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Caroline Cléroux, Elsa Cortijo, Jean-Claude Duplessy, Rainer Zahn. Deep-dwelling foraminifera as thermocline temperature recorders. *Geochemistry, Geophysics, Geosystems*, 2007, 8 (4), pp.n/a-n/a. 10.1029/2006GC001474 . hal-02958545

HAL Id: hal-02958545

<https://hal.science/hal-02958545>

Submitted on 9 Oct 2020

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Deep-dwelling foraminifera as thermocline temperature recorders

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[1] We measured the oxygen isotopic composition of the deep-dwelling foraminiferal species *G. inflata*, *G. truncatulinoides* dextral and sinistral, and *P. obliquiloculata* in 29 modern core tops raised from the North Atlantic Ocean. We compared calculated isotopic temperatures with atlas temperatures and defined ecological models for each species. *G. inflata* and *G. truncatulinoides* live preferentially at the base of the seasonal thermocline. Under temperature stress, i.e., when the base of the seasonal thermocline is warmer than 16°C, *G. inflata* and *G. truncatulinoides* live deeper in the main thermocline. *P. obliquiloculata* inhabits the seasonal thermocline in warm regions. We tested our model using 10 cores along the Mauritanian upwelling and show that the comparison of $\delta^{18}\text{O}$ variations registered by the surficial species *G. ruber* and *G. bulloides* and the deep-dwelling species *G. inflata* evidences significant glacial-interglacial shifts of the Mauritanian upwelling cells.

Components: 10,829 words, 12 figures, 3 tables.

Keywords: deep-dwelling foraminifera; depth habitat; isotopic temperature; thermocline; North Atlantic; Mauritanian upwelling.

Index Terms: 4813 Oceanography: Biological and Chemical: Ecological prediction; 4870 Oceanography: Biological and Chemical: Stable isotopes (0454, 1041); 4944 Paleooceanography: Micropaleontology (0459, 3030).

Received 8 September 2006; **Revised** 23 January 2007; **Accepted** 31 January 2007; **Published** 25 April 2007.

Cléroux, C., E. Cortijo, J.-C. Duplessy, and R. Zahn (2007), Deep-dwelling foraminifera as thermocline temperature recorders, *Geochem. Geophys. Geosyst.*, 8, Q04N11, doi:10.1029/2006GC001474.

Theme: Past Ocean Circulation

Guest Editors: C. Kissel, L. Labeyrie, J. Lynch-Stieglitz, and O. Marchal

1. Introduction

[2] Quaternary climatic variations resulted in large ocean circulation changes associated with the

atmospheric and sea surface temperature variations. Deep and intermediate water temperature changes can be reconstructed by isotopic or trace element analyses in benthic foraminifera [Martin et

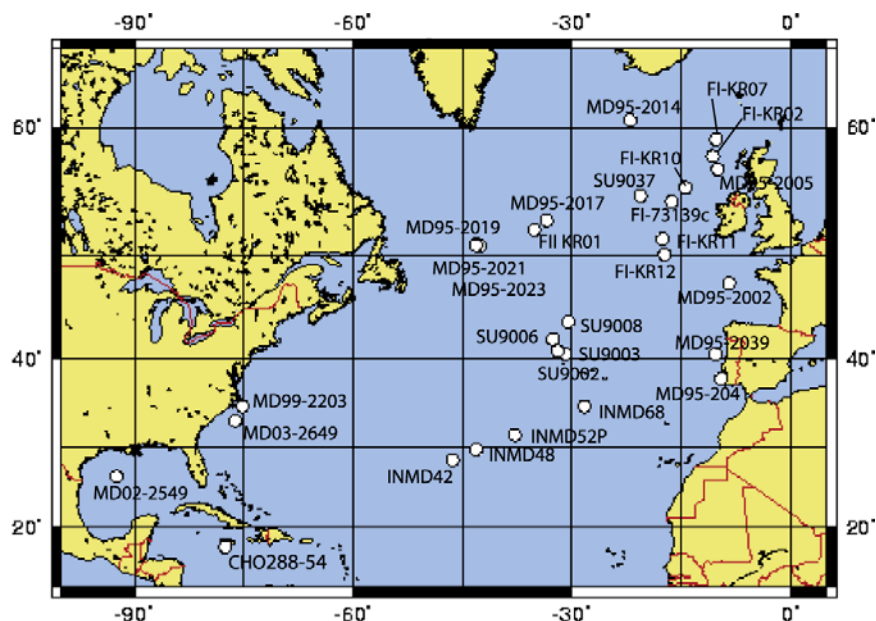


Figure 1. Locations and names of core tops. OMC, Martin Weinelt.

al., 2002; *Streeter and Shackleton*, 1979] or deep corals [*Schrag and Linsley*, 2002]. Assemblage analyses of fossil marine plankton communities, such as coccolithophores, surface dwelling foraminifera or diatoms are commonly used to infer past sea surface temperature [*Giraudeau et al.*, 2000; *Koç Karpuz and Schrader*, 1990; *Prell*, 1985]. However, little information is available on temperature variations in the upper 500 m of the water column, where most of the energy storage and heat transport occur [*Liu and Philander*, 2001].

[3] Deep-dwelling planktonic foraminifera inhabit the top few hundred meters of the ocean [*Bé*, 1977] and constitute potential recorders of thermocline conditions [*Fairbanks et al.*, 1980]. *Mulitza et al.* [1997] used the oxygen isotopic composition ($\delta^{18}\text{O}$) of *G. truncatulinoides* to monitor past seawater temperature variations at 250 m depth and suggested that the thermal stratification of the western equatorial Atlantic was weaker during the Last Glacial Maximum (LGM) than during the Holocene.

[4] However, reconstructing mixed layer and thermocline structure requires insight into ecological niches of deep-dwelling planktonic foraminifera including their growth seasons and calcification depths. In this paper, we use multispecies $\delta^{18}\text{O}$ analyses to better constrain these parameters and to

gain a fuller understanding of deep-dwelling foraminiferal habitats.

[5] We selected three species that are common in deep sea sediments: the transitional water species *Globorotalia inflata*, the warm and high salinity water species *Pulleniatina obliquiloculata* and the deep species *Globorotalia truncatulinoides* right and left coiling [*Bé*, 1977]. $\delta^{18}\text{O}$ values of these species sampled in modern core tops are used to calculate isotopic temperature (Tiso). These values constrain their calcification depths and seasonalities, when compared to modern hydrological data. We apply this concept to down-core isotope profiles from a suite of sediment cores from the Mauritanian margin to assess upwelling intensity during the LGM.

2. Samples and Methods

[6] We measured the oxygen isotopic composition of foraminifer shells from 29 core tops raised from the subtropical to northern North Atlantic, 28°–61°N (Figure 1). The samples cover three marine climatological regimes: the North Atlantic Current, the warm and well-stratified subtropical gyre and the deep mixed-layer zone in the north.

[7] Except for the 4 southernmost cores (centered around 30°N), the stratigraphy of all the cores

Table 1. Location, Water Depth, Age Control, and SST From Database and Surface-Dwelling Species^a

Core Top	Latitude, °N	Longitude, °W	Depth, m	Age Control MARGO ^b	References ^c	Summer SST ^d	Foraminifera SST ^e
CHO 288 54	17°25	77°39	1020	1	1	28.6	29.6
MD 02-2549	26°25	92°33	2049	4	3	29.2	28.7
INMD 42BX-8 ^f	28°34	46°21	3774	3 and 4	1, 2	26.9	22.9
INMD 48BX-1 ^f	29°48	43°13	2836	3 and 4	1, 2	26.4	23.3
INMD 52 P ^f	31°31	37°52	3631			26	25
MD03-2649	33°11	76°15	958	4	3	27.9	29.7
INMD 68BX-6 ^f	34°48	28°21	2520	3 and 4	1, 2	24	21.4
MD99-2203	34°58	75°12	620	1	3	27.1	27.3
MD95 2041	37°50	09°30	1123	3 and 4	2, 3	19.2	17.9
MD95 2039	40°34	10°20	3381	3	2	19.2	17.9
SU 9002 P	40°34	30°56	2220	3	2	22	16.8
SU 9003 P	40°5	32	2478	2 and 3	2, 3	22.1	20.2
SU 9006 P	42°	32	3510	3	2	21.7	19
SU 9008 P	43°5	30°35	3080	3 and 4	2, 3	20.1	20.3
MD95 2002	47°27	08°32	2174	3 and 4	2, 3	17.9	16.8
F I KR 12	50°15	17°37	4787	3 and 4	1, 2	13.4	14.2
MD95 2021	50°51	42°44	4283	3	2	13.6	12.3
MD95 2023	50°58	43°13	4198	3	2	13.6	13
MD95 2019	51°05	43°13	4262	3	2	11.6	12
F I KR 11	51°48	17°68	4654	3 and 4	1, 2	15.4	14.4
F II KR 01	52°28	35°25	3886	3 and 4	1, 2	12	10.1
MD95 2017	53°02	33°31	3100	3	2	12.5	9.7
F I 139 c	54°38	16°21	2209	1	1	14.3	14.6
SU 9037 S	55°06	20°44	2676	3	2	14	13.2
F I KR 10	55°6	14°48	2216	3 and 4	1, 2	13.9	13.6
MD95 2005	57°02	10°03	2130	3 and 4	2, 3	13.6	12.3
F I KR 02	58°08	10°72	2005	3	2	13.2	12.5
F I KR 07	59°25	10°22	482	3	2	12.7	11.5
MD95 2014	60°34	22°04	2397	3 and 4	2, 3	11.6	10.6

^aQuality of age control according to the four levels defined in MARGO and references. The two last columns allow comparison between modern sea surface temperature (SST) and isotopic temperature of surface-dwelling species.

^bChronostratigraphic quality levels go from 1 to 4 with different levels of uncertainty: Numbers 1 and 2 are for radiometric control within the intervals 0–2 ka and 0–4 ka, respectively, level 3 is used for specific stratigraphic control (like % *Globorotalia hirsuta* left coiling), and number 4 represents other stratigraphic constraints [Kucera *et al.*, 2005].

^cReferences: 1, Core top included in MARGO database; 2, J. Duprat, personal communication, 2006; 3, LSCE database.

^dFrom World Ocean Atlas.

^eMean isotopic temperature measured on *G. ruber* or *G. bulloides*. Mean one sigma range is about 1°C.

^fCores with no downcore stratigraphy.

indicates that the upper part correspond to an expanded Holocene section. This minimizes the influence of upward bioturbational mixing of older foraminiferal shells (from early Holocene or deglaciation). However, for all the cores, we use the Late Holocene stratigraphic quality levels as defined in MARGO [Kucera *et al.*, 2005] to ensure an Upper Holocene age of the samples and checked that the isotopic composition of the surface-dwelling species *G. ruber* and *G. bulloides* are consistent with modern seawater temperature and salinity (Table 1).

[8] Foraminifera were picked in different sizes fractions. *G. ruber* and *G. bulloides* were chosen in the 250–315 μm fraction. About 4 shells were taken for each $\delta^{18}\text{O}$ analysis. Deep-dwelling spe-

cies were picked in the 355–400 μm fraction. *G. inflata* specimens were also taken in the 250–315 μm size fraction to check for a possible size effect. 2 or 3 tests were used for analyses. 2 to 10 isotopic measurements on the same sample were performed to estimate the $\delta^{18}\text{O}$ variability within single sediment samples (Table S1¹).

[9] Prior to analysis, shells were ultrasonically cleaned in methanol to remove clays and other impurities and then roasted at 380°C during 30 min under vacuum to burn organic matter. Samples

¹Auxiliary materials are available at <ftp://ftp.agu.org/apend/gc/2006gc001474>.

were analyzed using Finnigan MAT 251 mass spectrometer equipped with an automated Kiel CARBO device for CO₂ production. We used both NBS 19 and NBS 18 as reference standards to ensure calibration over a large range of δ¹⁸O values [Ostermann and Curry, 2000]. All results are expressed as δ¹⁸O in ‰ versus V-PDB. The mean external reproducibility of carbonate standards is 0.07‰ for δ¹⁸O, this error is insignificant in our calculation.

3. Calcification Temperature Estimates

[10] Several authors have shown that many foraminiferal species do not precipitate their shell in isotopic equilibrium with ambient water but exhibit an offset called “vital effect” that is assumed to be constant. For surface-dwellers vital effect seems to be constant both within the same species across its optimum environmental regimes [Duplessy *et al.*, 1991; Wang *et al.*, 1995] and through stratigraphic time. For deep-dwelling species, contradictory results have been published in the literature. However, apparent disequilibria are rather small in the range 0 ± 0.3‰ [Deuser and Ross, 1989; Fairbanks *et al.*, 1980; Ganssen, 1983; Niebler *et al.*, 1999; Wilke *et al.*, 2006] which is equivalent to ±1°C.

[11] Neglecting isotopic equilibrium, we first quantify the depth habitat of the deep-dwelling species and then test the robustness of this approach by calculating the effect of a potential disequilibrium for each species.

[12] We calculated T_{iso} using the paleotemperature equation of Shackleton [1974] (equation (1)). This relation fits isotope measurements performed on benthic foraminifera and the slope of this relationship fits well with measurements performed on planktonic species [Bemis *et al.*, 1998; Bouvier-Soumagnac and Duplessy, 1985].

$$T_{\text{isotopic}} = 16.9 - 4.38 * (\delta^{18}\text{O}_{\text{foraminifera}} - \delta^{18}\text{O}_{\text{seawater}}) + 0.1 * (\delta^{18}\text{O}_{\text{foraminifera}} - \delta^{18}\text{O}_{\text{seawater}})^2 \quad (1)$$

This equation does not differ from other paleotemperature equations [Epstein *et al.*, 1953; Kim and O’Neil, 1997] by more than 0.8°C in the range 8–20°C.

[13] In this equation, δ¹⁸O of both foraminifera and water are measured against the same working standards. As we report here foraminifera δ¹⁸O against V-PDB and seawater δ¹⁸O against V-SMOW, a

0.27‰ correction factor was used to account for the difference between PDB-CO₂ and SMOW-CO₂ standards [Hull and Turnbull, 1973; Hut, 1987].

[14] We extracted salinity data from the World Ocean Atlas 2001 (WOA) [Conkright *et al.*, 2002] to estimate the δ¹⁸O_{seawater} value for each core top sample. We use the Goddard Institute for Space Studies database for the North Atlantic (<http://data.giss.nasa.gov/o18data>) to compute the relationship between δ¹⁸O_{seawater} and salinity in the North Atlantic Ocean between 0 and 500 meter depth. This gives a relationship very close to the GEOSECS equation defined between 0 and 250 m:

$$\delta^{18}\text{O}_{\text{seawater}} = -19.264 + 0.558 * \text{salinity} \quad (\text{in V-SMOW}) \quad (2)$$

At high latitude, salinity is nearly constant in the mixed layer and the thermocline. We calculated δ¹⁸O_{seawater} from the mean salinity value between 0 and 500 m (Figure A1). The same approach is applied for low latitude cores. In the subtropical gyre, salinity varies from 37 psu at the surface to 35.75 psu at 500 m depth. Taking a mean salinity/δ¹⁸O value for the water column results in an error on the isotopic temperature of ±1.5°C, which is small when compared to the observed temperature range within the thermocline which commonly exceed 10°C. Taking into account the experimental error of ±0.07‰ on the isotope measurement, the total error is about ±2°C.

[15] This calculation rests on the assumption of isotopic equilibrium of foraminifer carbonate shells with ambient seawater. If we assume a vital effect of ±0.3‰, which is the maximum value given by previous studies [Niebler *et al.*, 1999], isotopic temperatures will change by less than 1.5°C according to the paleotemperature equation (1). Given the large scatter of the measured δ¹⁸O values, such a small disequilibrium would not affect our conclusions.

4. Results and Discussion: A Modern Ecological Concept

[16] To compare T_{iso} with modern temperatures from atlas we applied the following method: To take account regional variability, we extracted, around each core, summer and winter temperature profiles from the four neighboring grid points. Figure 2 gives an example for the isotopic results of *G. inflata* in the core FI KR02 but we applied

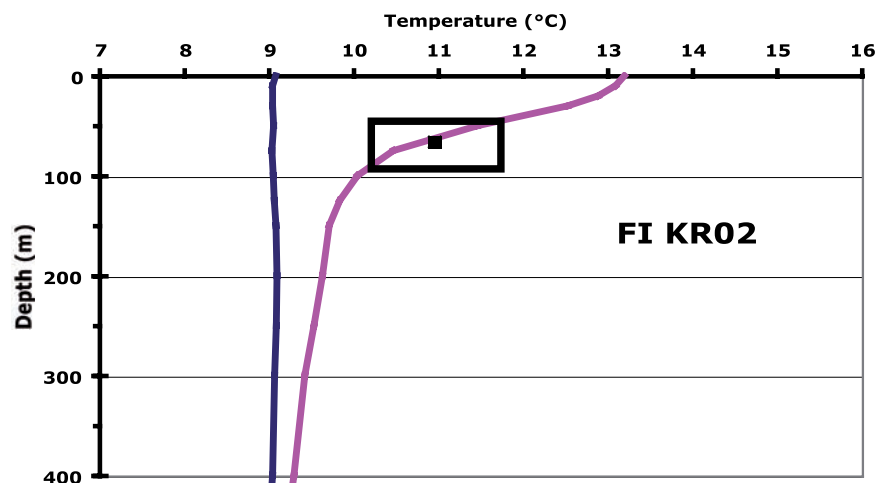


Figure 2. Comparison of the mean isotopic temperature (Tiso) of *G. inflata* with modern temperatures for the core FI KR02. Blue (pink) line is the coldest winter (warmest summer) temperature profile from WOA 2001. Square represents the mean Tiso. Rectangle indicates the possible habitat depth. The width of rectangle gives the one sigma range in Tiso resulting from replicate $\delta^{18}\text{O}_{\text{foraminifera}}$ measurements. The height of rectangle expresses this error in terms of water depth.

the same method for each core top and each species (Figures A2, A3, and A4).

[17] At midlatitudes and high latitudes, the Tiso of all species are higher than winter temperatures but coincide with summer temperatures around the base of the summer thermocline (BST hereinafter, which we define as the depth where the summer and winter profiles join). In agreement with the observation that planktonic blooms occur during summer time [Colebrook, 1982; Esaias *et al.*, 1986]. At low latitude, we cannot exclude the possibility of a surface habitat during winter based on our isotopic measurements [Deuser, 1987; Deuser and Ross, 1989; Deuser *et al.*, 1981].

4.1. *G. inflata*

[18] As results were similar for both size fractions (250–315 μm and 355–400 μm) we have combined the two data sets (Table S1). We defined the different ecological niches according to local hydrology. We have separated the water column into three units: the seasonal thermocline, the BST, and the main thermocline below this level.

[19] When the BST is colder than about 16°C, Tiso of *G. inflata* corresponds to the temperature at the BST (Figures A2a to A2u). When the BST is warmer than 16°C, Tiso of *G. inflata* indicates a deeper habitat, in the upper part of the main thermocline (Figures A2v to A2y). In the latter

case, it is impossible to determine whether this species lives throughout the year or only seasonally, because the temperature at this depth exhibits little seasonal variation.

[20] We develop a simple concept for this species: when the Tiso of *G. inflata* is lower than $16 \pm 1^\circ\text{C}$, we consider that it records the temperature at the BST. When the Tiso is higher than $16 \pm 1^\circ\text{C}$, it reflects warm conditions in the upper part of the main thermocline.

[21] Our ecological model is in agreement with several in-situ observations. In plankton tows and surface sediment studies from off NW Africa, Ganssen [1983] and Ganssen and Sarnthein [1983], used isotope differences between *G. ruber* and *G. inflata* to mirror seasonal temperature changes. As *G. ruber* lives during the warm season and *G. inflata* at the BST, of which temperature is close to that of winter condition, this interpretation fits well with our concept. The development of this species during warm season at midlatitude is confirmed by the plankton nets of Ottens [1992] collected between 30°N and 60°N in the Atlantic. Recently, living *G. inflata* were sampled in the SW-African margin water column during austral summer [Wilke *et al.*, 2006]. In this study they found a maximum for both the shell concentrations and the amount of calcification within the thermocline. From 1978 to 1984, Deuser and colleagues studied sediment traps in the Sargasso Sea and

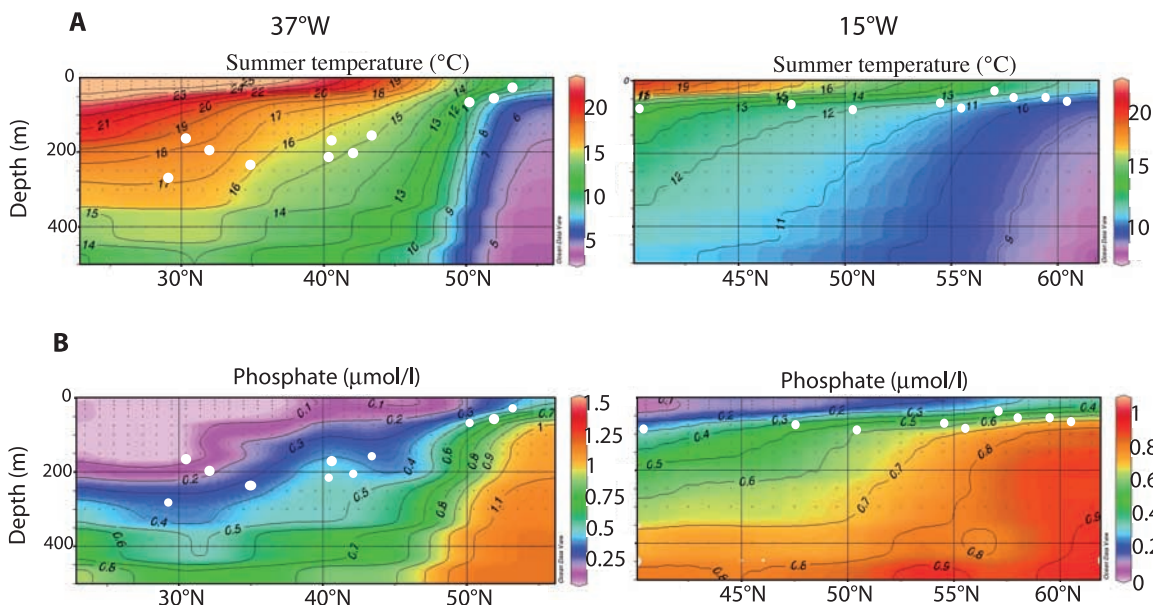


Figure 3. Depth positions of *G. inflata* 355–400 μm on summer temperature ($^{\circ}\text{C}$) and phosphate ($\mu\text{mol/l}$) cross section at (left) 37 $^{\circ}\text{W}$ and (right) 15 $^{\circ}\text{W}$. *G. inflata* depth habitats (white circle) were placed according to latitude of their core top and calculated Tiso on (a) two longitudinal temperature sections and (b) corresponding PO_4 section.

made oxygen isotopic measurements and foraminifer fluxes observations [Deuser, 1987; Deuser and Ross, 1989; Deuser et al., 1981]. They concluded that *G. inflata* lives in the winter mixed-layer. This result is in agreement with our observations at low latitude and provides additional information on the life season in this warm region. Plankton tows studies in the equatorial Atlantic show maximum abundance of *G. inflata* at the BST [Ravelo and Fairbanks, 1990] and oxygen isotopic measurements confirm this calcification depth [Ravelo and Fairbanks, 1992]. Finally the ecological niche defined in our study for *G. inflata* agrees with the calcification depth observed in the North Atlantic [Durazzi, 1981; Ganssen and Kroon, 2000; Mortyn and Charles, 2003].

[22] Along longitudinal sections across the North Atlantic, we found that the depth habitat of *G. inflata* follows the 0.3–0.4 $\mu\text{Mol/l}$ PO_4 concentration line in seawater (Figure 3). The BST is indeed a level of nutrient accumulation [Sarmiento et al., 2004] and concentration of phytoplankton is high, providing food for foraminifera.

4.2. *G. truncatulinoides* Dextral and Sinistral

[23] Both *G. truncatulinoides* right and left coiling exhibit roughly similar Tiso (Table S1) and there-

fore occupy the same ecological niche. Ganssen and Kroon [2000] have also found similar $\delta^{18}\text{O}$ for both coiling directions. However, we still separate them because they constitute different genetic species [de Vargas et al., 2001] and they have different behavior with respect to trace element incorporation (C. Cléroux et al., manuscript in preparation, 2007). In our data set, *G. truncatulinoides* right coiling has a greater temperature tolerance than *G. truncatulinoides* left coiling: the standard deviation of the Tiso at a given location is often larger for the right coiling form than for the left coiling (Figures A3i to A3m and A3r).

[24] When the BST is colder than about 16 $^{\circ}\text{C}$, *G. truncatulinoides* is found in the seasonal thermocline lower part (Figures A3a to A3n). When the BST is warmer than about 16 $^{\circ}\text{C}$, *G. truncatulinoides* lives deeper in the main thermocline (Figures A3o to A3t). Although *G. truncatulinoides* and *G. inflata* have similar depth habitat, *G. truncatulinoides* always lives at greater depth than *G. inflata* when both species are present in the same area. The great scatter of the calculated Tiso for low latitude samples reflects the wide temperature variation that occurs in the upper water column.

[25] We thus develop a concept similar to that of *G. inflata*: when the Tiso of *G. truncatulinoides* is

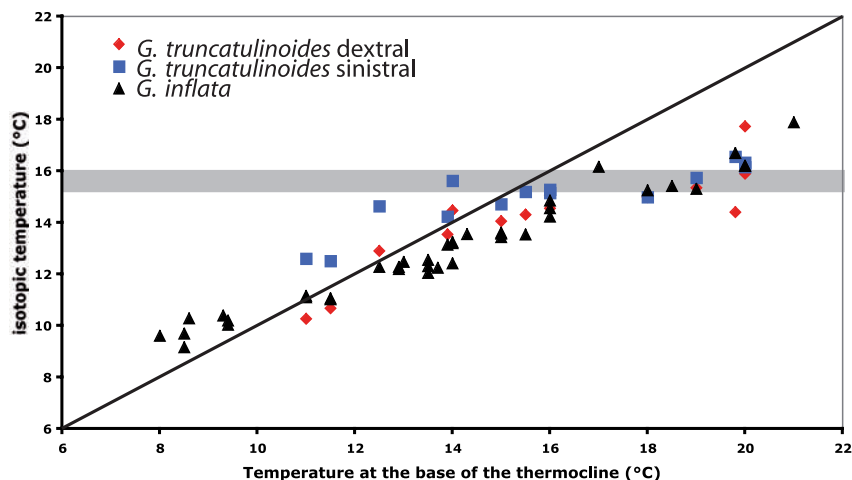


Figure 4. Tiso of *G. inflata* (black triangle), *G. truncatulinoides* dextral (red diamond), and sinistral (blue square) from Ganssen and Kroon [2000] versus temperature at the base of the summer thermocline extracted from modern atlas at their box core locations. Line of slope 1 is plotted. The gray area, from 15.7°C to 16°C, underlines the temperature threshold from which Tiso are no more equal to temperature at the BST.

lower than $16 \pm 1^\circ\text{C}$, we consider that it records the temperature at the BST. When the Tiso is higher than $16 \pm 1^\circ\text{C}$, it reflects conditions of the main thermocline.

[26] Local hydrology therefore fixes the depth habitat of *G. truncatulinoides*. LeGrande *et al.* [2004] predict *G. truncatulinoides* $\delta^{18}\text{O}$ for many South and North Atlantic core tops assuming (1) a single depth calcification at 350 m or (2) 30% of calcification at the surface and 70% of calcification at 800 m. We tested our concept with the North Atlantic data of LeGrande *et al.*'s [2004] paper. One fraction of their data comes from the study of Ganssen and Kroon [2000] and will be discussed further in the text. The other fraction corresponds to core tops located in warm regions, around the equator or in the Gulf stream water, where temperature at the BST largely exceed our threshold value of 16°C . Thus, according to our prediction, *G. truncatulinoides* calcifies in the main thermocline, in agreement with the model of LeGrande *et al.* [2004], which specifies that it is around 350 m. On the contrary, our concept does not fit with the South Atlantic LeGrande *et al.* [2004] data. Estimated isotopic temperatures are very low, in contradiction with the temperature preferences known for the North Atlantic *G. truncatulinoides*. It is possible that the genetic difference observed by de Vargas *et al.* [2001] between the North and South Atlantic *G. truncatulinoides*

corresponds to different ecological characteristics. We do not have elements to check that hypothesis and we consider that at the present stage the concept is not adapted for the South Atlantic.

[27] Our concept directly reproduces regional observations. In the Sargasso Sea, $\delta^{18}\text{O}$ values of *G. truncatulinoides* record average conditions near 200 meters depth [Deuser, 1987; Deuser and Ross, 1989; Deuser *et al.*, 1981; McKenna and Prell, 2004]. This depth corresponds to the BST with a temperature close to 16°C . Here, *G. truncatulinoides* inhabits its preferred habitat. In slope water, cold core rings of the Gulf Stream and Northern Sargasso Sea plankton tows, Fairbanks *et al.* [1980] observed that the main population of *G. truncatulinoides* is found between 125 to 175 m, which corresponds to the BST. Mulitza *et al.* [1999] also showed that *G. truncatulinoides* lives in phosphate-rich waters and is a good recorder of thermocline nutrient levels.

[28] To compare more easily our concept with previous studies, we apply our strategy and recalculate Tiso for *G. truncatulinoides* and *G. inflata* from the data of Ganssen and Kroon [2000]. Tiso for *G. truncatulinoides* and *G. inflata* follows the temperature at the BST up to $15.7^\circ\text{C} \pm 0.3$ (Figure 4). Above this temperature, Tiso become too low and reflect the sinking of the foraminifera in the main thermocline.

Table 2. Summary of Ecological Model for the Three Deep-Dwelling Foraminifera Species: *G. inflata*, *G. truncatulinoides*, and *P. obliquiloculata*

Species	Preferred Habitat	Temperature Threshold	Stress Habitat
<i>G. inflata</i>	base of the seasonal thermocline	16°C	Upper part of the main thermocline
<i>G. truncatulinoides</i> dextral and sinistral	base of the seasonal thermocline	16°C	Main thermocline
<i>P. obliquiloculata</i>	base of the seasonal thermocline	–	–

4.3. *P. obliquiloculata*

[29] *P. obliquiloculata* has a restricted geographical distribution and was found in only 7 core tops. Tiso of *P. obliquiloculata* reflect those at the BST (Figures A4a to A4g). This species inhabits the same ecological niche as *G. inflata* but is restricted to warm regions. In a core located south of Cuba (core CHO288-54, Figure A4f), *P. obliquiloculata* is in equilibrium with the seawater temperature at 175 m depth. In this region where seasonality is quasi-absent and stratification is strong throughout the year, this depth corresponds to the base of the upper thermocline.

[30] *Ravelo and Fairbanks* [1992] found the maximum occurrence of *P. obliquiloculata* at 60 m in equatorial Atlantic waters, i.e., at the BST. In a study off NW Africa, *Ganssen* [1983] concludes also that *P. obliquiloculata* delineates winter temperature. Except for one specimen collected in March, this species was not found in winter plankton tows. Moreover, calculated Tiso from sediment samples was often a little warmer than winter sea surface temperature thus compatible with temperature at the BST. In the Sargasso Sea, the sediment traps studies of [*Deuser, 1987; Deuser and Ross, 1989; Deuser et al., 1981*] yield a characteristic isotopic depth of 0–75 m which do not contradict these results.

[31] As the preferred habitat for all species discussed here is at the BST (Table 2), we compared Tiso with modern temperatures at the BST (ΔT), at each core-top location (Figure 5). In a foreseeable way, for the maximum number of analysis, Tiso of *G. inflata* and *P. obliquiloculata* is equal to the temperature at the BST ($\Delta T = 0$). In the histogram of *G. truncatulinoides* the higher peak is for $\Delta T = -1$ reflecting our observation that this species calcifies always a little deeper than *G. inflata*. *P. obliquiloculata* has a symmetric

histogram because it has only one depth habitat. On the contrary, *G. truncatulinoides* and *G. inflata* have distorted histograms toward negative values representing their stress habitats in the main thermocline.

5. Reconstruction of the Glacial Thermocline Structure Off Northwest Africa

[32] We selected 10 cores collected along the Northwest African margin from 15°N to 35°N within the Mauritanian upwelling regime (Figure 6) [*Zahn, 1986*]. Data are reported in Table 3. Two cores (M12-328 and M16-030) are located in the today's center of perennial upwelling (Figure 6), cores M13-289 and M12-347 south of this zone and M15-637 outside. Others cores are distributed along the coast, north of the maximum intensity upwelling area. $\delta^{18}\text{O}$ of *G. ruber*, *G. bulloides* and *G. inflata* has been analyzed previously [*Zahn, 1986*] for the Holocene and LGM using benthic $\delta^{18}\text{O}$ for stratigraphy [*Sarnthein et al., 1994; Zahn and Sarnthein, 1987*]. *G. bulloides* is a surface-dwelling species typical of upwelling season. This species provides seawater temperature estimates for that period [*Ganssen, 1983; Ganssen and Kroon, 2000; Ganssen and Sarnthein, 1983; Zahn, 1986*]. *G. ruber* lives in the surface mixed layer during the warm season [*Ganssen and Kroon, 2000*]. We derive Tiso from these $\delta^{18}\text{O}$, using modern seawater $\delta^{18}\text{O}$ values for Holocene data and already reconstructed LGM seawater $\delta^{18}\text{O}$ for the same cores, or for very nearby cores, for LGM data [*Duplessy et al., 1991*]. Results are reported in Table 3. We used the same method developed for the construction of our concepts to compare Holocene Tiso and modern temperatures from atlas (Figure A5). For all cores, the calculated Holocene Tiso of *G. inflata* are close to the threshold value of 16°C and nicely fit with those of the BST along the

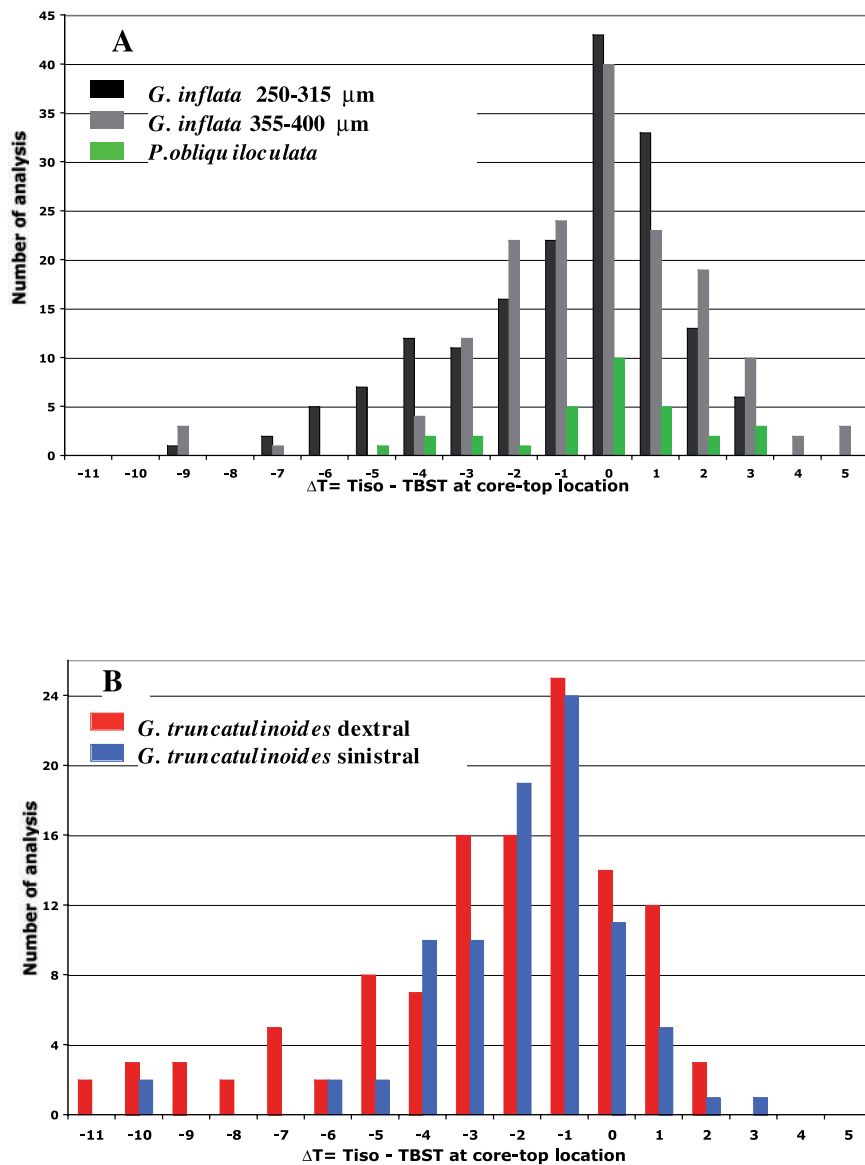


Figure 5. Histogram of the difference between Tiso and the modern temperature at the base of seasonal thermocline (TBST) from WOA 2001 at each core-top location for (a) *G. inflata* and *P. obliquiloculata* and (b) the two coiling directions of *G. truncatulinoides*.

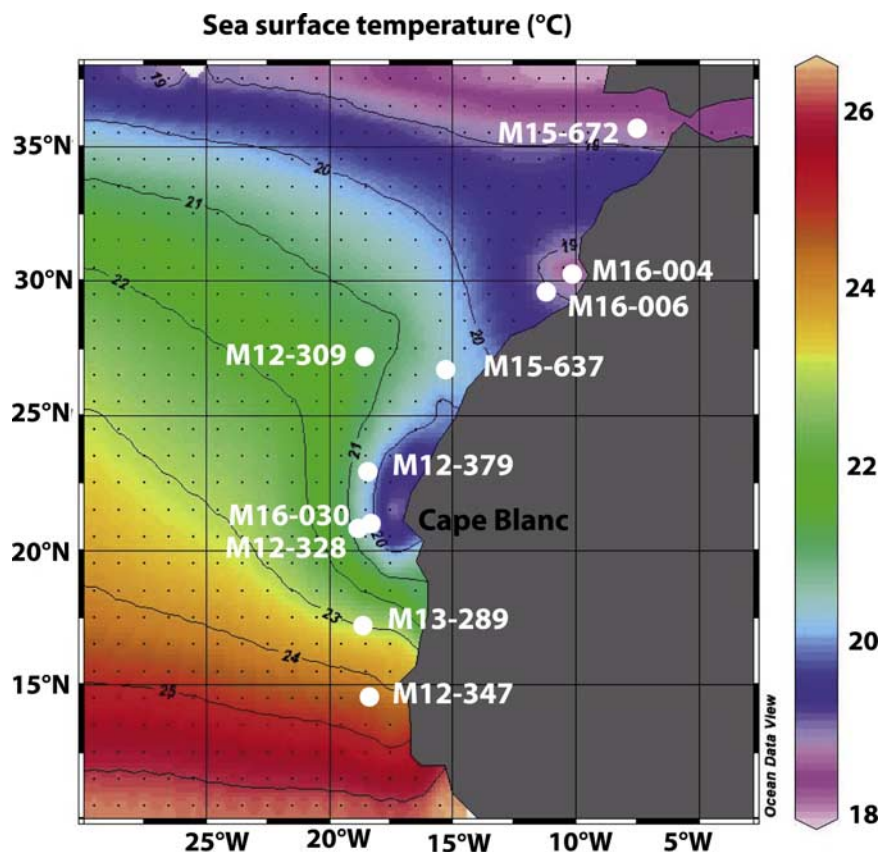


Figure 6. Sea surface temperatures and locations of the cores used to reconstruct upwelling intensity along the NW African margin.

Northwest African Margin (Figure A5). We highlighted in this paper that *G. inflata* might change his depth habitat when seawater becomes warmer; as Tiso for LGM samples are colder than the present we assume that *G. inflata* did not change its habitat from LGM time to Holocene. Accordingly, we consider that the calculated LGM Tiso reflect conditions at the BST.

[33] The upwelling activity, which exist at the cores M12-328, M16-030 and M16-004 locations (Figures 6 and 7), is reflected by several indicators: Tiso of *G. bulloides* are low; Tiso of *G. inflata* are also low because the temperature at the BST is linked to the coldest month conditions. Thus Tiso differences between *G. bulloides* and *G. inflata* under upwelling conditions are small. We shall use the whole set of these indicators to characterize upwelling activity. In the other cores, outside the main upwelling cell, mean Tiso of *G. bulloides* is about 21°C (M13-289, M12-309 and M16-006). The absence of upwelled cold water is well marked

between 23°N and 29°N with the warm Tiso of *G. inflata* (Figure 7).

[34] During LGM, in the southern cores M12-347 and M13-289, Tiso of *G. inflata* are low (about 12.5°C), whereas those of *G. bulloides* are high (19.1°C and 19.5°C, respectively), resulting in large temperature difference between *G. bulloides* and *G. inflata* (6.9°C and 6.6°C). This suggests that the strong cooling observed at the BST is not associated with upwelling during glacial conditions but is probably due to a water mass circulation different from the present [Sarnthein *et al.*, 1994].

[35] In the cores M12-328, M16-030, M12-379 and M12-309, Tiso for *G. inflata* is comprised between 14°C and 15°C, and the mean Tiso of *G. bulloides* is 19°C. The mean temperature difference between the two species is about 4.5°C. According to Holocene observations, it reflects hydrological area with moderate upwelling activity. We conclude that during LGM, upwelling activity

Table 3. Characteristics of the NW African Margin Cores, Oxygen Isotopic Data, Oxygen Isotopic Composition of the Water, and Calculated Isotopic Temperature for Holocene and LGM Periods^a

Core	Latitude, Longitude, Depth,			Holocene										LGM					
	°N	°W	m	$\delta^{18}\text{O}$ <i>G. ruber</i> ^b	$\delta^{18}\text{O}$ <i>G. inflata</i> ^b	$\delta^{18}\text{O}$ <i>G. bulloides</i> ^b	$\delta^{18}\text{O}$ sea SMOU ^c	T* <i>ruber</i>	T* <i>inflata</i>	T* <i>bulloides</i>	ΔT <i>G. bulloides</i> - <i>G. inflata</i>	$\delta^{18}\text{O}$ <i>G. ruber</i> ^b	$\delta^{18}\text{O}$ <i>G. inflata</i> ^b	$\delta^{18}\text{O}$ <i>G. bulloides</i> ^b	$\delta^{18}\text{O}$ seawater SMOW ^d	T* <i>ruber</i>	T* <i>inflata</i>	T* <i>bulloides</i>	ΔT <i>G. bulloides</i> - <i>G. inflata</i>
M15-672	34.51	8.07	2455	-0.22	0.85	0.29	1.08	21.5	16.7	18.5	2.7	1.85	2.70	2.31	2.15	17.0	13.4	15.0	1.7
M16-004	29.58	10.38	1512	-0.24	0.90	0.29	1.02	21.3	16.2	18.9	2.7	1.81	2.58	1.83	2.18	17.3	14.0	17.3	3.2
M16-006	29.14	11.29	796	-0.04	0.67	-0.15	1.10	20.8	17.6	21.3	3.7	1.84	2.50	1.56	2.18	17.2	14.4	18.4	4.1
M15-637	27	18.59	3849	-0.71	0.65	-0.03	1.29	24.8	18.5	20.8	2.4	1.51	2.46	1.88	2.41	19.7	15.5	18.0	2.5
M12-309	26.5	15.06	2820	-0.36	0.50	-0.03	1.12	22.3	18.4	20.8	2.4	1.45	2.38	1.32	2.21	19.1	15.0	19.7	4.7
M12-379	23.08	17.44	2136	-0.64	0.61	0.61	1.12	23.6	18.0	15.2	-0.9	1.25	2.59	1.55	2.18	19.8	14.0	18.5	4.5
M16-030	21.14	18.03	1500	-1.13	0.84	1.05	0.92	25.0	16.1	15.2	-0.9	0.49	2.44	1.44	2.18	23.3	14.6	19.0	4.4
M12-328	21.08	18.34	2778	-1.00	0.74	0.26	0.91	24.4	16.5	18.6	2.1	0.84	2.53	1.53	2.18	21.7	14.2	18.6	4.4
M13-289	18.04	18.01	2490	-1.19	0.90	-0.20	0.85	25.0	15.5	20.4	4.9	0.99	2.92	1.40	2.16	20.9	12.5	19.1	6.6
M12-347	15.5	17.52	2576	-1.38	0.72	0.72	0.77	25.5	15.9	15.9	4.9	1.16	2.81	1.23	2.08	19.8	12.6	19.5	6.9

^a For both periods, isotopic temperature difference between *G. bulloides* and *G. inflata* is calculated. T*, isotopic temperature.

^b From *Zahn* [1986].

^c From World Ocean Atlas.

^d From *Duplessy et al.* [1991].

disappeared or was strongly reduced between 21°N and 26.5°N. In agreement with these data, a productivity smaller than today was deduced for the LGM in an extensive study of the coastal upwelling off Cape Blanc [Bertrand *et al.*, 1996; Martinez *et al.*, 1999].

[36] For the northern cores (M15-637, M16-006, M16-004 and M15-672) the reconstructed LGM Tiso for *G. bulloides* are the lowest (17.2°C in mean) and the Tiso differences between *G. bulloides* and *G. inflata* are small (2.9°C) compared to southern cores. We interpret these data as an evidence for enhanced upwelling activity, in agreement with stronger LGM productivity off Morocco [Freudenthal *et al.*, 2002]. The shift of the main upwelling cell to the north, which is also seen in changes of coccolith morphology and distribution [Henderiks and Bollman, 2004] reflects the enhanced trade winds intensity about 36°N to 24°N during LGM [Hooghiemstra *et al.*, 1987].

6. Conclusions

[37] We propose here a simple ecological concept to constrain the habitat and seasonality for *G. inflata*, *G. truncatulinoides* right and left coiling and *P. obliquiloculata*, based on the comparison between isotopic temperatures in North Atlantic core tops and modern atlas data. These species inhabit preferentially the base of the seasonal thermocline. Under high temperature stress, *G. inflata* and *G. truncatulinoides* sink within the main thermocline to reach colder waters. These depth habitats correspond to abundant phytoplankton level that provides food for these large non-symbiotic foraminifera. This ecological concept fits well with previous in-situ studies.

[38] The depth habitat of these species in the water column is now well-characterized. Paired analyses of surface and deep-dwelling planktonic foraminifera along a single sediment core offers possibility to reconstruct temperature at critical levels of the water column, i.e., the surface and base of the thermocline. We have tested this concept under glacial conditions using several cores raised off West Africa. By comparison with the modern pattern, our results show a shift of the main upwelling cells from Cape Blanc to Morocco and Canary basin during the LGM. Agreement between this conclusion and previous micropaleontological reconstructions indicates that our ecological concept should be valid back in time.

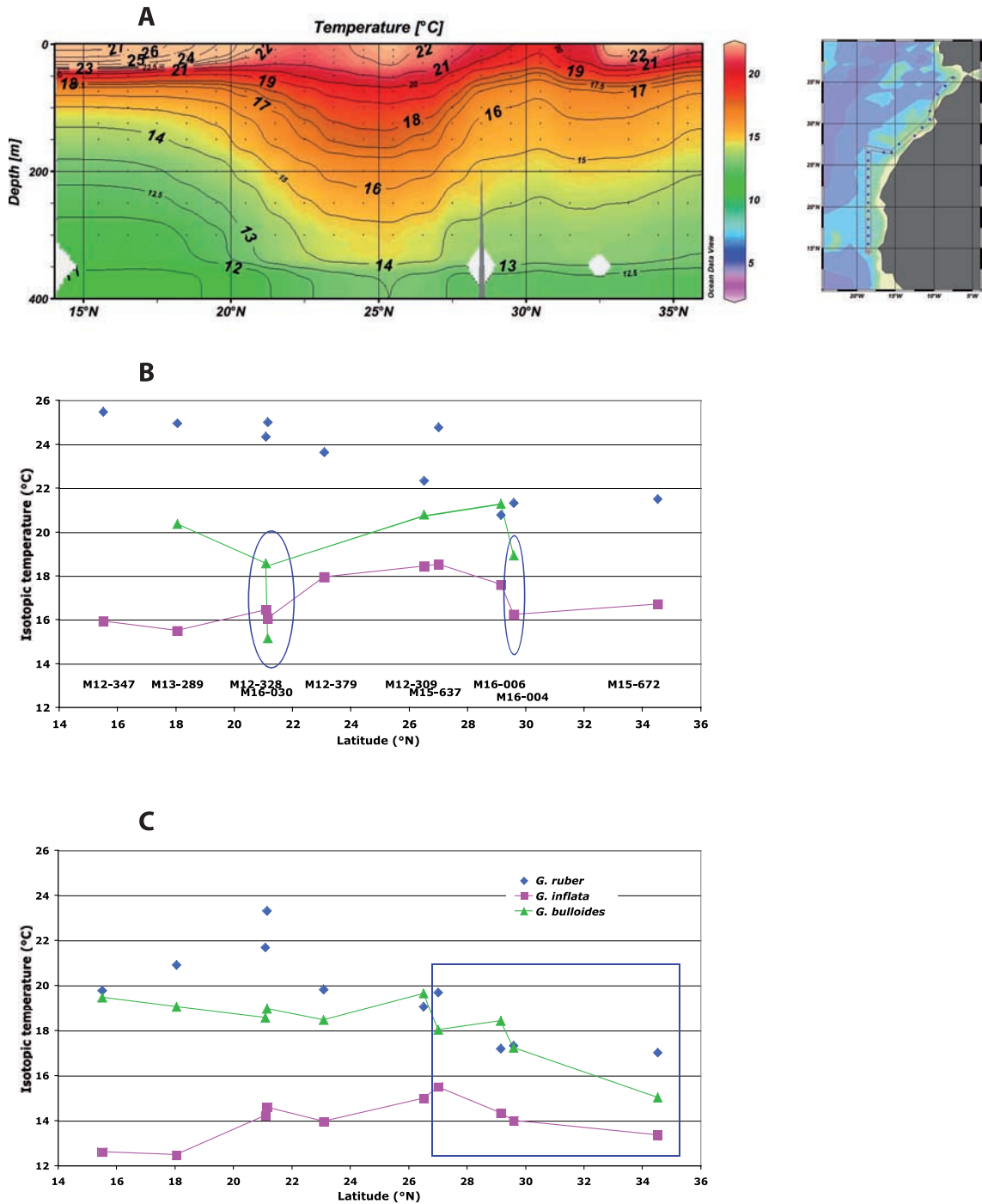


Figure 7. (a) Summer temperature versus depth for a section which passes through each core location (see map). (b) Holocene T_{iso} of *G. ruber* (blue), *G. bulloides* (green), and *G. inflata* (pink) in a latitudinal transect. (c) LGM T_{iso} for the same species. Blue circles and rectangle underline location of the main upwelling cells.

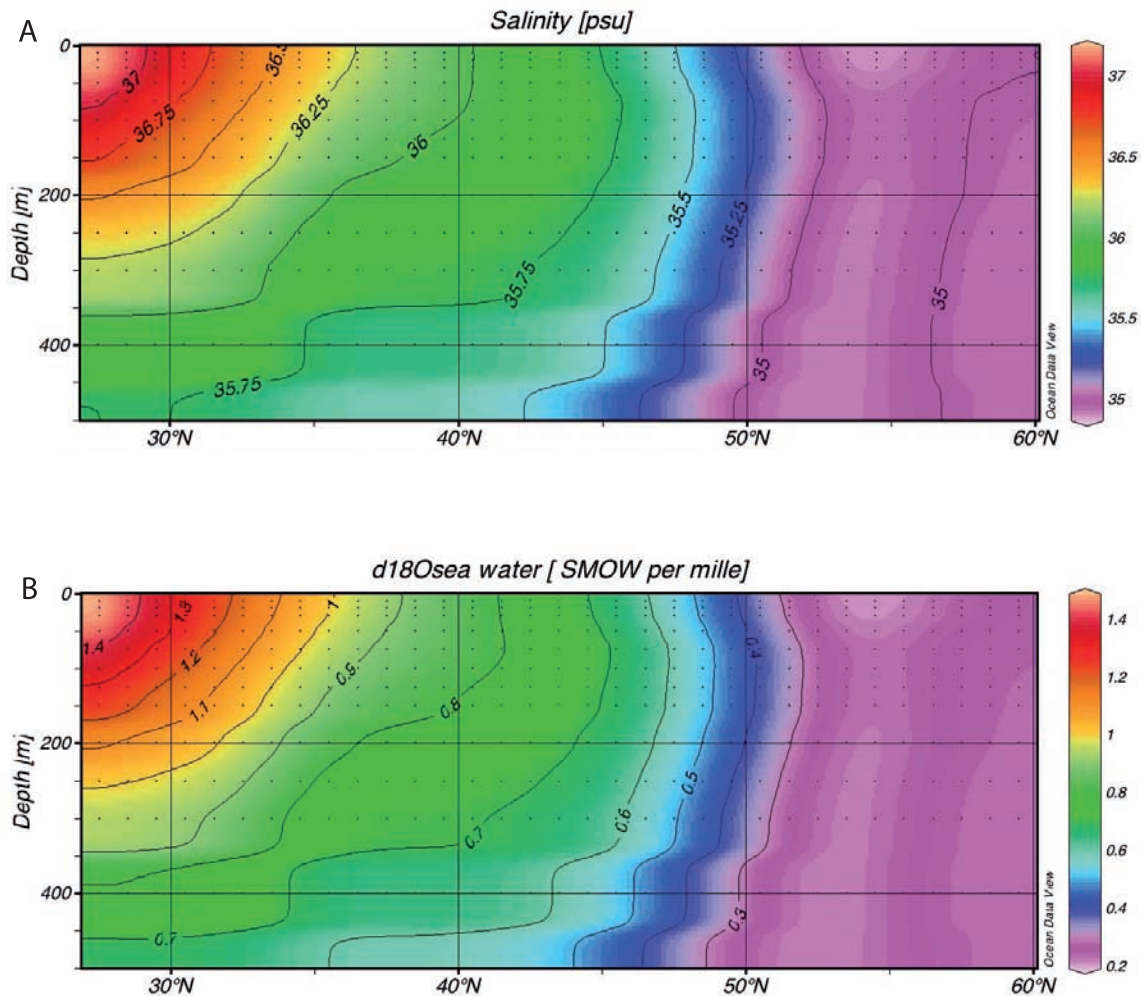


Figure A1. (a) Mean annual salinity and (b) corresponding oxygen isotopic composition of seawater along a 30°W section between 0 and 500 m depth.

Appendix A

[39] Figure A1 shows the decrease of water column stratification from low to high latitudes. North of 45°N, salinity and isotopic composition of seawater are constant through the first five hundred meters. At low latitude, maximum salinity (isotopic composition of seawater) change over this depth is 1.25 psu (0.7‰).

[40] Calcification depth of *G. inflata* in each core top is drawn in Figure A2. When the BST (base of the summer thermocline; see text) is colder than about 16°C, Tiso (isotopic temperature; see text) of *G. inflata* corresponds to the temperature at the BST (Figures A2a to A2u). When the BST is warmer than 16°C, Tiso of *G. inflata* indicates a deeper habitat, in the upper part of the main thermocline (Figures A2v to A2y).

[41] Figure A3 shows the calcification depth of *G. truncatulinoides* dextral and sinistral. They calcify in the lower part of the seasonal thermocline (Figures A3a to A3n) when the BST is colder than about 16°C. But when the BST is warmer than about 16°C, *G. truncatulinoides* lives deeper in the main thermocline (Figures A3o to A3t).

[42] Figure A4 shows that Tiso of *P. obliquiloculata* reflect those at the BST.

[43] Figure A5 shows the good resemblance between reconstructed Holocene summer profiles from Holocene Tiso of *G. ruber* and *G. inflata* and modern temperature profiles extracted from World Ocean Atlas (2001) for the cores along the NW African margin.



Figure A2. Comparison of the Tiso of *G. inflata* with modern temperatures. Blue (pink) line is the coldest winter (warmest summer) temperature profile from WOA 2001. Square represents the mean Tiso. Rectangle indicates the possible habitat depth according to one sigma range in Tiso resulting from replicate $\delta^{18}\text{O}_{\text{foraminifera}}$ measurements. (a) FI KR02, (b) FI KR07, (c) MD95-2014, (d) MD95-2005, (e) FI 139c, (f) FI KR11, (g) FI KR10, (h) FI KR12, (i) FII KR01, (j) MD95-2017, (k) MD95-2002, (l) MD95-2023, (m) MD95-2021, (n) MD95-2019, (o) SU90-37s, (p) SU90-03, (q) SU90-06, (r) SU90-08, (s) SU90-02, (t) MD95-2039, (u) MD95-2041, (v) INMD48, (w) INMD68, (x) INMD42, (y) INMD52.

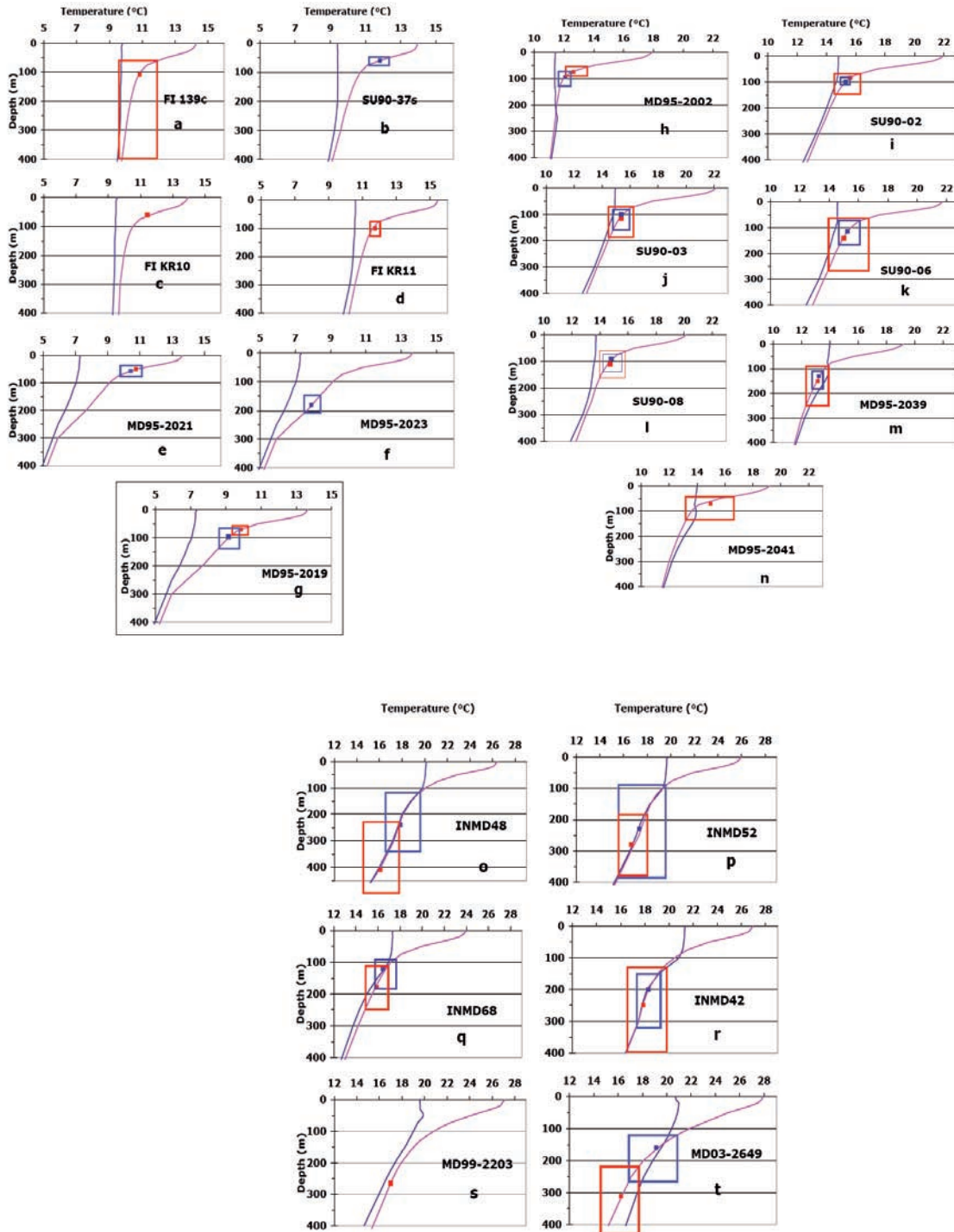


Figure A3. Comparison of Tiso of *G. truncatulinoides* with modern temperatures. Caption same as Figure A2. Red color is used *G. truncatulinoides* dextral data. Blue color is used for *G. truncatulinoides* sinistral data. When only one measurement was made no rectangle was drawn. (a) FI 139C, (b) SU90-37s, (c) FI KR10, (d) FI KR11, (e) MD95-2021, (f) MD95-2023, (g) MD95-2019, (h) MD95-2002, (i) SU90-02, (j) SU90-03, (k) SU90-06, (l) SU90-08, (m) MD95-2039, (n) MD95-2041, (o) INMD48, (p) INMD52, (q) INMD68, (r) INMD42, (s) MD99-2203, (t) MD03-2649.

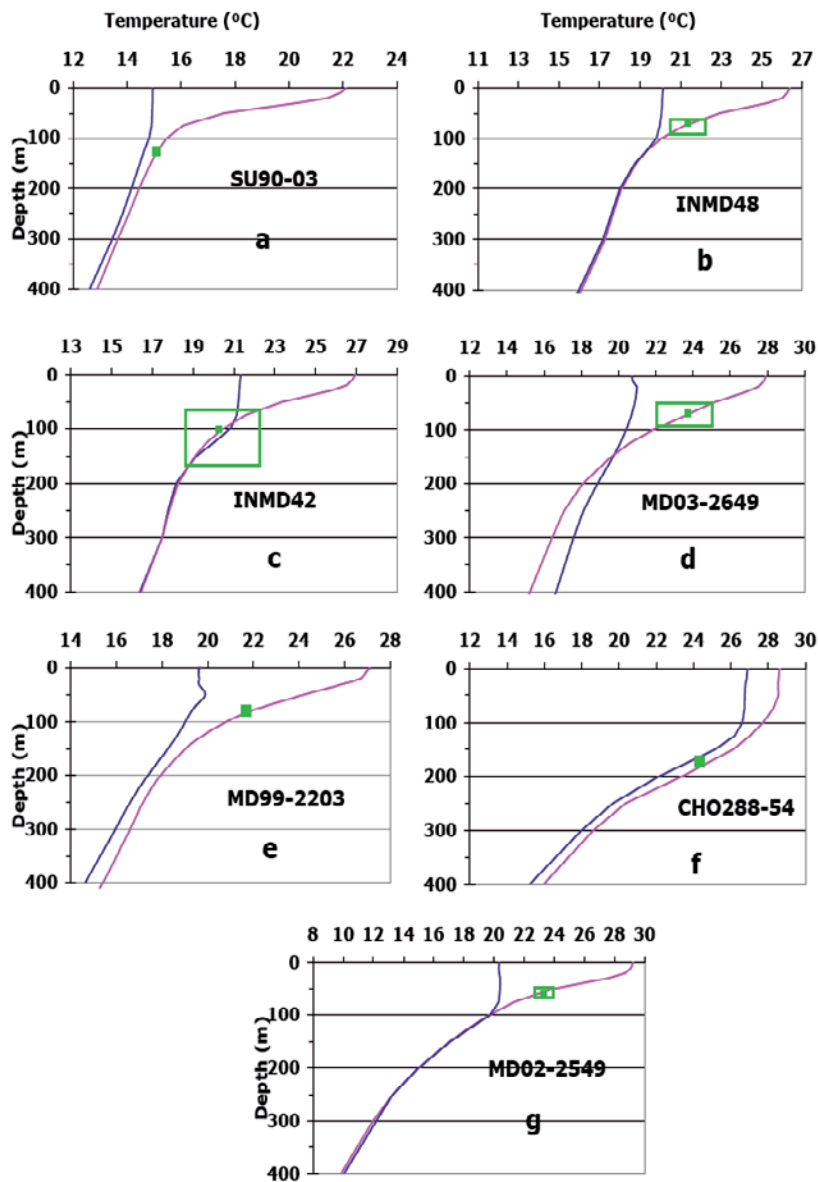


Figure A4. Comparison of Tiso of *P. obliquiloculata* with modern temperatures. Caption same as Figure A2. (a) SU90-06, (b) INMD48, (c) INMD42, (d) MD03-2649, (e) MD99-2203, (f) CHO288-54, (g) MD02-2549.

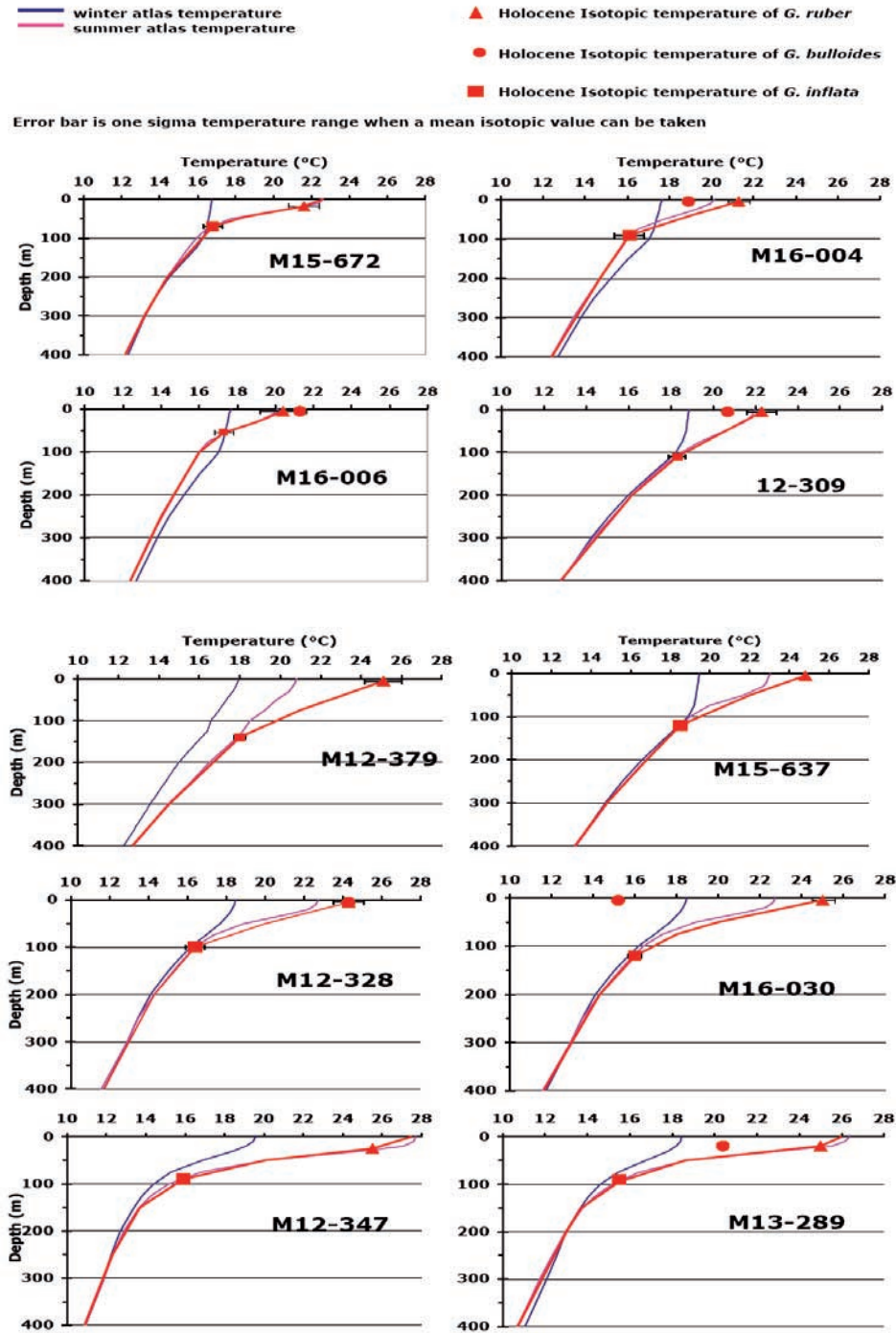


Figure A5. Comparison of Holocene Tiso of *G. ruber*, *G. bulloides* and *G. inflata* with modern temperature profiles for the cores along the NW African margin.

Acknowledgments

[44] The material for the calibration was taken during several oceanographic cruises, noticeably the IMAGES cruises. We thank IFREMER and IPEV for technical support and making the R/V available. We thank the Scripps Institution of Oceanography for providing the INMD samples and J. Duprat (EPOC-Bordeaux) for establishing the stratigraphy of many cores. We thank colleagues of LSCE, C. Waelbroeck, L. Labeyrie, and E. Michel, for careful reading and constructive remarks, and F. Dewilde and B. Le Coat for mass spectrometer analyses. C.C. is supported by a French Research Ministry fellowship. Basic support from CNRS and CEA to LSCE is acknowledged. ANR Forclim and PICC grants provided funds for this study.

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