decrease of 0.1°C in our reconstructed temperatures. However, the calibration error is much larger and is estimated to be ~1.4°C (Dekens et al., 2002). The range in Mn/Ca values in our samples is 0.021 ± 0.033 mmol/mol (2SD, n=42) which allows us to not be ignore *Mn-Fe-oxide* coating related complications. Additionally, no correlations were found between Mg/Ca and Fe/Ca ( $R^2=0.006$ ) or with Mn/Ca ( $R^2=0.008$ ), and between B/Ca ratio and Mn/Ca ( $R^2=0.003$ ) or Fe/Ca ( $R^2=0.062$ ) ratios.

Contamination by clays was monitored with Ti/Ca calculated from blank corrected intensities. Al/Ca ratios were not reliable as we are using an alumina injector for HF matrix in our lab. A minor correlation was found between Ti/Ca and Mg/Ca ( $R^2=0.1388$ ) but none with B/Ca ( $R^2=0.0887$ ).

### **Calcification depth determination**

The first approach involves comparing measured  $\delta^{18}\text{O}_c$  with theoretical predictions of  $\delta^{18}\text{O}_c$  based on vertical profiles of temperature and the  $\delta^{18}\text{O}$  of seawater ( $\delta^{18}\text{O}_w$ ). We assume  $\delta^{18}\text{O}_c$  is in equilibrium with seawater. First,  $\delta^{18}\text{O}_w$  was calculated using location-specific  $\delta^{18}\text{O}_w$ -salinity relationships and salinity profiles. We used salinity values from the World Ocean Atlas database (Boyer et al., 2013). Oxygen isotopes may be affected by both temperature and salinity. As our sites present different hydrographic settings and freshwater inputs, location-specific  $\delta^{18}\text{O}_w$ -salinity relationship relationships are utilized for accurate  $\delta^{18}\text{O}_w$  reconstructions. For Site CD107-a, we used a  $\delta^{18}\text{O}_w$ -salinity relationship of 0.56\*S-19.3 (Duplessy et al., 1991). For FC01-a and FC02-a, we used a  $\delta^{18}\text{O}_w$ -salinity relationship of 0.24\*S-7.8 (Sime et al., 2005), and for FC13-a and FC12-b, we used a  $\delta^{18}\text{O}_w$ -salinity relationship of 0.28\*S-9.24-0.27 (Rosteket al., 1993). Then, we used the calculated ambient  $\delta^{18}\text{O}_w$  in concert with: (1) temperature profiles from the World Ocean Atlas database (Boyer et al., 2013), and (2) published calcite-water oxygen isotope fractionation factors, to calculate theoretical values for  $\delta^{18}\text{O}_c$ . Species-specific

relationships were used when available, including for *T. sacculifer* (Mulitza et al., 2003), *G. ruber* (Mulitza et al., 2003), and *O. universa* (Bemis et al., 2002, medium light). For all other species we used the calcite equation from Kim and O’Niel (1997), adapted to a quadratic form by Bemis et al., (1998) following the approach of Sime et al., (2005). To take into account the ecology of each species, theoretical  $\delta^{18}\text{O}_c$  profiles were made for the season of maximum abundance (Table S4). Therefore spring and summer profiles were used for *T. sacculifer*, summer profiles used for *G. ruber*, and winter and annual average profiles was used for *N. dutertrei*. Annual average profiles were used for the other species.

For the two sites WP07-1 and A14, a different approach was necessary because  $\delta^{18}\text{O}_c$  data is sparse. At these sites, and for our other sites, we utilized Mg/Ca-derived temperatures to estimate calcification depths (Table S6).  $T_{\text{Mg/Ca}}$  was derived using species-specific Mg/Ca-temperature calibrations (Table S6) along with the Mg/Ca ratios determined in this study. Calcification depth was estimated by comparing  $T_{\text{Mg/Ca}}$  to modern temperature profiles from the World Ocean atlas database 2013 (Boyer et al., 2013) in light of the ecology (seasonality of growth) of the species of interest. A caveat is that in certain cases  $T_{\text{Mg/Ca}}$  may be partially biased by a carbonate ion effect or salinity effect (Russell et al., 2004; Elderfield et al., 2006; Ferguson et al., 2008; Arbuszewski et al., 2010; Martinez-Botí et al., 2011). These artifacts on  $T_{\text{Mg/Ca}}$  may be significant at high-latitude sites such as CD107-a which is located in the North Atlantic Ocean.

### Depth habitat

Planktonic foraminifera live in the upper 500 m of the water column. Their preferred depth habitat depends on their ecology, which in turn relies on the hydrographic conditions. For example, *G. ruber* is commonly found in the mixed layer (Fairbanks and Wiebe, 1980; Dekens et al., 2002; Farmer et al., 2007) during summer (Deuser et al., 1981) whereas *T. sacculifer* (n or ns) is present in the mixed layer until the mid-thermocline depth (Farmer et al., 2007) during spring and summer (Deuser et al., 1981, 1989). Specimens of *P. obliquiloculata* and *N. dutertrei* are found during winter (Deuser et al., 1989), in the mixed layer (~60m) for *P. obliquiloculata*, and at mid-thermocline depth for *N. dutertrei* (Farmer et al., 2007). Whereas, *O. universa* tends to record annual average conditions and is living within the mixed layer. Specimens of *G. menardii* calcify within the seasonal thermocline (Fairbanks et al., 1982, Farmer et al., 2007, Regenberg et al., 2009) even upper thermocline (Farmer et al., 2007) and records annual temperatures. And specimens of *G. tumida* are found at the lower thermocline or below the thermocline and record annual average conditions (Fairbanks and Wiebe, 1980; Farmer et al., 2007, Birch et al., 2013). Our calcification depth reconstructions are summarized in Table 3, also see Table S6 for comparison.

### Atlantic Ocean

Farmer et al., (2007) determined the depth habitat for *O. universa* to be ranging from 0 to 60m (LL, Bemis et al., 1998). Our calculation, through  $\delta^{18}\text{O}$  measurement, suggests a deeper habitat of around 70m (LL, Bemis et al., 1998), 80m (ML, Bemis et al., 2002). Whereas, the Mg/Ca method derived depth habitat calculation yields a depth habitat of 50 m. The lower habitat depth can also come from the different size fractions, as our size fraction is lower than Farmer’s. *O.universa* is thought to migrate to shallower depth along its ontogeny (Emiliani et al., 1954) younger individuals are thus living deeper but smaller individuals might also have a deeper habitat as already suggested by Hönisch and Heming, (2004). Since most of the published studies have used the  $\delta^{18}\text{O}$ -based depth calcification, we will preferentially adopt this method.

### **Indian Ocean**

Calcification depths for the Indian Ocean cores have already been determined for majority of the species by Sime et al., (2005). Additionally, Birch et al., (2013) have reconstructed the depth habitat of multiple species from a core collected in the offshore region of Tanzania (Glow 3). In Indian Ocean specimens of *G. ruber* is found in the top 50m (Birch et al., 2013) and until 60 m (Sime et al., 2005), *T. sacculifer* is found in the surface mixed layer (SML) but also in the upper thermocline between 50-70 m for Birch et al., (2013) and between 60 to 80 m for Sime et al., (2005). Our results are consistent with these reported depth habitats. We calculate that specimens of *G. ruber*, *T. sacculifer* with and without sac are living in the top 80m; *O. universa* lives between 50 to 90 m (Sime et al., 2005, Birch et al., 2013). For *N. dutertrei* we calculate a depth habitat of 90m at site FC01a, calcification depths derived from both  $\delta^{18}\text{O}$  and Mg/Ca methods agree with the 93 m estimate by Sime et al., (2005). At site FC02a the calculated calcification depth based on  $\delta^{18}\text{O}$  method is 65 m, and, the Mg/Ca derived depth is 100m; however, Sime et al., (2005) proposed a calcification depth of 146 m. A deeper depth habitat than site FC01a seems to be in line with the weaker stratification of the water column at site FCO2a. The depth habitat for *P. obliquiloculata*'s was determined to be 106–120m by Sime et al., (2005); however, our calculations predict a lower and narrower depth habitat of 60 – 70m. Calcification depth for *G.menardii* has been calculated to be 60 – 70m, which is consistent with an upper thermocline depth habitat. Specimens of *G.tumida* is commonly found at the bottom of the thermocline which is around 200-250m at our Indian Ocean sites, Birch et al., (2013) found this species ranging from 100 to 200 m but our  $\delta^{18}\text{O}$  based habitat reconstruction suggests a shallower depth of 70m at both sites. It seems that the calcification derived Mg/Ca for *G. tumida* is more realistic than with our  $\delta^{18}\text{O}_\text{c}$  reconstructions, the Mg/Ca based calculation predicts a depth habitat of 100 – 130 m.

### **Arabian Sea**

In the Arabian Sea foraminifera are affected by changes in local hydrology caused by the Indian summer and winter monsoons. The specimens of different species collectively record a shallower habitat during SW monsoon (e.g., upwelling) and a deeper habitat during NE monsoon (Peeters and Brummer, 2002). Except for *N. dutertrei*, our two methods of calcification depth reconstruction closely agree with each other within their respective uncertainties. The depth habitat reconstructions for *G. ruber* and for *T. sacculifer* are consistent with species living in the shallow mixed layer (SML) at a depth of 30m for *G. ruber* and 40 m for *T. sacculifer*. Specimens of *O. universa* are calculated to live at 30m depth; *N. dutertrei* at site FC12-b (water depth 151m) is living around 40m and at 150m at site FC13-b (water depth 3200m), which is consistent with the hydrography at this site (Fig. 4). The depth habitat of *P. obliquiloculata* is calculated to be 50m at both sites. Specimens of *G. menardii* is found at depths of 60m, consistent with Peeters and Brummer, (2002) estimate of 50 – 130m.

### **Pacific Ocean**

For Pacific Ocean samples the Mg/Ca derived calcification depths were used in absence of  $\delta^{18}\text{O}_\text{c}$  values. The Sites WP07-01 and A14 are located in the Western Equatorial Pacific with Site WP07-01 characterized by a deep thermocline. At these sites *G. ruber* and *T. sacculifer* have deep depth habitat of around 100m for *G. ruber* (Elderfield and Ganssen, 2000) and around 125m for *T. sacculifer* (Rickaby et al., 2005). The depth habitat for specimens of *O. universa* was determined to be 75m depth at site WP07-01 and at 55m depth at site A14. We

calculate that *P. obliquiloculata* is living at 125m deep. Rickaby et al., (2005) estimated the living depth of *N. dutertrei* at 165m in agreement with our calculated depths (~125m). Specimens of *G. menardii* were determined to live at 180m like *G. tumida* (Rickaby et al., 2005).

### The low $\delta^{11}\text{B}$ *T. sacculifer* in the WEP, microenvironment and partial dissolution

Hönisch and Hemming, (2004) and Ni et al. (2007) observed a positive trend based on the  $\delta^{11}\text{B}_{\text{carbonate}}$  and size fraction for *T. sacculifer* (sacc) in the Pacific and Indian Oceans. This trend has been attributed to the microenvironment pH (Hönisch and Hemming, 2004) and/or the preferential dissolution of ontogenetic calcite relative to the light  $\delta^{11}\text{B}$  of gametogenic calcite (Ni et al., 2007; Seki et al., 2010; Henehan et al., 2016).

Bé et al. (1980) observed that “Gametogenesis is signaled by the formation of a sacc-like chamber [...] about 24-48h gamete releases” and that “individual without sacc-like can undergo gametogenesis” too. Even though, the final-sacc chamber is an indication that the species likely underwent gametogenesis, individual w/o sacc can also form gametogenic calcite. The relative proportion of gametogenic versus ontogenetic calcite has been reported to be around ~30% in *T. sacculifer* (sacc).

When comparing for the same size fraction of site WP07-a (Pacific) our  $\delta^{11}\text{B}_{\text{carbonate}}$  for *T. sacculifer* (w/o sacc) with  $\delta^{11}\text{B}_{\text{carbonate}}$  of *T. sacculifer* (sacc), the  $\delta^{11}\text{B}_{\text{carbonate}}$  for *T. sacculifer* (w/o sacc) is lower than *T. sacculifer* (sacc) of  $2.0 \pm 0.3\text{‰}$ .

If the preferential dissolution is the 1<sup>st</sup> order to explain the  $\delta^{11}\text{B}$  then the proportion of gametogenic calcite relative to ontogenetic calcite should be higher in *T. sacculifer* (w/o sacc) than *T. sacculifer* (sacc). However, to our knowledge, the proportion of gametogenic calcite relative to ontogenetic calcite is not yet reported for *T. sacculifer* (w/o sacc), this explanation can't be excluded.

The  $\delta^{11}\text{B}_{\text{borate}}$  difference induced by the different depth habitats of *T. sacculifer* (sacc) (e.g. 80m) and *T. sacculifer* (w/o sacc) (e.g. 125 m) used in this study is  $0.9 \pm 0.7\text{‰}$  translated to a difference in of  $\delta^{11}\text{B}_{\text{carbonate}}$  of  $0.7\text{‰}$ , not enough to explain the  $2\text{‰}$  difference. However, the vital effect due to microenvironment pH can explain this offset.  $\delta^{11}\text{B}_{\text{carbonate}} - \delta^{11}\text{B}_{\text{borate}}$  ( $\Delta^{11}\text{B}$ ) for *T. sacculifer* (sacc) is equal to  $+1.5\text{‰}$  when  $\Delta^{11}\text{B}$  for *T. sacculifer* (w/o sacc) is equal to  $-0.3\text{‰}$  thus microenvironment pH effect accounting for  $1.7 \pm 0.8\text{‰}$  of the difference and can explain the  $2.0 \pm 0.3\text{‰}$  offset. The lethal temperature for *T. sacculifer* is  $14^\circ\text{C}$ , which at site WP07-01 corresponds to a  $\delta^{11}\text{B}_{\text{borate}}$  of  $17.5\text{‰}$  makes our low  $\delta^{11}\text{B}_{\text{carbonate}}$  realistic when the microenvironment pH reduction is taking into account. A difference in depth habitats and related microenvironment pH might explain the low  $\delta^{11}\text{B}_{\text{carbonate}}$  for *T. sacculifer* (w/o sacc).

The 1<sup>st</sup> order control of the  $\delta^{11}\text{B}_{\text{carbonate}}$  between the microenvironment pH and preferential dissolution remains unclear and further studies are still needed. However, our data are consistent with a principal influence by the microenvironment pH.

### Microenvironment calculations

We observe a trend between  $\Delta^{11}\text{B}$  (eg.  $\Delta^{11}\text{B} = \delta^{11}\text{B}_{\text{carbonate}} - \delta^{11}\text{B}_{\text{borate}}$ ) with derived calcification depth (Fig. S2). In order to verify why the WEP  $\delta^{11}\text{B}_{\text{carbonate}}$  of *T. sacculifer* (w/o sacc) is low and to test the hypothesis of the depth habitat we try to recalculate independently the theoretical water depth habitat based on culture results from Jorgensen et al., (1985) and our microenvironment pH results. A change of microenvironment pH for *T. sacculifer* will change the theoretical light intensity needed to reach this microenvironment pH. The compensation light

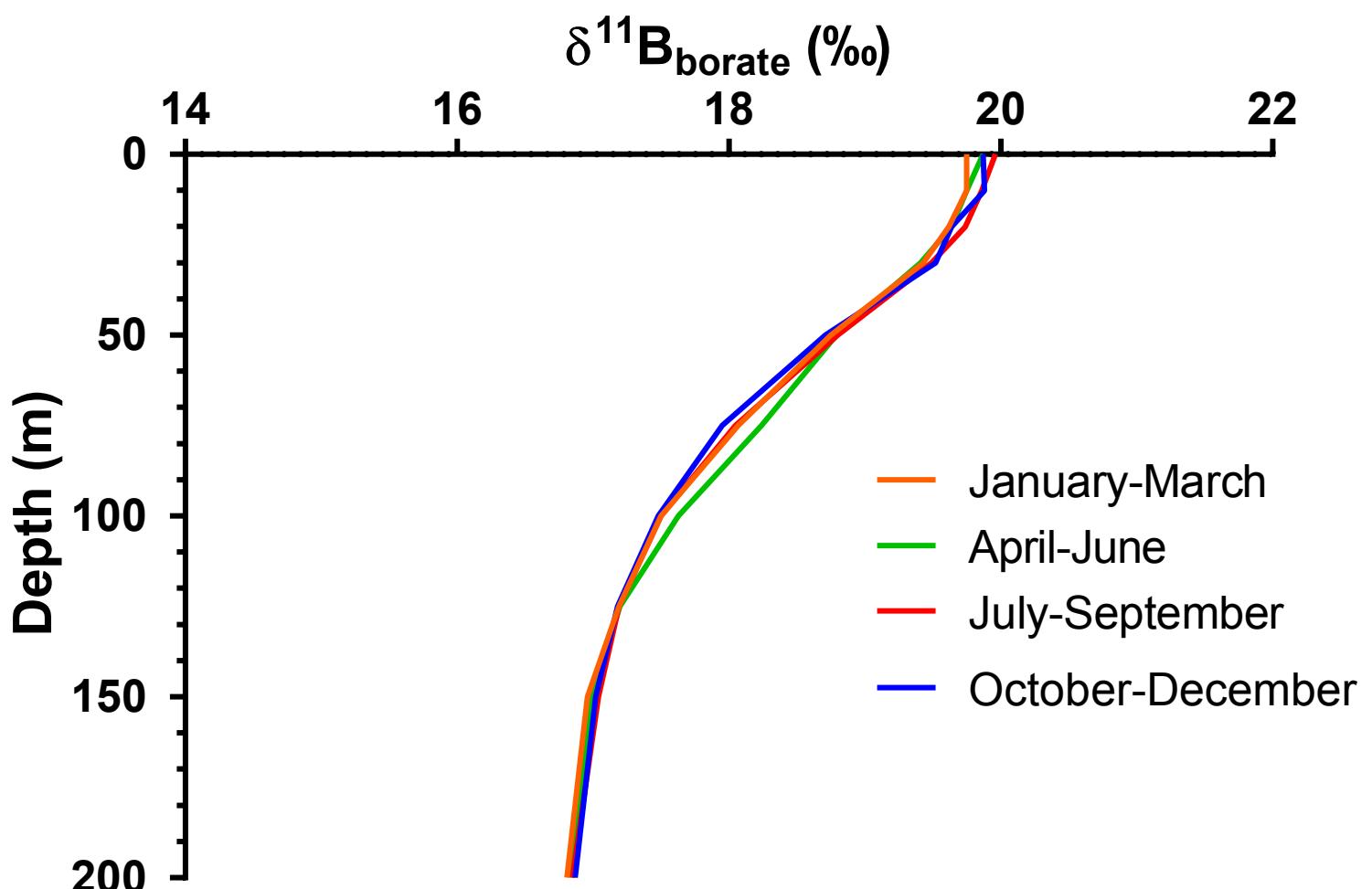
intensity ( $E_c$ ) for *T. sacculifer* has been calculated by Jorgensen et al., (1985) to be  $\sim 30 \mu\text{Eistn.m}^{-2}\text{s}^{-1}$ ,  $E_c$  corresponds to the energy where photosynthesis compensates respiration or where  $\delta^{11}\text{B}_{\text{carbonate}}$  reaches the 1:1 theoretical line. We tested two microenvironment pH,  $\Delta\text{pH}_1 = -0.04$  and  $\Delta\text{pH}_2 = -0.06$  (Fig S3). We've recalculated the light energy needed to decrease the pH of  $\Delta\text{pH}_1$  and  $\Delta\text{pH}_2$  and apply these changes to the light penetration profile determined with an insolation  $E_0$  in the WEP of  $220 \text{ J.s}^{-1}\text{m}^{-2}$  (Weare et al., 1981) and a light attenuation coefficient of 0.028 (Wang et al., 2008). A decrease of  $\Delta\text{pH}_1$  would lead to a decrease of  $15 \mu\text{Eistn.m}^{-2}\text{s}^{-1}$  and a decrease of  $\Delta\text{pH}_2$  would lead to a decrease of  $24 \mu\text{Eistn.m}^{-2}\text{s}^{-1}$  (Jorgensen et al., 1985). These results correspond in our case of a light penetration of 12% to reach  $E_c$ , 5% for a decrease of  $\Delta\text{pH}_1$  and 1% for a decrease of  $\Delta\text{pH}_2$ . This means that in the WEP if *T. sacculifer* calcifies below 75m where  $E_c$  is reached the  $\delta^{11}\text{B}_{\text{carbonate}}$  is below the theoretical 1:1 line. *T. sacculifer* (w/o sacc) in the WEP is decreasing its pH of  $\sim\Delta\text{pH}_1$  which would imply a calcification depth of 110m consistent with the reconstruction of Rickaby et al., (2005).

$$\Delta\text{microenvironment pH} = -\log\left(\frac{(\delta^{11}\text{B}_{\text{seawater}} - \delta^{11}\text{B}_{\text{carbonate}}) \times K_b^*}{\varepsilon - \delta^{11}\text{B}_{\text{seawater}} + \delta^{11}\text{B}_{\text{carbonate}}}\right) - \text{pH}_{\text{seawater}}$$

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**Figure S1**

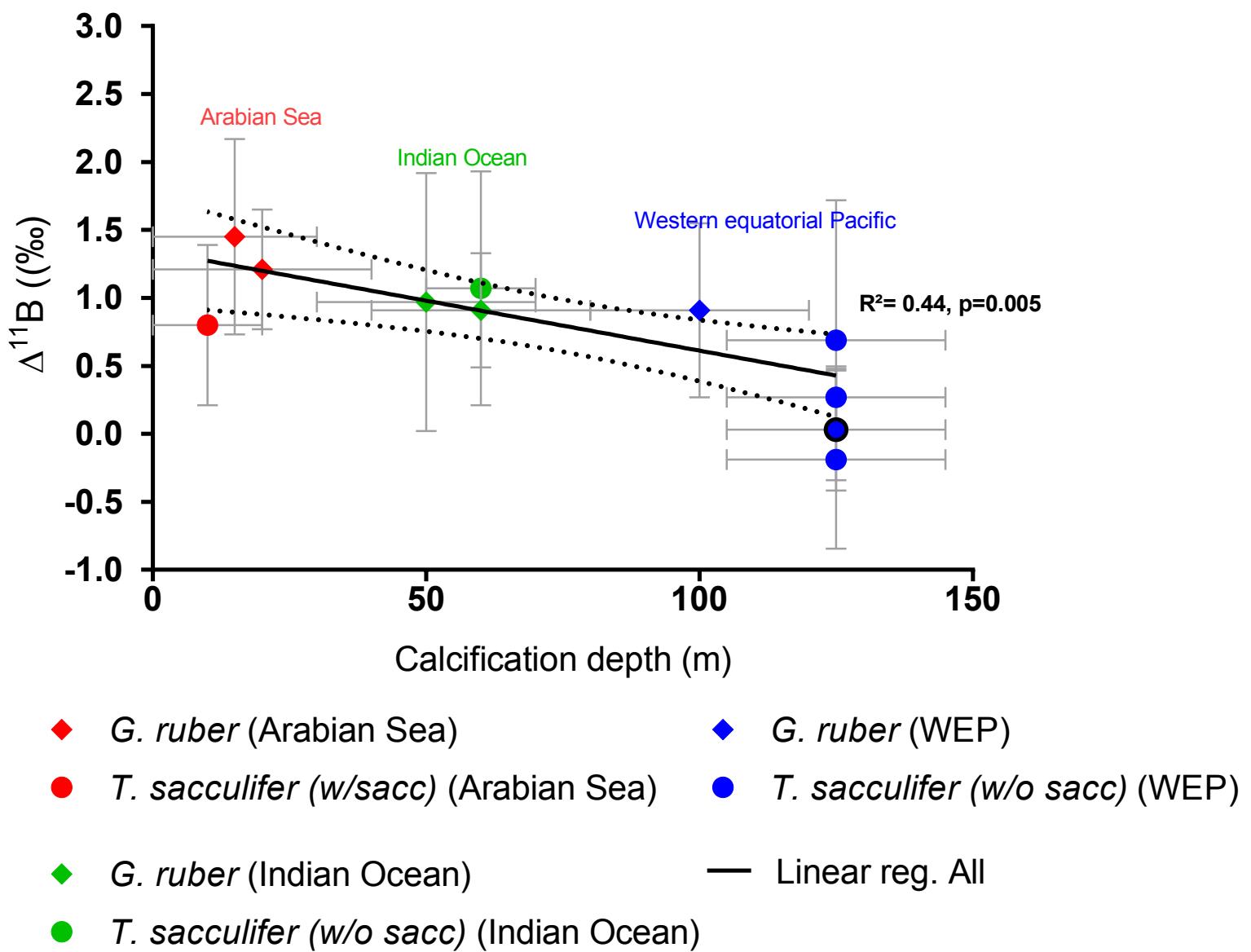
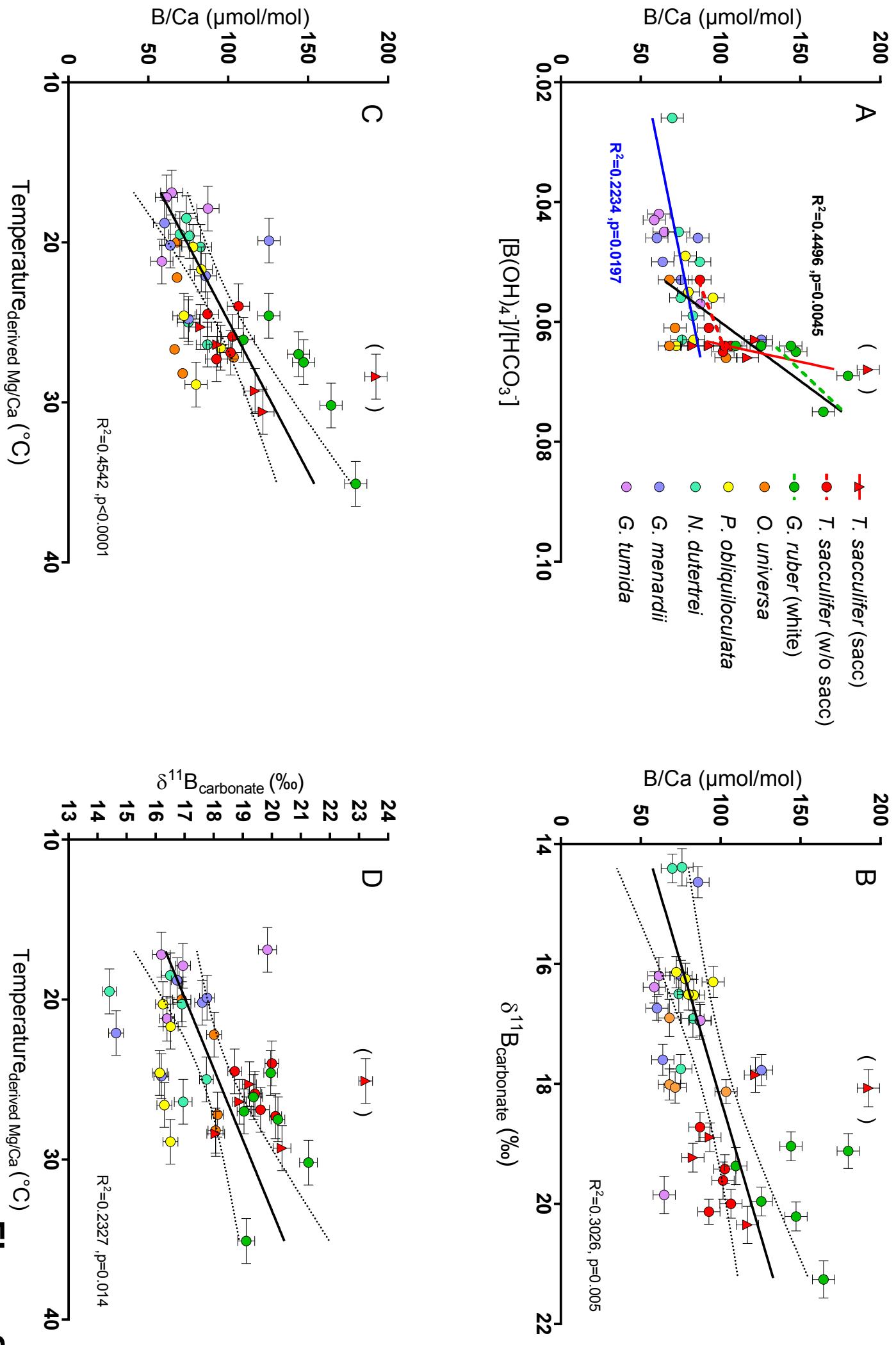
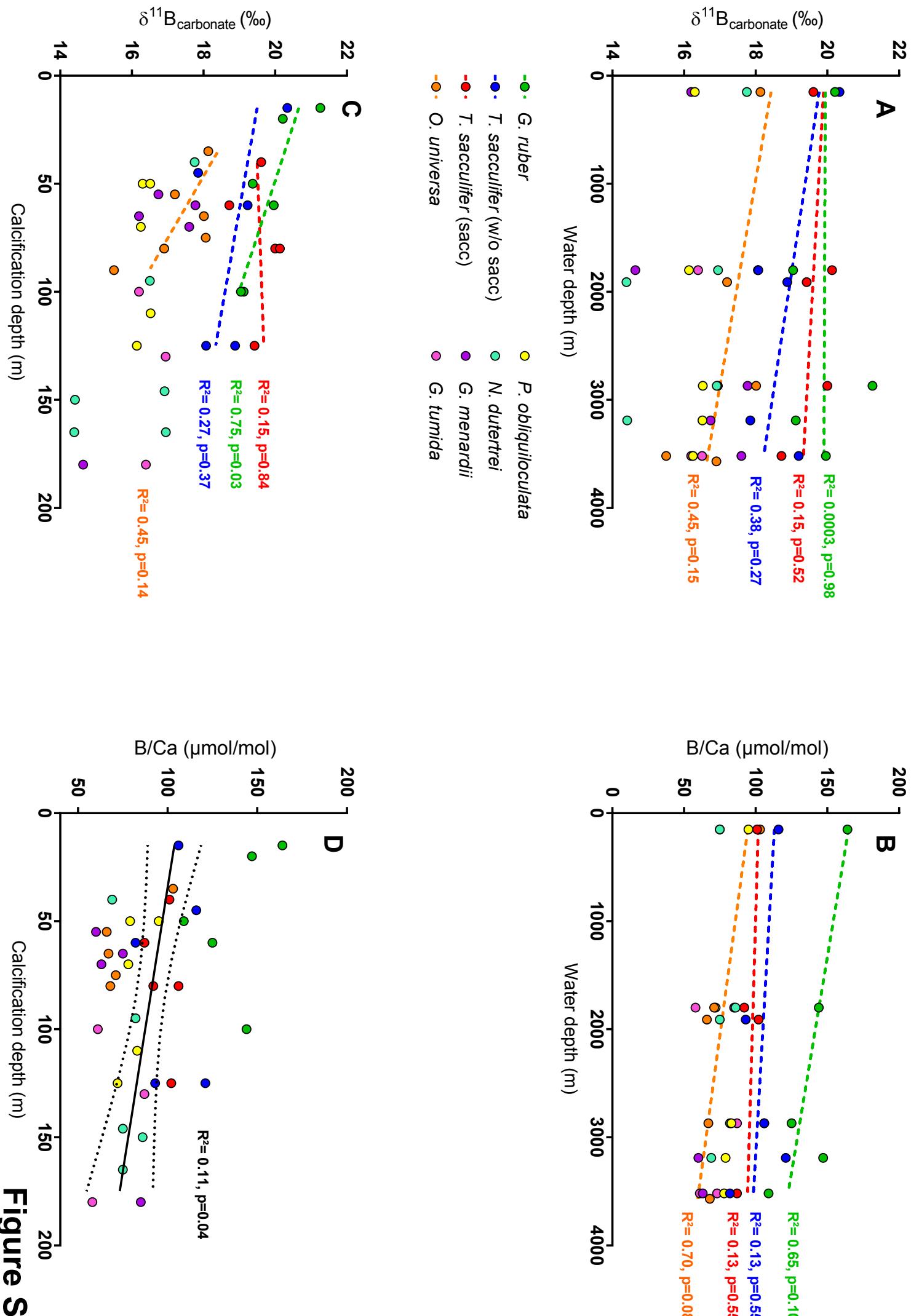


Figure S2



**Figure S3**



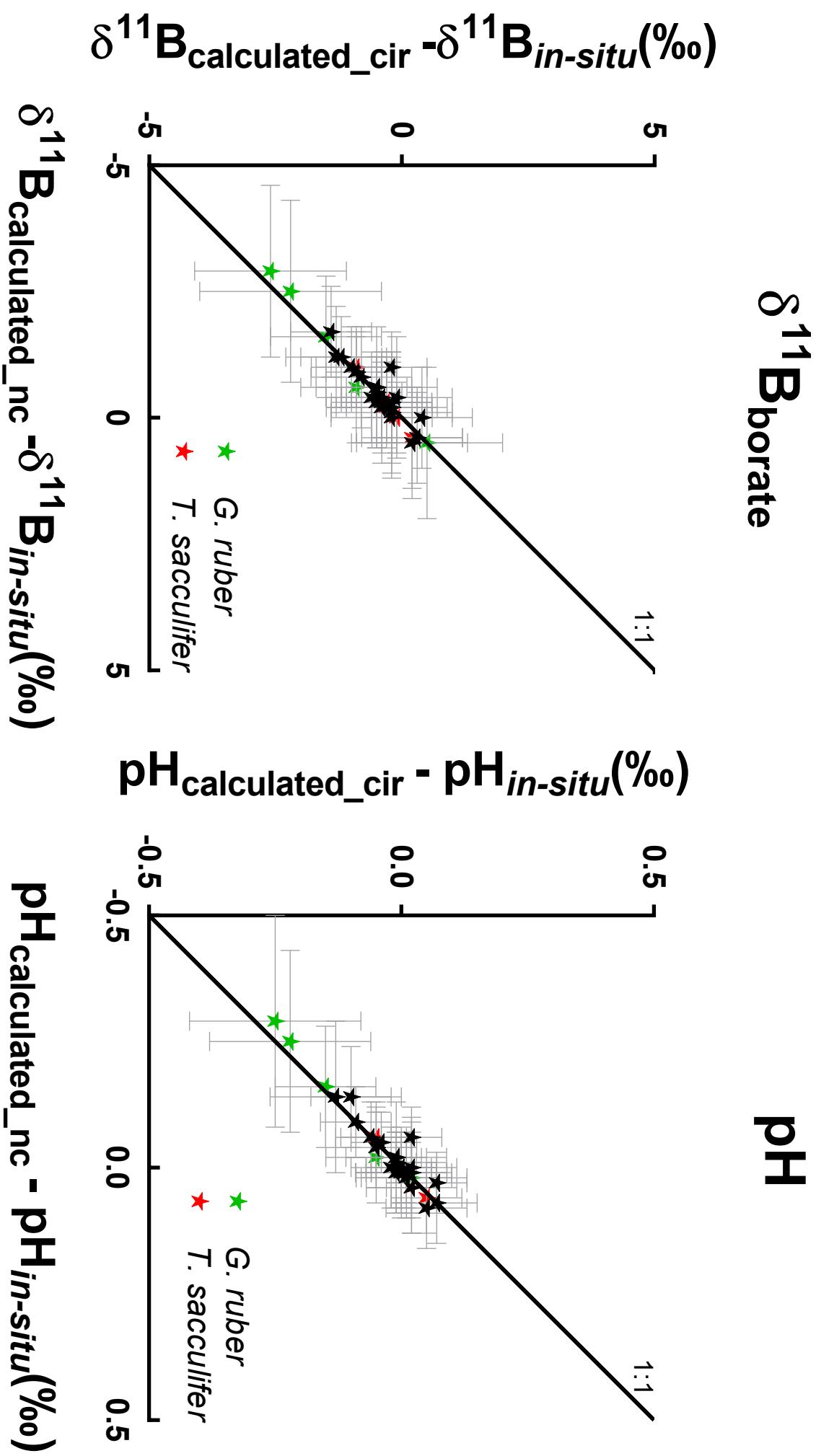


Figure S5

Table S1

Elemental ratios	Li/Ca	B/Ca	Mg/Ca	Al/Ca	Sr/Ca	Cd/Ca	Ba/Ca	U/Ca	Mn/Ca	Fe/Ca
	μmol/mol	μmol/mol	mmol/mol	mmol/mol	mmol/mol	μmol/mol	nmol/mol	μmol/mol	μmol/mol	mmol/mol
Standard solution 0	0.8	9	0.10	0.131	0.00	0.03	0.6	31	1	0.01
Standard solution 1	2.3	38	0.31	0.112	0.49	0.05	1.9	38	12	0.02
Standard solution 3	6.8	108	1.31	0.177	1.06	0.13	3.0	53	39	0.04
Standard solution 5	14.6	216	3.17	0.223	1.57	0.23	5.1	62	129	0.08
Standard solution 6	19.0	278	5.23	0.352	1.97	0.28	5.5	74	196	0.11
Standard solution 8	25.0	281	6.07	0.602	2.99	0.50	20.1	390	501	0.50
Standard solution 9		408			4.89					
Standard solution 10		519			8.01					
Standard solution 11		607			9.93					

Table S2

<b>Standard</b>	<b><math>\delta^{11}\text{B}_1</math> (%)</b>	<b>2SD<sub>AEl21</sub></b>	<b>n<sub>AEl21</sub></b>	<b><math>\delta^{11}\text{B}_2</math> (%)</b>	<b>2SD<sub>AEl21</sub></b>	<b>n<sub>AEl21</sub></b>	<b>Reference</b>
NEPI	25.21	0.25	11	25.22	0.25	11	This study
NEP2	25.00	0.30	12				This study
NEP3	24.70	0.30	12				This study
NEP4	25.40	0.21	11				This study
NEP5	25.32	0.21	11	25.33	0.21	11	This study
NEP6	25.22	0.21	11				This study
NEP7	25.26	0.26	15				This study
NEP8	25.39	0.26	15				This study
NEP9	26.15	0.26	15				This study
NEP10	25.97	0.26	15				This study
NEP11	26.09	0.26	15	26.09	0.26	15	This study
NEP12	26.22	0.26	15	26.29	0.26	15	This study
NEP13	26.19	0.26	15	26.21	0.26	15	This study
NEP14	26.12	0.26	15	26.13	0.26	15	This study
NEP15	26.00	0.26	15				This study
NEP16	26.04	0.26	15				This study
NEP17	26.02	0.29	12				This study
NEP18	25.86	0.29	12	25.86	0.26	14	This study
NEP19	25.78	0.26	14				This study
NEP20	25.42	0.15	3	25.32	0.15	3	This study
NEP21	25.54	0.22	6	26.16	0.22	6	This study
NEP22	26.42	0.22	6				This study
JCP-1-1	24.07	0.10					This study
JCP-1-2	24.17	0.11		24.17	0.10		This study
JCP-1-3	24.01	0.11					This study
JCP-1-4	23.92	0.26					This study
JCP-1-5	24.03	0.26		24.05	0.39		This study
JCP-1-6	24.18	0.36		24.16	0.36		This study

<b>Standard</b>	<b>Average <math>\delta^{11}\text{B}</math></b>	<b>2SD</b>	<b>n</b>	<b>Reference</b>
NEP	25.70	0.93	22	This study
NEP	26.20	0.88	27	Holcomb et al., 2015
NEP	25.80	0.89	6	Sutton et al., 2018
JCP-1	24.06	0.20	6	This study
JCP-1	24.37	0.32	57	Holcomb et al., 2015
JCP-1	24.42	0.28	7	Sutton et al., 2018

Table S3

Date of analysis	Standard		Li/Ca μmol/mol	B/Ca μmol/mol	Mg/Ca mmol/mol	Sr/Ca mmol/mol	Cd/Ca μmol/mol	Ba/Ca μmol/mol	U/Ca nmol/mol	Mn/Ca μmol/mol	Fe/Ca mmol/mol	Reference
10/7/17	CamWuel 1		16.0	204	1.22	1.31	0.26	4.6	43	67	0.04	This study
10/7/17	CamWuel 2		16.3	209	1.24	1.32	0.28	4.6	45	69	0.04	This study
10/7/17	CamWuel 3		16.3	209	1.23	1.31	0.26	4.6	44	77	0.04	This study
10/7/17	CamWuel 4		16.0	207	1.23	1.32	0.28	4.6	44	74	0.04	This study
10/7/17	CamWuel 5		16.4	210	1.23	1.32	0.27	4.6	42	74	0.04	This study
10/7/17	CamWuel 6		16.0	208	1.24	1.31	0.26	4.6	42	74	0.04	This study
10/7/17	CamWuel 7		16.6	213	1.23	1.32	0.28	4.6	44	74	0.04	This study
11/7/17	CamWuel 1		16.0	203	1.22	1.32	0.26	4.6	41	72	0.04	This study
11/7/17	CamWuel 2		16.1	205	1.22	1.32	0.27	4.6	42	76	0.04	This study
11/7/17	CamWuel 3		16.2	204	1.22	1.32	0.27	4.6	41	72	0.04	This study
11/7/17	CamWuel 4		16.1	205	1.22	1.32	0.27	4.5	41	71	0.04	This study
11/7/17	CamWuel 5		15.8	204	1.21	1.32	0.27	4.6	42	73	0.04	This study
11/7/17	CamWuel 6		16.1	206	1.22	1.32	0.27	4.6	42	68	0.04	This study
11/7/17	CamWuel 7		16.0	207	1.22	1.32	0.26	4.6	43	66	0.04	This study
11/7/17	CamWuel 8		15.9	203	1.21	1.32	0.27	4.6	42	68	0.04	This study
12/7/17	CamWuel 1		16.3	201	1.22	1.31	0.22	4.6	41	66	0.03	This study
12/7/17	CamWuel 2		16.1	203	1.22	1.32	0.23	4.6	42	67	0.03	This study
12/7/17	CamWuel 3		16.4	202	1.22	1.32	0.23	4.6	42	69	0.04	This study
12/7/17	CamWuel 4		16.3	202	1.22	1.31	0.22	4.6	41	68	0.04	This study
12/7/17	CamWuel 5		16.6	202	1.22	1.31	0.23	4.6	44	67	0.03	This study
12/7/17	CamWuel 6		16.6	205	1.22	1.31	0.24	4.5	42	66	0.03	This study
12/7/17	CamWuel 7		16.1	204	1.22	1.31	0.22	4.6	42	67	0.03	This study
12/7/17	CamWuel 8		16.4	204	1.22	1.31	0.23	4.6	41	68	0.04	This study
12/7/17	CamWuel 9		16.4	202	1.22	1.32	0.23	4.6	43	64	0.03	This study
13/7/2017	CamWuel 1		16.2	198	1.22	1.31	0.31	4.6	42	74	0.04	This study
13/7/2017	CamWuel 2		16.4	200	1.22	1.30	0.30	4.6	43	73	0.04	This study
13/7/2017	CamWuel 3		16.2	201	1.23	1.31	0.31	4.7	43	74	0.04	This study
13/7/2017	CamWuel 4		16.3	198	1.22	1.31	0.30	4.6	42	73	0.04	This study
13/7/2017	CamWuel 5		16.6	200	1.23	1.30	0.30	4.6	42	73	0.04	This study
13/7/2017	CamWuel 6		16.5	198	1.22	1.31	0.31	4.6	44	74	0.04	This study
13/7/2017	CamWuel 7		16.1	201	1.22	1.30	0.32	4.7	43	74	0.04	This study
<b>Average CamWuel</b>		<b>16.2</b>	<b>204</b>	<b>1.22</b>	<b>1.31</b>	<b>0.27</b>	<b>4.6</b>	<b>42</b>	<b>71</b>	<b>0.04</b>	<b>This study</b>	
2SD		0.4	7	0.01	0.01	0.06	0.1	2	7	0.01		
n		31	31	31	31	31	31	31	31	31	31	
<b>Published CamWuel</b>	<b>16.4</b>	<b>202</b>	<b>1.23</b>	<b>0.29</b>	<b>4.8</b>	<b>44</b>	<b>71</b>					<b>Misra et al., 2014</b>
2SD	0.8	7	0.06	0.02	0.2	2						
n	180	180	180	180	180	180						

**Table S4**

Species	Seasonality
<i>T. sacculifer</i> (sacc)	Spring
<i>T. sacculifer</i> (w/o sacc)	Spring
<i>G. ruber</i> (white)	Summer
<i>N. dutertrei</i>	Winter
<i>G. tumida</i>	Annual average
<i>G. menardii</i>	Annual average
<i>O. universa</i>	Annual average
<i>P. obliquiloculata</i>	Winter

Table S5

Species	B	A	Reference
<i>T. sacculifer</i> (sacc)	0.377	0.090	Anand et al., 2003
<i>T. sacculifer</i> (w/o sacc)	0.347	0.090	Anand et al., 2003
<i>G. ruber</i> (white)	0.300	0.089	Dekens et al., 2002
<i>N. duterrei</i>	0.600	0.008	Dekens et al., 2002
<i>G. tumida</i>	0.380	0.090	Anand et al., 2003
<i>G. menardii</i>	0.360	0.091	Regenberg et al., 2009
<i>O. universa</i>	0.595	0.090	Anand et al., 2003
<i>P. obliquoculata</i>	0.328	0.090	Anand et al., 2003
Species	A	B	C
<i>O. universa</i>	16.500	4.800	-0.27
<i>O. universa</i>	15.700	4.460	-0.27
<i>O. universa</i>	14.900	4.800	-0.27
<i>T. sacculifer</i>	14.910	4.350	-0.27
<i>G. ruber</i>	14.200	4.440	-0.27
All	16.900	4.380	-0.2
All	17.000	4.520	-0.22
All	16.100	4.640	-0.27
dw correction	Condition	Reference	Equation
	LL	Bemis et al., 1998	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W})$
	ML	Bemis et al., 2002	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W}) + C^*(\delta^{18}O_{C} - \delta^{18}O_{W})^2$
	HL	Bemis et al., 1998	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W})$
		Mulitza et al., 2003	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W})$
		Mulitza et al., 2003	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W})$
		Shackleton et al., 1974	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W}) + C^*(\delta^{18}O_{C} - \delta^{18}O_{W})^2$
		Erez and Luz, 1983	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W}) + C^*(\delta^{18}O_{C} - \delta^{18}O_{W})^2$
		Kim and O'Neill, 1997	$T = A - B^* (\delta^{18}O_{C} - \delta^{18}O_{W}) + C^*(\delta^{18}O_{C} - \delta^{18}O_{W})^2 + C^*(\delta^{18}O_{C} - \delta^{18}O_{W})^3$

**Table S6**

Core	Species	CD <sub>1</sub>	CD <sub>2</sub>	CD <sub>3</sub>	Reference
FC-01a	<i>G. ruber</i> (white ss)	83 ± 20	30 ± 10	50 ± 20	Sime thesis 2006
FC-02a	<i>G. ruber</i> (white ss)	56 ± 10	15 ± 10	60 ± 20	Sime thesis 2006
FC-12b	<i>G. ruber</i> (white ss)	Surface ± 10	0-30	60 ± 10	Peeters and Brumer, 2012 (non upwelling station Arabian sea)
FC-13a	<i>G. ruber</i> (white ss)	Surface ± 10	20 ± 20	60 ± 10	Peeters and Brumer, 2012 (non upwelling station Arabian sea)
WP7-01	<i>G. ruber</i> (white ss)			100±20	Elderfield and Ganssen, 2000
A14	<i>G. ruber</i> (white ss)		60 ± 10	100±20	Elderfield and Ganssen, 2000
FC-01a	<i>T. sacculifer</i> (sacc)	48 ± 10	50 ± 10	60 ± 10	Sime et al., 2005
FC-02a	<i>T. sacculifer</i> (sacc)	7 ± 10	30 ± 10	80 ± 20	Sime et al., 2006
FC-12b	<i>T. sacculifer</i> (sacc)	15 ± 10	40 ± 10		
WP7-01	<i>T. sacculifer</i> (sacc)		80 ± 20	125 ± 15	Rickaby et al., 2005
A14	<i>T. sacculifer</i> (sacc)		60 ± 10	125 ± 15	Rickaby et al., 2005
FC-01a	<i>T. sacculifer</i> (w/o sacc)	88 ± 20	50 ± 10	60 ± 10	Sime thesis 2006 (Wind22-b)
FC-02a	<i>T. sacculifer</i> (w/o sacc)	32 ± 10	10 ± 10	80 ± 20	Sime thesis 2006
FC-12b	<i>T. sacculifer</i> (w/o sacc)	0-15 ± 10	30 ± 10	45 ± 20	Peeters and Brumer, 2012 (non upwelling station Arabian sea)
WP7-01	<i>T. sacculifer</i> (w/o sacc)		80 ± 20	125 ± 15	Rickaby et al., 2005
A14	<i>T. sacculifer</i> (w/o sacc)		60 ± 10	125 ± 15	Rickaby et al., 2005
CD107a	<i>O. universa</i>	80 ± 20	50 ± 20	0-50	Farmer et al., 2007
FC-01a	<i>O. universa</i>	45 ± 10	60 ± 10	90 ± 20	Sime et al., 2005
FC-02a	<i>O. universa</i>	127 ± 20	45 ± 15	65 ± 10	Birshe et al., 2013
FC-12b	<i>O. universa</i>	35 ± 10	30 ± 20		
WP7-01	<i>O. universa</i>		75 ± 25		
A14	<i>O. universa</i>		55 ± 15		
FC-01a	<i>P. obliquiloculata</i>	70 ± 20	75 ± 15	106 ± 20	Sime et al., 2005
FC-02a	<i>P. obliquiloculata</i>	226 ± 20	60 ± 10		
FC-12b	<i>P. obliquiloculata</i>	40 ± 10	50 ± 10		
FC-13a	<i>P. obliquiloculata</i>	65 ± 10	50 ± 10		
WP7-01	<i>P. obliquiloculata</i>		125 ± 25		
FC-01a	<i>N. dutertrei</i>	95 ± 20	90 ± 20	93 ± 20	Sime et al., 2005
FC-02a	<i>N. dutertrei</i>	65 ± 10	100 ± 20	146 ± 20	Sime et al., 2005
FC-12b	<i>N. dutertrei</i>	40 ± 10	50 ± 10		
FC-13a	<i>N. dutertrei</i>	45 ± 10	150 ± 20		
WP7-01	<i>N. dutertrei</i>		125 ± 25	165	Rickaby et al., 2005
A14	<i>N. dutertrei</i>		110 ± 20	165	Rickaby et al., 2005
FC-01a	<i>G. menardii</i>	135 ± 20	70 ± 20		
FC-02a	<i>G. menardii</i>	60 ± 10	60 ± 10		
FC-12b	<i>G. menardii</i>	65 ± 10	55 ± 15	60 ± 10	Peeters and Brumer, 2012 (non upwelling station Arabian sea)
FC-13a	<i>G. menardii</i>	55 ± 10	70 ± 10	60 ± 10	Peeters and Brumer, 2012 (non upwelling station Arabian sea)
WP7-01	<i>G. menardii</i>		180 ± 20		
FC-01a	<i>G. tumida</i>	70 ± 20	100 ± 10	160 ± 20	Birshe et al., 2013
FC-02a	<i>G. tumida</i>	70 ± 20	130 ± 20	160 ± 20	Birshe et al., 2013
WP7-01	<i>G. tumida</i>		180 ± 20	210 - 240	Rickaby et al., 2005

CD<sub>1</sub>: Depth habitat estimated from  $\delta^{18}\text{O}_\text{c}$ CD<sub>2</sub>: Depth habitat estimated from Mg/Ca derived temperatureCD<sub>3</sub>: Depth habitat from literature

Table S7

\* uncertainties calculated using Henehan's 2016 R code  
 \*\* propagated uncertainty on pH including all temperature

\*\*\* propagated uncertainty on  $\text{pCO}_2$  including dL1B temperature, salinity, Alk, and

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