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Quantifying sea surface temperature ranges of the Arabian Sea for the past 20 000 years

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Abstract

The oxygen isotopic composition of planktonic foraminifera tests is one of the widest used geochemical tools to reconstruct past changes of physical parameters of the upper ocean. It is common practice to analyze multiple individuals from a mono-specific population and assume that the outcome reflects a mean value of the environmental conditions during calcification of the analyzed individuals. Here we present the oxygen isotope composition of individual specimens of the surface dwelling species *Globigerinoides ruber* and *Globigerina bulloides* from sediment cores in the Western Arabian Sea off Somalia inferred as indicators of past seasonal ranges in temperature. Combining the δ^{18}O measurements of individual specimens to obtain temperature ranges with Mg/Ca based mean calcification temperatures allows us to reconstruct temperature extrema. Our results indicate that over the past 20 kyrs the seasonal temperature range has fluctuated from its present value of 16 °C (14 to 30 °C), to 11 °C (15 to 26 °C) during the LGM. The range during the LGM suggests that the maximum temperature was lower, whilst minimum temperature remained approximately constant.

1 Introduction

Since Cesare Emiliani's paper (1955) "Pleistocene Temperatures" indicated that the stable oxygen isotope ratio in the tests of foraminifera could be used to infer the temperature during calcification, the δ^{18}O of planktonic foraminifera is one of the most applied methods for reconstructing past ocean temperature changes. Various geochemical methods upon marine archives have been applied since, including the Mg/Ca ratio of the foraminiferal calcite (e.g. Nürnberg et al., 1996; Elderfield and Ganssen, 2000; Lea et al., 1999), the alkenone-based temperatures (Prahl and Wakeman, 1987) and TEX86 (Schouten et al., 2002) on organic material. To date, the simultaneous use of different proxies, referred to as a multi-proxy approach, is generally accepted to result in the highest possible accuracy and precision to reconstruct past ocean surface-water temperatures. Multi-proxy reconstructions however, require sufficient and well-suited material from an oceanic setting, where the different signal carriers (reflecting the ocean conditions) are indeed produced and transported simultaneously to the sea-floor to form the archive.

The interpretation of the oxygen isotope composition of planktonic foraminifera ($\delta^{18}O_c$) in terms of temperature variation is not straightforward, as the signal is determined by both the sea-water temperature and the oxygen isotope composition of the water ($\delta^{18}O_w$) in which they calcify. Furthermore the shells may secrete their calcite tests at different depths in the water column (Emiliani, 1954) and seasons of the year (Hemleben et al., 1989). Conventional isotope analysis (CIA) is based upon a number of specimens of planktonic foraminifera, typically ten to fifty, to obtain a mean isotope value for the selected population. The resulting value may include specimens having formed their calcite at various depths and seasons; hence, the CIA does not reflect the range of $\delta^{18}O_c$ and hence temperature.

Recent technological improvements in Isotope Ratio Mass Spectrometry (IRMS) allow measurements of small quantities of calcium-carbonate down to ~5 µg including individual specimen analyses (ISA) of planktonic forminifera.

The first application of ISA focused upon the isotopic variability of *Orbulina universa*, *Globigerinoides conglobatus* and *Globorotalia tumida* from the equatorial Pacific. Killingley et al. (1981) interpreted this variation as a result of changes in temperature, salinity, depth habitat and seasonal and inter-annual variations as of metabolic effects. Attempts to determine the influence of size, and therefore growth (Spero and Williams, 1990), upon the oxygen isotopic signal of test calcite ($\delta^{18}O_c$) of *Orbulina universa* from the Orca Basin during the Late Pleistocene revealed no obvious relationship. The variability range from 2.08 to 5.31‰ was explained by temperature and salinity changes of the deglacial meltwater. Oba (1990) interpreted the isotope differences in *Globigerinoides sacculifer* of up to 2.8‰ in sediment trap samples from northwest Pacific Ocean as a reflection of the temperatures of the vertical calcification range for this species (50–200 m). He further assigned the depth habitat of eleven species based on ISA (Oba, 1991). Based on ISA upon *G. sacculifer*, *Globigerinoides ruber*, *Globigerinella aequilateralis*, *Globorotalia inflata*, and *O. universe*, Tang and Stott (1993) reconstructed seasonal and interannual low salinity conditions of the eastern Mediterranean during sapropel S1. Using *G. ruber* and *G. sacculifer* from equatorial Atlantic boxcores (Stott and Tang, 1996), they concluded that the effect of bioturbation upon the Glacial/Holocene δ^{18}O change is relatively minor, when 25 or more individual specimens are combined in a CIA. Reductions of variance of ISA upon *G. ruber* as monthly recorders of ocean surface conditions near Galapagos Islands were interpreted as a drastic attenuation of the ENSO amplitude during the mid-Holocene (Koutavas et al., 2006). The analysis of individual shells of *Neoloboquadrina dutertrei* by Leduc et al. (2009) in the equatorial Pacific reveals the variability of ENSO activities during the past 50 ka. Attempting to unravel seasonality in sea-surface temperatures Wit et al. (2010) used paired single specimen oxygen isotope and Mg/Ca analyses upon *G. ruber* concluding that other parameters than temperature affect these proxies.

In a review paper Waelbroeck et al. (2005) concluded that a quantitative reconstruction of seasonality by means of oxygen isotope values of individual planktonic foraminifera is difficult as all aspects of the environmental sensitivity of species during their life cycle is not fully understood. We here present measurements based upon single shells of surface-dwelling planktonic foraminifera, which allow assessment of $\delta^{18}O_c$ population variability and hence reconstruction of past seasonal SST variability.

2 Approach, material and methods

Highest seasonal temperature change in the tropics are presently found off Somalia: During late winter and spring temperatures higher than 30 °C prevail, yet during the upwelling season sea-surface temperatures may drop down to 16 °C (Swallow and Bruce, 1966). This high seasonal amplitude in surface water temperatures of >14 °C together with only minor variability in salinity (<0.5 PSU) and $\delta^{18}O_w$ (<0.1‰) in the upper 200 m of the water-column makes the ideal setting to evaluate the potential of ISA to reflect the modern temperature range. We performed ISA of *G. ruber* and *Globigerina bulloides* from a depth transect and a piston-core off Somalia (Fig. 1) in the western Arabian Sea. Studies conducted on depth-stratified plankton tows and sediment traps in this region show that both species calcify predominantly in the upper 50 m of the water column (Peeters et al., 2002). While *G. ruber* is continuously present throughout the year, *G. bulloides* predominantly grows during May to October (SW monsoon), when upwelling conditions prevail (Kroon and Ganssen, 1989; Conan and Brummer, 2000; Peeters and Brummer, 2002).

Analysis was performed upon single shells from a restricted size-range of 355–400 µm for *G. ruber* and 300–355 µm for *G. bulloides* from surface sediments (0–1 cm, box cores 902–907, Fig. 1). Water depths range from 459 m to 2807 m. Due to the high (seasonal) productivity caused by intense coastal upwelling, sedimentation rate along the sampled transect is between 20 and 40 cm ka^{-1}, with mean surface sediment calendar ages between modern and 300 years BP (de Moel et al., 2009, Table 1).

The lysocline according to the definition of Berger (1971) is the visible alteration of the foraminiferal assemblage composition, an increase in dissolution resistant species, is observed between station 906 and 907 (Ivanova, 1999). Slight dissolution effects are indeed detectable on the fauna from core 907. To avoid any bias of the geochemical data by dissolution we excluded core 907 from further analyses.

The age model for piston core 905 is based on 24 radiocarbon dates between 0 and 35 kyr (Ivanochko et al., 2005). The conversion from AMS^{14}C dates to calendar ages of samples 25 000 yr and younger was done using Calib 4.4 (Stuiver et al., 1998). Bioturbation depth is calculated at 15 cm for one of the cores along the transect (core 905) by means of ^{210}Pb (de Moel et al., 2009). Only well-preserved shells with identical morphology were picked for geochemical analysis.

Stable isotope analyses were performed on single specimens of the two species using a Finnigan MAT252 mass spectrometer coupled to a Finnigan (Kiel-II type) preparation device. External reproducibility of a carbonate laboratory standard in the weight range (8–20 µg) of a single specimen is 0.15‰ (1 σ) for δ^{18}O. For each sample along the transect analysis was performed on between 30 and 40 individual specimen for both species.

For conversion of oxygen isotope values to temperatures we used the equation of Kim and O'Neill (1997)

$$T = 16.1 - 4.64 \times (\delta_c - \delta_w) + 0.09 \times (\delta_c - \delta_w)^2 \quad (1)$$

where δ_c and δ_w are the oxygen isotope values of the foraminifera and the water, respectively.

Analysis of 23 surface water samples covering the transect was performed on the same mass spectrometer coupled to a Finnigan MAT water equilibration unit with a reproducibility of 0.1‰ (1 σ). The mean value is 0.25 ± 0.08‰ (V-SMOW). Conversion from V-SMOW to V-PDB follows Hut (1987).

Temperature data derived from Mg/Ca ratios of the two species are based on about 30 specimens in the fractions 250–300 µm. The foraminiferal samples were gently crushed under glass plates and homogenized for Mg/Ca measurement. Samples for Mg/Ca analyses were chemically cleaned using the method of Barker et al. (2003) before analysis by ICPOES (de Villiers et al., 2002).

Temperature estimates based on Mg/Ca of *G. ruber* and *G. bulloides* were obtained using species-specific equations obtained from Atlantic sediment trap and core top calibrations (Anand et al., 2003; Elderfield and Ganssen, 2000). The Mg/Ca-temperature equations used in this study are

$$T = (1/0.09) \cdot \mathrm{LN}\,(\mathrm{Mg/Ca}/0.449) \quad (2)$$

(see Anand et al., 2003 for *G. ruber*) and

$$T = (1/0.102) \cdot \mathrm{LN}\,(\mathrm{Mg/Ca}/0.528) \quad (3)$$

(see Elderfield and Ganssen, 2000 for *G. bulloides*). The utilization of different size fractions for stable isotope and Mg/Ca analysis has no significant effect upon the established temperature (Table 2). The observable decrease in the Mg/Ca ratio with increasing water depth and distance from the coast is related to the position of the upwelling cell which is centered at the position of core 905, where highest productivity as shown by % organic carbon (Ivanova, 1999) and highest oxygen isotope values (lowest temperatures) coincide.

The modern temperatures used for the validation of our approach are monthly mean sea-surface temperatures constrained between 1960 and 1993, the year of the initial instrumental recording and sediment sampling, and derive from four 1 × 1° grids which cover the sampling area (http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.php) (Fig. 1).

Temperature ranges were obtained as follows:

1. The δ^{18}O measurements performed upon single shells are evaluated for potential outliers. Since we consider our present dataset too small to conclude that δ^{18}O data of singe shells are normally distributed, we used a method that identifies outliers based on the interquartile range (IQR) for each δ^{18}O data set This means we define a measurement to be an outlier if it falls outside the range [Q1 – 1.5 (Q3 – Q1), Q3 + 1.5 (Q3 – Q1)], with Q3 and Q1 being the third and first quartile of the data and IQR = Q3 – Q1.

2. The Mg/Ca-calcification temperature then is used to anchor the mean δ^{18}O value. Since the Mg/Ca calcification temperatures is based on about 30 specimens it is considered to mirror mean calcification temperature of the fossil population.

3. Temperature extrema are calculated by using the maximum and minimum δ^{18}O values obtained for each species: the maximum calcification temperature is obtained from $T_{\mathrm{Mg/Ca}} + (\delta^{18}$ Ominimum – δ^{18}Oaverage)/−0.22 and the minimum temperature as $T_{\mathrm{Mg/Ca}} - (\delta^{18}$ Omaximum – δ^{18}Oaverage)/−0.22.

4. The total range of calcification temperatures is calculated by subtracting the highest temperature of the warmest species from the lowest temperature of the coldest

species. In case the species are known to have an offset from SST, a correction factor may be applied to convert the calcification temperature range to SST range. Peeters et al. (2002) concluded that the calcification temperature indeed is 1.7 and 1.3 °C lower than SST for *G. ruber* and *G. bulloides*, respectively.

3 Modern temperatures and validation of approach

The observed ranges in oxygen isotopes measurements from the individual specimens are equivalent to temperature ranges of about 13 °C for *G. bulloides* and 11 °C for *G. ruber*, with a total range for both species of 16 °C (Fig. 2). This is approximately 3 °C higher than the observed modern range (Fig. 1) and can be explained by the fact that modern observations represent monthly averaged temperatures over a period of 34 years, thus excluding extreme temperatures that may have occurred in the region during periods of less than a month. The two species have a life cycle of one month or even two weeks (Bijma et al., 1994; Loncaric et al., 2005) only and one chamber of the shell is formed within a few hours (Be, 1977) and can register also short-lasting, extreme temperatures in their skeletons. This might apply especially for the low temperature end, where sporadically extreme cold upwelling events (Swallow and Bruce, 1966) are averaged out in the monthly mean temperature but might be registered when one or several chambers of a specimen are formed. Furthermore, the modern data set is based on data from the upper 5 m while the signals registered in foraminifera are indicative of the upper 50 m of the watercolumn (Peeters et al., 2002).

Prior analysis using conventional methods suggest that there is minimum variability from both species (<0.3‰) along the transect (unpublished data).

The mean oxygen isotope values from all box-cores for *G. ruber* and *G. bulloides* give temperatures of 25.0 °C and 21.7 °C (Eq. 1), respectively and compare well with the mean temperatures obtained by Mg/Ca analysis (Anand et al., 2008, Fig. 2) of the two species in the fraction 250–300 µm from the same box-core transect: 25.4 °C for *G. ruber* and 21.2 °C for *G. bulloides*. This finding justifies the use of the Mg/Ca temperatures as an anchor point for the mean δ^{18}O values based on the ISA.

4 Seasonality during the past 20 000 years

Once validated using modern sediments from the box-core transect, we performed the ISA on *G. ruber* and *G. bulloides* on twelve, equally spaced depth intervals from piston core 905P. This is located below the modern upwelling center and enables us to reconstruct changes of sea-surface temperature ranges (seasonality) over the past 20 kyrs (Fig. 3). The time equivalent of each 1 cm sample is according to the age model (Ivanochko et al., 2005) less than 100 years and the sampling intervals range from about 800 to 2900 years.

The cumulative plots of the individual oxygen isotope measurements (Fig. 3 left panel) show a wide range for both species, with generally lower (warmer) values for *G. ruber* compared to *G. bulloides*, as can be expected from the seasonal preferences of each species. From 360 cm (13.2 kyr) to 460 cm (20.7 kyr) the range in δ^{18}O shift to higher values is indicative for the higher global $\delta^{18}O_w$ of glacial sea-water linked to lowered sea-level.

The mean temperature range for the Holocene is calculated at 13.1 °C which is significantly higher than for the glacial and Glacial/Holocene transition (10.6 and 10.8 °C, respectively, Fig. 3 right panel).

This difference is mainly caused by a decrease of the highest temperatures with mean values of 28.7 (Holocene), 28.4 °C (Termination I) and 26.2 °C (Glacial), whilst lowest (summer) temperatures do not show a clear differences between the three interval.

While various studies (e.g. Wang et al., 2005) indicate that upwelling was reduced in intensity and/or length of duration during the last glacial, the data presented here do not indicate an increase of the temperatures of upwelling water.

At 320 cm, corresponding to the Younger Dryas interval, the highest temperatures at the low-temperature end of the whole record are reached (18.2 °C). The relative abundance of the upwelling-indicator species *G. bulloides* in this sample is as low as during glacial conditions (Ivanova, 1999) and the mean temperature of this species recorded by the Mg/Ca ratio reaches the highest value (22.3 °C) within the record. Either, relatively high temperatures of the upwelling sub-surface waters and/or high air temperatures leading to a rapid warming of the upwelled waters are the most plausible explanations for this observation. At the high-temperature end *G. ruber* reflects the highest mean temperatures in the Mg/Ca record and the maximum temperature of 29.5 °C is perfectly in line with the modern values. This suggests that during the Younger Dryas period the SW-monsoon was still in its glacial mode while during winter the Holocene-like conditions of the NE-monsoon prevailed.

A maximum temperature range of less than 10 °C is only observed at 1.8 ka. Here both seasons are characterized by less extreme temperatures compared to the neighboring intervals, while the mean Mg/CA temperatures do not show a significant change. Based on this observation we conclude that severe changes of seasonal extremes in temperature occur on the millennial to centennial time scale while the mean temperatures of both seasons are constant. A higher sampling resolution may show the seasonality characteristic for rapid climate change.

5 Conclusions

Our study demonstrates that the oxygen isotope composition of individual shells of *G. ruber* and *G. bulloides* from deep-sea sediments off Somalia documents the extreme seasonal temperature contrasts in the tropics caused by the West-Asian monsoon system. Seasonal temperature ranges differ for the last glacial (10.6 °C) compared to the Holocene (13.1 °C). During the Younger Dryas period the SW-monsoon was still relatively weak, comparable to the last glacial, while the NW-monsoon operated already in its Holocene mode. Our approach enables us to reconstruct sea surface water temperature maxima and minima with high accuracy, precision and resolution. Future work following our approach may prove to be extremely useful to better understand and model sea surface temperature extremes and seasonal behavior of climate change.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/6/2795/2010/cpd-6-2795-2010-supplement.pdf.

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We dedicate this paper to our esteemed colleague Orson van der Plassche, who passed away much too early.

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Table 1. Water depth and position of the sediment cores. Radiocarbon dates (where available) of the upper 1 cm performed on surface-dwelling foraminifera.

box cores	water depth (m)	latitude	longitude	^{14}C age	calendar age (years BP) after reservoir age correction of 800 years
902B	459	10°46.72′	51°34.64′	768	modern
903B	789	10°46.97′	51°39.48′		
904B	1194	10°47.27′	51°46.23′		
905B	1567	10°54.94′	51°56.65′	327	modern
906B	2020	10°48.70′	52°07.76′		
907B	2807	10°48.24′	52°14.96′	–24	modern
piston core					
905P	1586	10°46.01′	51°57.04′		198–123

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Table 2a. Mg/Ca data for *G. ruber* in three different size fractions.

fraction (µm)	site	water depth (m)	Mg/Ca ratio (mmol/mol)	Mg/Ca-temperature (°C)
250–300	902	459	4.67	26.02
	903	789	4.54	25.71
	904	1194	4.62	25.90
	905	1567	4.15	24.71
	906	2020	4.06	24.47
	907	2807	4.51	25.63
				mean 25.40
300–355	902	459	4.81	26.36
	903	789	4.81	26.35
	904	1194	5.11	27.03
	905	1567	4.55	25.73
	906	2020	4.33	25.19
	907	2807	4.36	25.25
				mean 25.98
355–425	902	459	4.99	26.76
	903	789	5.05	26.90
	904	1194	4.42	25.41
	905	1567	4.50	25.62
	906	2020	4.26	25.01
	907	2807	3.99	24.28
				mean 25.66

Table 2b. Oxygen isotopes of *G. ruber* in two different size fractions from core 905B, 0–1 cm.

G. ruber 355–400 µm	*G. ruber* 300–355 µm
δ^{18}O mean: -1.50, $n = 40$	δ^{18}O mean: -1.47, $n = 35$

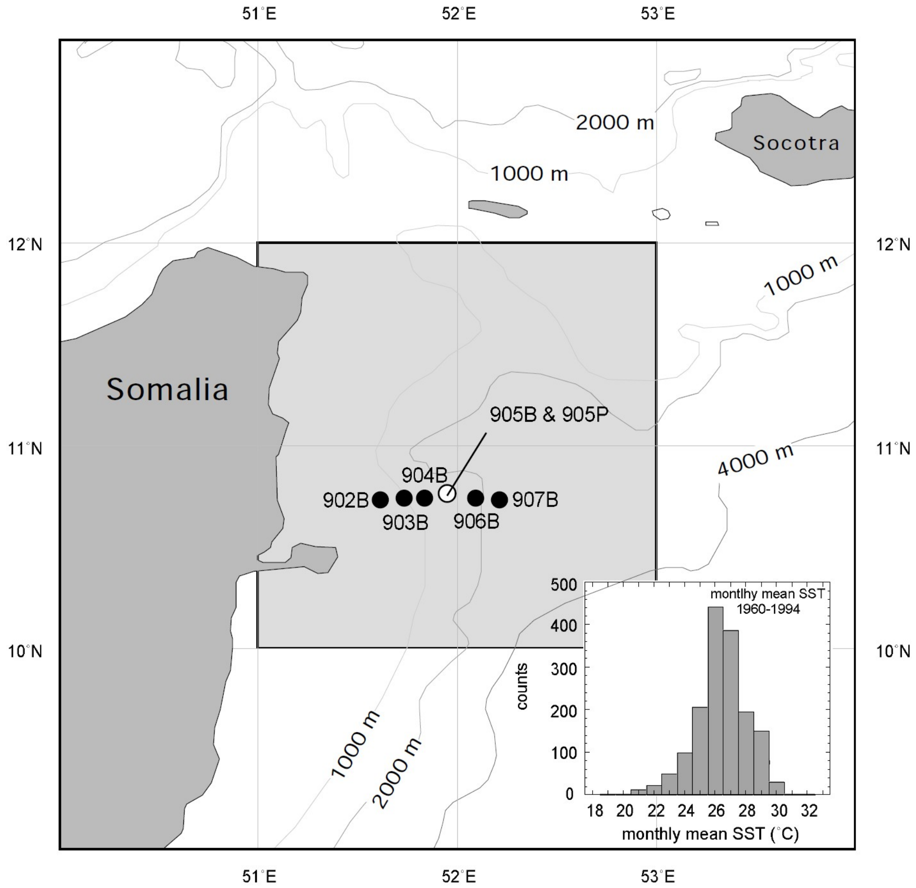

Fig. 1. Core locations of box cores 902 to 907 and piston core 905P. The histogram shows the distribution of modern monthly mean sea surface temperatures from the area indicated in grey. The modern temperatures used for the validation of the approach are monthly mean sea-surface temperatures between 1960 and 1993 (the year of the sediment sampling).

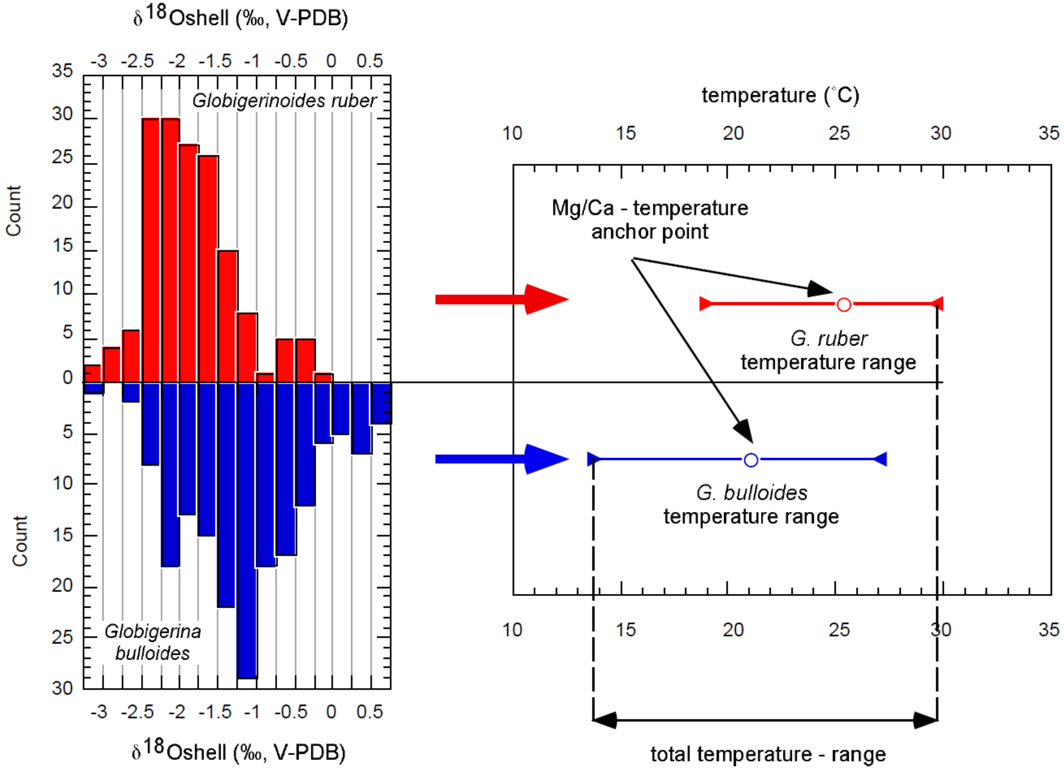

Fig. 2. Oxygen isotope data from all boxcores (902–906) for *G. ruber* ($n = 160$) and *G. bulloides* ($n = 177$) plotted in 0.25‰ wide bins (left panel) and inferred calcification temperature ranges for both species (right panel). Open dots are the mean temperatures derived from the Mg/Ca analysis of surface sediments from the same cores, the lines indicate the total range of calcification temperatures obtained for each species with the most extreme values indicated by triangles.

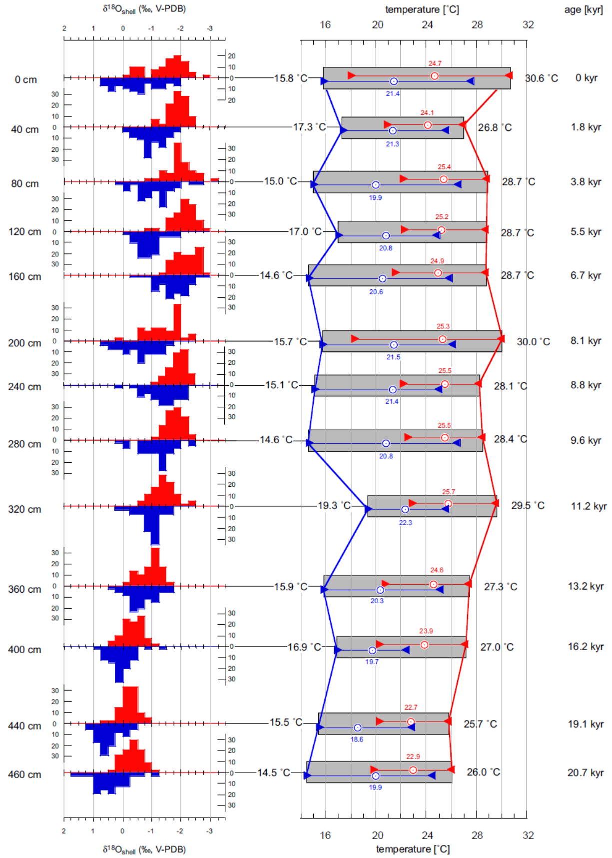

Fig. 3. Oxygen isotope data for piston core 905P *G. ruber* (in red) and *G. bulloides* (in blue) plotted in 0.25‰ wide bins in % (left panel). Inferred calcification temperature ranges for both species (right panel). Open dots are the mean temperatures derived from the Mg/Ca analysis for both species of the respective samples, the lines indicate the total range of calcification temperatures obtained for each species with the most extreme values indicated by triangles.