

Tracking the Recent and late Pleistocene Azores front by the distribution of planktic foraminifers

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Abstract

South of the Azores Islands, the population dynamics and sedimentation of planktic foraminifers are significantly influenced by the hydrography of the Azores Front Current System (AFCS). Planktic foraminifers collected from the water column during seasonal cruises across the Azores Front, record the temporal and spatial scale of hydrographic and faunal dynamics within this area. Surface sediment analysis reveals the presence of a large number of pteropod shells indicating preservation of aragonite and, therefore, little alteration of the calcitic foraminiferal tests. Consequently, most of the seasonal and spatial variability of the Azores Front is expected to be recorded by the planktic foraminiferal assemblages present within the surface sediment. In particular, *Globorotalia scitula*, a subsurface-dwelling species, decreases significantly in abundance to the south of the Azores Front, and shows fine-scale changes at the glacial/interglacial time scale. Enhanced faunal proportions of *G. scitula* in a sediment core that is located to the south of the modern Azores Current indicate a southward shift of the Azores Front Current System during the glacials and the presence of a transitional water mass at the Azores region.

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1. Introduction

We analyse the impact of the Azores Current (AC) and associated Azores Front (AF) on the distribution of planktic foraminifers in surface sediments. As the southeastern branch of the Gulf Stream, the AC including the AF may be of vital importance in unravelling the Late Quaternary North Atlantic hydrography and

global thermohaline circulation. Modern planktic foraminifers mirror the hydrographic patterns of the Azores region on a fine scale (Schiebel et al., *in press*), and have a high fossilization potential in deep-sea sediments (Berger, 1971; Bé, 1977; Hemleben et al., 1989; Dittert et al., 1999). Changes in the planktic foraminiferal distribution are shown to be an appropriate paleoceanographic tool to examine the ancient AF and to record the persistence and position of the late Quaternary AC.

Today, as the northern branch of the Gulf Stream, the North Atlantic Current (NAC) transports heat towards the Arctic Ocean up to the Norwegian–Green-

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land Sea, and a wide region of transitional surface water masses exists between subpolar and subtropical waters. A major portion of deep-water formation in high latitudes, which drives the global thermohaline circulation, takes place in the North Atlantic Ocean (Stommel, 1958; Broecker, 1997; van Kreveld et al., 2000), and is strongly affected by the NAC.

During the last glacial maximum (LGM), polar to tropical planktic foraminiferal assemblages co-occurred in a zonal band around 35°–40°N, suggesting the absence of a North Atlantic Drift as it is developed today, but the presence of a well developed subpolar gyre (McIntyre et al., 1976). Polar waters were present down to latitudes of the Bay of Biscay (45°N) (McIntyre et al., 1976; Villanueva et al., 1998; Keffer et al., 1988; Van Kreveld-Alfane, 1996), and the northern North Atlantic was covered by ice-sheets at

least during winter (van Kreveld et al., 2000). Fresh surface waters (meltwater) did not allow significant deep-water formation (e.g., Sarinthein et al., 1995; Broecker, 1997; Curry and Oppo, 1997; Rosell-Melé et al., 1998; de Vernal et al., 2000), the Gulf Stream was significantly weaker than today, and transitional water masses were compressed to a narrow band between 37° and 45°N (Lynch-Stieglitz et al., 1999).

2. Material and methods

Hydrographical data (temperature and salinity) were recorded with a SEA-BIRD CTD (H. Meggers, Bremen University) to determine the position of the AF (Figs. 1 and 2). Data on the topography and structure of the seafloor (e.g., sediment thickness over the basaltic base-

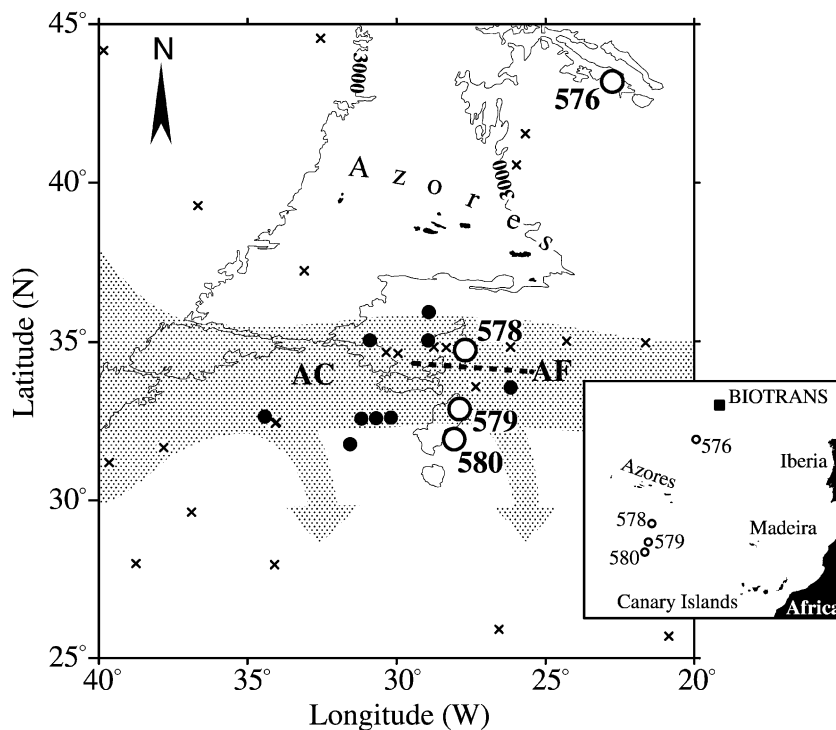


Fig. 1. Sediment samples (large circles) across the Azores Front Current System were obtained during October 1999. The water column (solid dots) was sampled during January 1999 and August 1997. The total range of the modern Azores Current (AC, shaded) is redrawn from Klein and Siedler (1989), and includes the range of the Azores Front (AF; Kåse and Siedler, 1982; Alves and de Verdière, 1999). During October 1999, the AF (hatched line) was located just south of station 578 (see Fig. 2). Additional samples from the Brown University Foraminiferal Data Base (Prell et al., 1999) are indicated by crosses (x). The Mid Atlantic Ridge, a major transform fault at 43–45°N, and large seamounts south of the Azores Islands are displayed by the 3000-m isobath (thin line). The outline map shows the position of the Azores area and the BIOTRANS site (solid square) relative to Iberia and northwestern Africa.

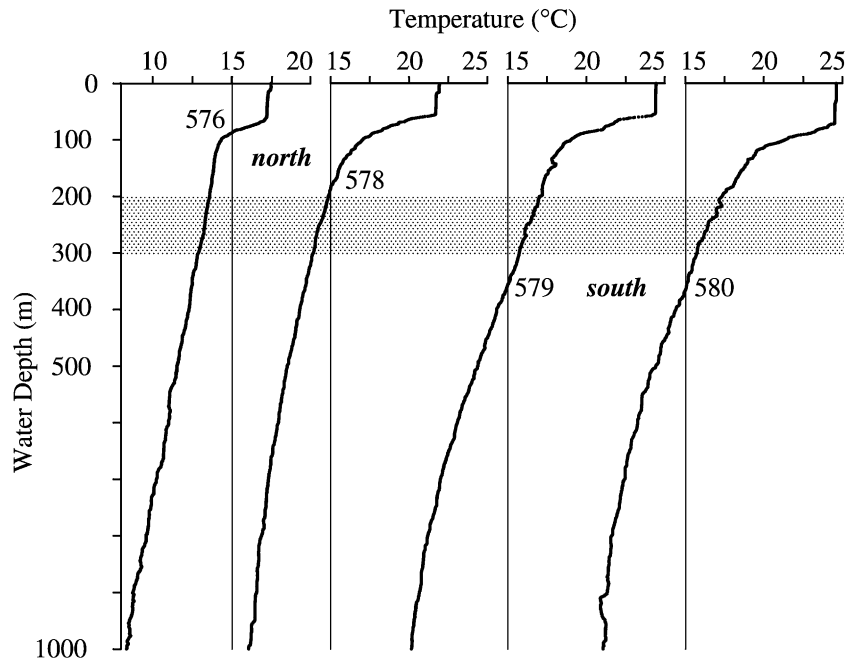


Fig. 2. Water temperature as recorded by CTD during October 1999 (H. Meggers, Bremen University, 2000). The vertical lines mark the 15 °C isotherm. According to the 15 °C criterion (Gould, 1985), sites 576 and 578 are located north of the AF (15 °C isotherm above 200 m), and sites 579 and 580 are located south of the AF (15 °C isotherm below 300 m). For detailed information on sites 576 to 580 see Table 1.

ment) were digitally acquired with the shipboard Parasound system (PARADIGMA) of RV Meteor.

Planktic foraminifers from the upper 500 m of the water column south of the Azores (Fig. 1) were sampled in August 1997 and January 1999 with a multinet device (50*50 cm opening, 5 cups, >100 µm mesh size). The samples were fixed in a 4% formaldehyde solution and buffered with hexamethyltetramine at pH 8.2, washed over 63-µm gauze, dried at 20 °C, sieved, and analyzed for the planktic foraminiferal fauna >125 µm (Schiebel et al., in press). For comparison, published planktic foraminiferal data from the Eastern North Atlantic Water (ENAW), at 47°N, 20°W (BIOTRANS) (Schiebel and Hemleben, 2000), are included in the analysis (Fig. 1).

Surface sediments were sampled with a multicorer device (MC; acrylic glass-tubes of 10 cm in diameter) during the RV Meteor cruise 45/5, in October 1999. Short cores were recovered from four sites, following a north-to-south transect across the Azores Front Current System (AFCS) (Table 1). To avoid sampling of sediments affected by thermodynamic dissolution of the

planktic foraminiferal test calcite, only locations above 3200-m water depth were selected, which is above the modern lysocline (~ 4500 m) in the northeast Atlantic Ocean along 35°N (e.g., Takahashi, 1975; Archer, 1996). This implies that the sampling sites are located at the flank of the Mid Atlantic Ridge, or its associated transform faults and seamounts (Fig. 1), which are areas of steep topography.

The surface sediment at the northern site 576 (Fig. 1) was a sticky, light-brownish silty to sandy clay. At

Table 1

Number, position and physical properties of the multicorer (MC) samples from the surface sediment (upper 0.5 cm) in October 1999

Site #	MC #	Water depth (m)	Latitude (N)	Longitude (W)	Wet volume (ml)	%Dry mass, >63 µm
576	608	3024	43°22.4'	22°29.2'	76.5	35
578	610	2060	34°46.8'	27°39.8'	20	73
579	611	3008	32°46.5'	27°59.4'	73	45
580	612	3143	31°36.7'	28°00.9'	65	46

the three stations to the south of the Azores Islands, the surface sediment was a planktic foraminiferal ooze, but a sticky clay occurred at depths below 6 cm. Pumice and basalt were present at all four sites and the sediment surface was covered with pteropod tests, indicating preservation of aragonite and, therefore, little alteration of the calcitic foraminiferal tests. Cores with undisturbed sediment surfaces were selected and cut into horizontal 0.5- and 1-cm slices above and below 2-cm core depth, respectively. At station 578, a distinct boundary between the bottom

water and the sediment surface could not be recognized, and a 2–3-mm-thick sediment-water suspension was included into the 0–0.5-cm surface sediment sample. Samples were fixed with an ethanol/Rose Bengal (two grams per liter) solution and stored in Polyethylene vessels. In the laboratory, the wet volume of the sediments was determined and samples were washed over a 63- μ m screen. Both the residue and the fine fraction were dried at 60 °C for 24 h and weighed. The larger residues were then dry sieved, split into manageable aliquots, and the size fraction

Table 2

Stable isotope data ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of sediment core GeoTü 90, site 580 (Fig. 1), and the relative faunal part of dominant species that have a significant distribution with regard to the modern AC and AF (Fig. 6)

Core Depth (cm)	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$ (PDB)	Isotope stage	<i>T. humilis</i>	<i>G. inflata</i>	<i>G. ruber</i> (white)	<i>G. scitula</i>	<i>G. trunc.</i> (sinistral)	<i>G. trunc.</i> (dextral)	<i>G. sacculifer</i>	<i>T. quinqueloba</i>
2	0.96	−0.06	1	10.4	3.2	21.4	4.3	3.9	3.2	4.3	0.4
10	0.84	0.11	1	6.9	6.2	14.6	2.3	3.5	0.4	4.6	0.4
20	0.68	1.15	2	2.7	9.1	9.0	12.5	1.9	3.9	0.4	1.0
30	0.92	0.94	3	2.0	6.7	6.7	11.4	2.4	2.4	3.5	3.9
40	1.04	0.86	3	2.8	3.6	11.3	8.9	1.6	5.6	0.4	1.6
50	0.70	1.09	4	1.6	7.1	10.4	8.8	0.8	2.5	0.3	1.4
60	0.83	0.91	5	3.2	11.1	15.4	8.6	5.2	1.1	0.7	0.5
70	0.95	0.66	5	0.8	8.3	7.5	7.3	3.9	3.6	0.8	2.8
80	1.00	0.47	5	2.1	7.5	13.3	4.6	4.1	3.7	1.2	0.8
90	0.55	0.39	5	0.6	7.8	12.5	4.5	4.1	7.0	0.8	1.6
100	0.67	0.41	5	1.7	1.2	13.0	5.1	2.4	2.6	0.3	2.7
110	0.57	0.36	5	1.6	1.9	14.0	2.7	2.3	1.6	0.8	2.7
120	0.49	0.02	5	—	5.6	13.6	3.6	6.8	2.4	4.0	2.8
130	0.52	−0.01	5	0.2	4.5	10.3	6.8	0.9	1.5	1.4	6.0
140	0.46	1.26	6	—	11.8	14.0	11.1	1.6	2.5	—	3.8
150	0.35	1.23	6	—	9.5	9.5	9.1	0.8	2.4	0.4	3.6
160	0.38	1.21	6	0.3	8.3	13.6	6.3	1.7	4.6	0.7	7.6
170	0.20	0.87	6	—	10.5	14.3	10.5	—	4.1	0.4	5.3
180	0.43	0.99	6	0.8	10.1	8.2	8.2	0.8	2.5	0.3	8.5
190	0.71	0.73	7	0.3	11.4	6.7	6.4	1.1	3.3	—	2.2
200	0.73	0.48	7	0.8	3.8	15.4	5.0	3.3	5.8	0.4	2.5
210	0.91	0.27	7	4.0	8.6	11.7	2.2	3.4	3.4	0.9	5.2
220	0.98	0.22	7	0.8	9.6	9.1	4.8	2.0	5.3	1.3	2.0
230	0.42	0.45	7	2.2	7.0	15.0	3.1	0.9	3.5	1.8	0.4
240	0.51	0.74	7	0.4	7.9	10.6	3.0	3.0	2.3	0.4	1.1
250	0.68	0.50	7	0.4	13.9	13.9	3.0	3.0	4.5	3.4	3.0
260	0.61	0.41	7	0.4	10.6	16.9	2.8	—	5.5	4.7	1.2
270	0.81	0.53	7	—	11.8	8.5	3.5	0.3	2.6	0.6	4.1
280	0.28	1.14	8	0.3	9.4	15.9	10.3	5.0	2.4	1.5	5.9
290	0.23	1.21	8	—	13.2	11.5	6.2	1.8	6.6	0.4	4.4
300	0.14	0.97	8	0.3	14.3	9.8	3.1	1.4	7.0	3.1	1.4
310	0.36	1.12	8	0.4	10.0	11.1	3.6	4.6	2.1	2.5	1.4
320	0.63	0.83	8	1.0	8.6	12.2	3.0	9.1	0.5	2.0	0.5
330	0.88	0.52	8	0.9	8.0	13.9	3.1	6.1	—	0.7	0.5

For the full species names see Table 4.

>125 μm was analyzed for planktic foraminifers to the species level according to the taxonomy of Hemleben et al. (1989). At least 350 planktic foraminiferal tests per sample were counted.

Sediment core GeoTü 90 was obtained during RV Meteor cruise 45/5 at site 580 (Table 1, Fig. 1) with a piston corer. The sediment is composed of a pale brown to yellowish brown foraminiferal and nano-plankton ooze, which is slightly stratified, and moderate to strongly bioturbated sections occur at depth of 90–150, 157–192, and 210–235 cm. The relative black-and-white reflectance was scanned at 2-cm spacing over the full core length of 502 cm. Samples for foraminiferal and stable isotope analysis were taken with a 10-ml syringe at 10-cm spacing. Samples were washed over a 63- μm screen, dried at 60

$^{\circ}\text{C}$, and dry sieved at 125 μm . The larger residue was split into manageable aliquots, and analyzed for the planktic foraminiferal fauna in the same way as the MC samples. In this paper, a planktic foraminiferal analysis of the upper 330 cm of GeoTü 90 is presented (Table 2). The stable isotopes $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ were measured on the planktic foraminiferal species *G. ruber* (white) at ETH-Zürich employing a MICROMASS PRISM mass spectrometer, with a long-term reproducibility of 0.1 ‰ ($\delta^{18}\text{O}$) and 0.08 ‰ ($\delta^{13}\text{C}$). The values are reported relative to the PEEDEE belemnite (PDB) scale. To compensate for the vital effect of *G. ruber* (white), 0.2 ‰ was added to each $\delta^{18}\text{O}$ value according to Deuser (1987).

An age model was constructed from the $\delta^{18}\text{O}$ record based on a graphic comparison with the stack

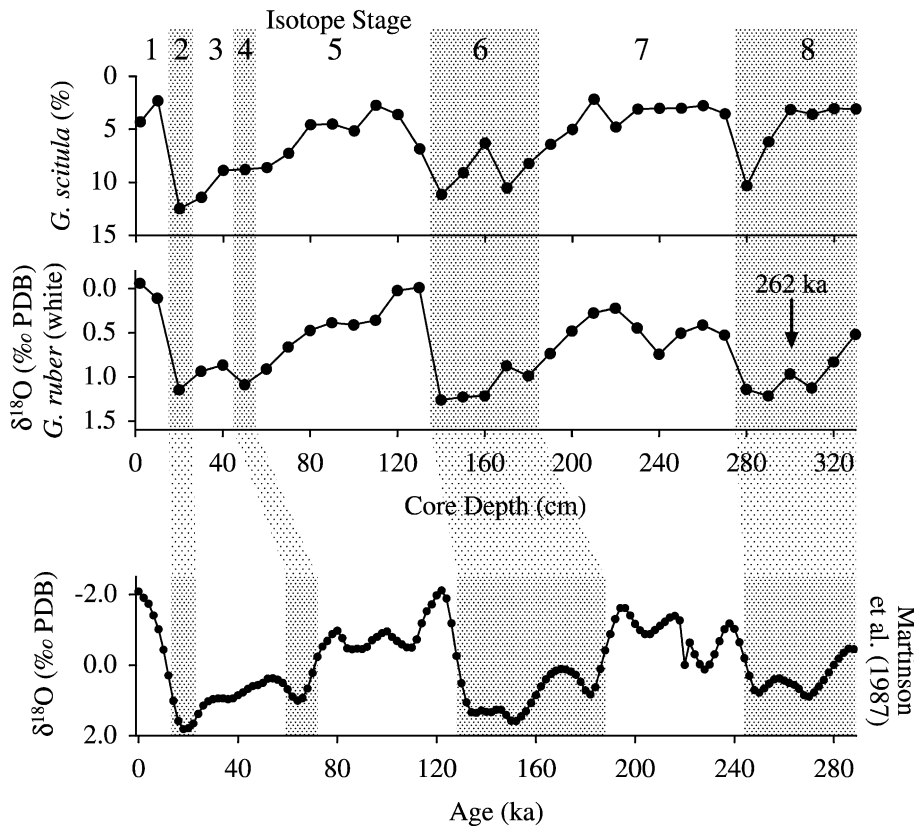


Fig. 3. The upper 330 cm of piston core GeoTü 90 (site 580; Fig. 1) include the last ~ 290 ka according to the comparison of the $\delta^{18}\text{O}$ value of *G. ruber* (white) with the Martinson et al. (1987) standard stack (lower panel). Isotope stages are given on top of the figure and the cold stages are indicated by shading. The downcore distribution of *G. scitula* (faunal %) is significantly impacted by the glacial/interglacial succession and resembles the main trends of the $\delta^{18}\text{O}$ curve. The end of the dominance interval of the coccoliths *Gephyrocapsa* spp. at 306-cm depth (arrow), 262 ka BP (Bollmann et al., 1998), is used as an independent time-control.

of Martinson et al. (1987) (Fig. 3). According to this age model, the average sedimentation rate at site 580 is $\sim 1.1 \text{ cm ka}^{-1}$. The age model is confirmed by a decrease in the black-and-white reflectance, from about 75% between 330–318-cm core depth to an average of 62% (max. 71.7%) above 316-cm depth, that indicates the interval of *Gephyrocapsa* spp. dominance that ends at 262 ka BP (Bollmann et al., 1998) (Fig. 3).

3. Hydrography

The Azores Front Current System (AFCS) is centered at 34°N south of the Azores Islands (Fig. 1). The eastward flowing AC is the southern branch of the

Gulf Stream, forms the northeastern boundary of the subtropical gyre, and is present throughout the year (Käse and Siedler, 1982; Klein and Siedler, 1989; Alves and Simões, 1997). The AC extends to water depths of at least 1000 m and is about 50-km wide (Gould, 1985; Alves and de Verdière, 1999). Southeast of the Azores Islands, the AC turns south (Sy, 1988). The AC is meandering and accompanied by eddies and cyclonic recirculation to the north and anti-cyclonic recirculation to the south (Gould, 1985; Käse and Siedler, 1982; Pingree, 1997; Pingree and Sinha, 1998). Regional upwelling and downwelling is common (McClain and Firestone, 1993; Alves and de Verdière, 1999). The AF separates the 18°C Subtropical Mode Waters from the colder and fresher water masses of the transitional to subpolar zone. During

Table 3

Composition of the planktic foraminiferal fauna (faunal %) in the upper 500 m of the water column, at the northern, central, and southern Azores Front (AF), during January 1999, and August 1997 refer to Schiebel et al. (in press)

Taxa	January central AF	January southern AF	August northern AF	August southern AF	Annual BIOTRANS
<i>D. anfracta</i>	<0.1	0.1	–	1.2	–
<i>G. bulloides</i>	4.2	3.0	3.1	11.4	15.7
<i>G. conglobatus</i>	–	–	–	3.1	–
<i>N. dutertrei</i>	0.1	0.3	0.8	0.3	<0.1
<i>G. falconensis</i>	7.2	1.7	–	0.7	0.8
<i>G. glutinata</i>	3.6	6.7	12.8	13.6	12.9
<i>G. hirsuta</i>	0.4	0.9	–	–	0.6
<i>T. humilis</i>	6.3	6.0	–	–	<0.1
<i>N. incompta</i>	2.2	0.3	1.1	3.3	32.7
<i>G. inflata</i>	<0.1	0.1	<0.1	–	6.6
<i>N. pachyderma</i> (sin)	0.8	0.1	0.1	–	–
<i>T. parkerae</i>	0.2	0.7	2.4	6.5	–
<i>H. pelagica</i>	–	0.2	4.3	0.2	<0.1
<i>T. quinqueloba</i>	0.7	0.1	2.3	4.2	8.4
<i>G. ruber</i> (pink)	0.2	<0.1	14.3	0.6	–
<i>G. ruber</i> (white)	2.8	2.0	21.6	30.4	1.2
<i>G. rubescens</i>	0.3	0.2	1.5	3.7	–
<i>G. sacculifer</i>	2.9	0.8	12.3	5.5	1.6
<i>G. scitula</i>	0.2	0.2	4.2	1.9	5.9
<i>G. siphonifera</i>	3.4	6.1	2.1	1.0	8.9
<i>G. tenella</i>	2.9	1.7	13.1	5.5	<0.1
<i>G. truncatulinoides</i> (dex)	58.2	65.2	–	–	–
<i>G. truncatulinoides</i> (sin)	1.8	2.2	–	–	–
<i>G. truncatulinoides</i> (total)	–	–	0.5	0.5	–
<i>O. universa</i>	<0.1	<0.1	0.7	1.4	3.4
Others	1.5	1.4	3.5	5.1	1.1
Planktic foraminifers	37.0	30.8	12.7	7.2	85.0

Data on the average faunal composition at BIOTRANS (47°N , 20°W) refer to Schiebel and Hemleben (2000). The species are arranged in alphabetical order. Numbers on planktic foraminifers (last row) are specimens per m^3 of sampled sea water.

winter, the AF is shielded from the direct influence of atmospheric effects by the mixed layer, while in summer the AF is capped by an intense seasonal thermocline. Thus, the frontal structure is most distinct below the thermocline at a depth of about 100 m (Stramma and Müller, 1989; Rios et al., 1992; Alves, 1996).

The position of the AF corresponds to the area of strongest dipping isotherms and can be deduced from the depth of the 15 °C isotherm. According to Gould (1985), a 15 °C isotherm shallower than 200 m characterizes waters north of the front. At the central front, the 15 °C isotherm ranges between 200- and 300-m depth. South of the front, the 15 °C isotherm is below 300 m. Applying the 15 °C criterion, the AF was located between site 578 and 579 during our October 1999 campaign (Figs. 1

and 2). The thickness of the mixed layer (MLD) ranged between 50 and 60 m. The surface water temperature at the northern site 576 was 17.5 °C, typical of ENAW coming from the Bay of Biscay (Emery and Meincke, 1986; Pollard et al., 1996). The surface water temperature south of the Azores (site 578 and 580) was >24 °C.

4. Results

4.1. Distribution of planktic foraminifers in the water column

Based on the annual average obtained at BIO-TRANS (Fig. 1), the living planktic foraminiferal fauna of the ENAW to the north of the Azores Islands

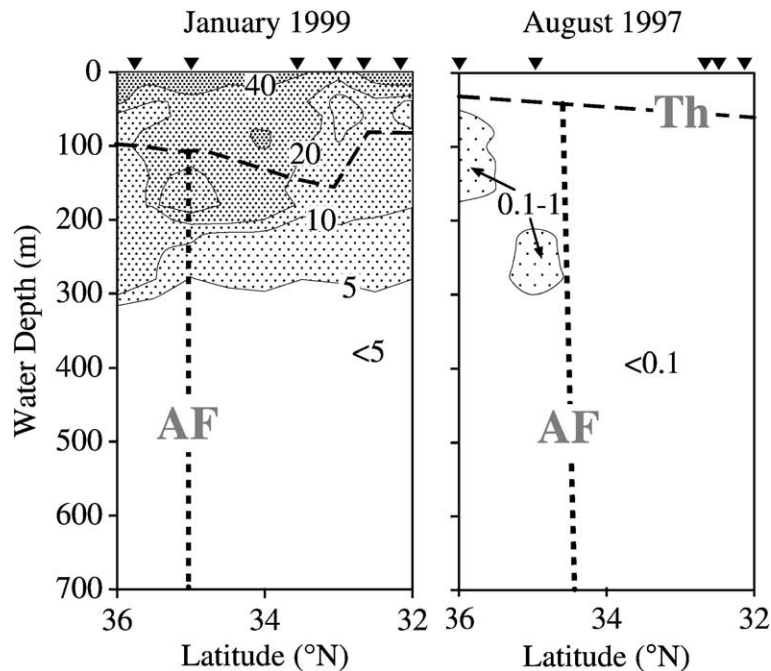


Fig. 4. Distribution of *G. truncatulinoides* (specimens per m^{-3} , given by isolines and shading) south of the Azores Islands during January 1999 (left panel) and August 1997 (right panel). During January 1999, a subsurface maximum of >40 specimens m^{-3} (97% *G. truncatulinoides* sinistral) occurred in 60–100-m water depth within the main jet of the AC (cf. Alves and Simões, 1997; Alves and de Verdière, 1999). Concentrations of more than 40 specimens per m^{-3} occurred also in the upper 20 m of the water column. In August 1997, *G. truncatulinoides* numbers were comparatively low (<1 spec. m^{-3}) and restricted to north of 34°N, which was to the north of the AF (vertical hatched line). The thermocline (Th) and the Azores Front (AF) are indicated by the horizontal and vertical hatched lines, respectively. The positions of the sampling locations are marked by the black triangles on top of the panels. Faunal data are integrated for 20-m intervals and 0.5° latitude, and interpolated for quadrants.

is dominated by *N. incompta*, *G. bulloides*, and *G. glutinata* (Table 3). Although these species are also frequent to the south of the Azores, the southern fauna is dominated by *G. ruber* (white) during August 1997, and *G. truncatulinoides* (dextral) during January 1999. *Globorotalia truncatulinoides* (dex) was most abundant in the upper 40 m and frequent down to a depth of 200 m across the AF during January 1999, with a subsurface maximum at a depth of 60–100 m to the south of the AF (Fig. 4). The distribution of *G. truncatulinoides* (dex) contrasted with the total planktic foraminiferal and *G. falconensis* abundances, which were higher in the central AF than south of the AF (Table 3). In general, during January 1999, the planktic foraminiferal fauna was largely similar

throughout the Azores region and focussed on the upper 150 m of the water column.

In August 1997, *G. truncatulinoides* was rare. The faunal composition and the specific depth habitats were much more diverse and spread over a depth range of several hundred meters (Fig. 5), while the planktic foraminiferal standing stock was three to four times lower than in January 1999. During August, the planktic foraminiferal standing stock to the north of the AF was almost double that to the south, and significant differences in the faunal portion of many species were recognized across the AF (Table 3). In particular, *Globorotalia scitula* and *Globigerinoides sacculifer* were more abundant to the north than to the south of the AF.

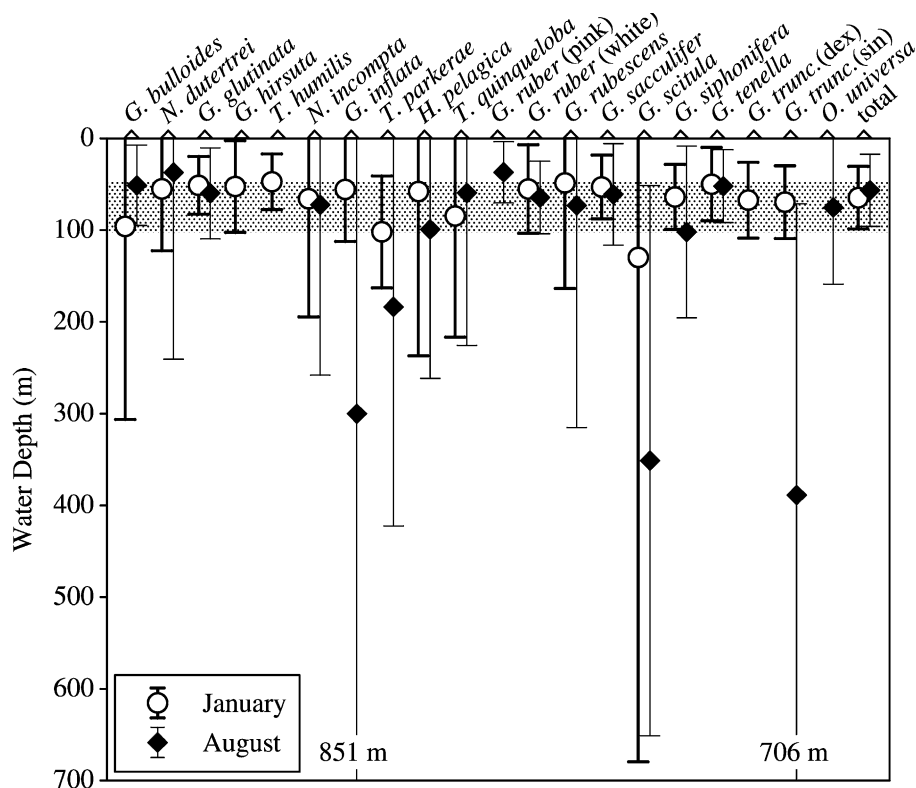


Fig. 5. During January 1999 most of the planktic foraminiferal species were living between ca. 40- and 100-m depth (shaded) in the Azores Front Current System (circles; the standard deviation is given as a solid line). In contrast, during August 1997, the specific depth habitats were much more diverse (black diamonds; the standard deviation is given as a thin line). Right (dex) and left (sin) coiling *G. truncatulinoides* were discriminated only during January; during August *G. truncatulinoides* were rare and dominated by left coiling specimens. Only species with an average abundance of >0.1 specimens m^{-3} are displayed. The average total planktic foraminiferal habitat was similar during January and August, indicating that the fauna is dominated by shallow dwelling species throughout.

4.2. Distribution of planktic foraminifers in the surface sediment

The planktic foraminiferal fauna of the surface sediment at the northern site 576 was dominated by *N. incompta*, *G. inflata*, *Turborotalita quinqueloba*, *G. scitula*, *G. bulloides*, and *G. glutinata* (Table 4). The latter two of these species were also frequent across the AF region to the south of the Azores islands. However, the faunal composition in surface sediments to the south of the Azores differs from that to the north of the Azores. To the south of the Azores, at the sites 578, 579, and 580 (Fig. 1), *G. ruber* (white) was frequent throughout (Table 4). In contrast, *G. scitula* was frequent only at the two sites, 578 and 579, yet its abundance declined significantly to the southern site 580 (Fig. 6). *G.*

sacculifer, *G. falconensis*, and *Turborotalita humilis* were most frequent at the central site 579. *T. quinqueloba*, *G. inflata*, and *G. truncatulinoides* (dex) decreased in relative frequency from the north to the south of the AF region, along with a decrease of the absolute number of tests per gram of dry sediment (Table 4). *Globorotalia truncatulinoides* (sin) increased in its faunal portion from north to south, and the ratio between left (sinistral) and right (dextral) coiled *G. truncatulinoides* changed from about 1:5 to 2:1, respectively.

4.3. Distribution of planktic foraminifers in the late quaternary

G. scitula is one of the most significant planktic foraminiferal species in terms of its changing frequency

Table 4

Composition (faunal %) of the planktic foraminiferal fauna (>125 µm) in the surface sediment (0–0.5 cm) across the Azores Front (Table 1 and Fig. 1), and total planktic foraminiferal numbers per gram of dry surface sediment

Taxa	Site			
	576	578	579	580
<i>Dentagloborotalia anfracta</i>	–	0.5	–	–
<i>Globigerina bulloides</i>	16.4	31.5	16.7	24.3
<i>Globigerinoides conglobatus</i>	–	0.2	2.9	1.0
<i>Neogloboquadrina dutertrei</i>	4.7	7.6	–	1.3
<i>Globigerina falconensis</i>	2.1	2.7	6.2	1.6
<i>Globigerinita glutinata</i>	12.2	5.7	21.6	19.8
<i>Globorotalia hirsuta</i>	2.5	1.5	1.1	1.9
<i>Turborotalita humilis</i>	1.3	3.5	11.8	7.2
<i>Neogloboquadrina incompta</i>	13.2	0.1	1.2	–
<i>Globorotalia inflata</i>	13.2	5.8	3.2	2.4
<i>Neogloboquadrina pachyderma</i> (sin)	3.0	2.1	–	2.5
<i>Hastigerina pelagica</i>	–	0.02	–	–
<i>Turborotalita quinqueloba</i>	8.4	1.9	0.8	0.5
<i>Globigerinoides ruber</i> (pink)	0.1	0.4	–	0.2
<i>Globigerinoides ruber</i> (white)	1.8	16.7	12.2	17.9
<i>Globoturborotalita rubescens</i>	0.3	–	–	0.8
<i>Globigerinoides sacculifer</i>	1.6	2.3	3.8	1.8
<i>Globorotalia scitula</i>	8.4	7.7	8.2	2.8
<i>Globigerinella siphonifera</i>	1.7	1.5	3.4	2.3
<i>Globoturborotalita tenella</i>	1.6	0.5	0.3	3.6
<i>Globorotalia truncatulinoides</i> (dex)	5.2	3.2	1.5	2.1
<i>Globorotalia truncatulinoides</i> (sin)	0.9	2.8	3.8	4.4
<i>Orbulina universa</i>	1.2	0.4	0.5	0.5
Others	0.1	1.5	1.1	1.1
Total planktic foraminifers	17 625	43 041	31 816	29 151

The species are arranged in alphabetical order.

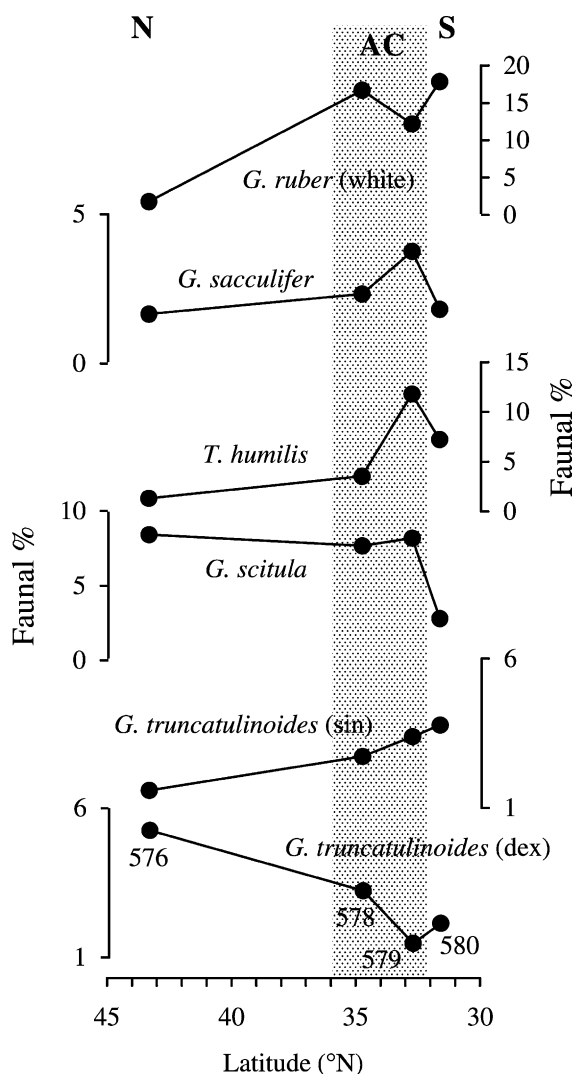


Fig. 6. Distribution of the most significant planktic foraminiferal species (relative faunal part) with regard to their distribution in surface sediments across the Azores Current (AC), from the north (N) to the south (S) of the Azores region (Fig. 1). The species are arranged according to their average depth habitat within the water column, with the shallow-dwelling species on top and the deep-dwelling species at the bottom of the figure.

across the AC and AF (Table 4, Fig. 6), and shows pronounced changes in its contribution downcore GeoTü 90, with the highest frequency during glacial stages 2, 6, and 8, and the lowest abundance during the interglacial stages 1, 5, and 7 (Table 2, Fig. 3). *T. humilis* was rare (<3%) during most of the Pleistocene,

with only a subordinate maximum during stage 7, and a significant increase during stage 1 towards the Recent. An increase in relative abundance during stage 1 is also evident in *G. ruber* (white), but no distinct shifts occur during the Pleistocene. Highest numbers of *G. sacculifer* (around 4%) occur during stages 1, 3, early stage 5, and early stage 7. In contrast, *T. quinqueloba* was most frequent during stages 6 and 8. The average abundance of *G. inflata* increases downcore, while this species seems to be more abundant during glacial than during interglacial stages (Table 2). For the distribution of *G. truncatulinoides* (sinistral and dextral) no significant trends or peaks can be referred.

5. Discussion

5.1. Planktic foraminifers in the water column

The large-scale pattern of the distribution and composition of planktic foraminiferal assemblages in the eastern North Atlantic reflects different water masses, the Subtropical Mode Waters of the eastern subtropical gyre and the temperate water masses (ENAW) to its north (e.g., Talley, 1999). The ENAW hosts a temperate planktic foraminiferal fauna at both northern locations considered in this study, BIOTRANS and 576 (Bé and Tolderlund, 1971; Bé, 1977; Schiebel et al., 1995, 2001; Schiebel and Hemleben, 2000). The ENAW fauna, although highly variable, is distinctly different from the fauna obtained from the AFCS (Table 3). Ottens (1991) and Ottens and Nederbragt (1992) report a change in planktic foraminiferal assemblages at the AF, and, in addition, subdivide the transitional ENAW fauna at about 44°N. However, on a smaller scale, the planktic foraminiferal fauna also changes within the AFCS across the AF (Table 3). As the frontal character is most pronounced below the thermocline, mainly deep-dwelling species are affected in their distribution. In particular, *G. scitula* has been found to be typical of water masses north of the AF and below the thermocline, and occurs only sporadically within the mixed layer and south of the AF (Schiebel et al., in press). Shallow living species, which comprise most of the planktic foraminiferal fauna, have a different relationship to the AF than deep living species, and are more closely related to the surface 18 °C Mode Water. The changes in the shallow living fauna are displayed by

higher standing stocks in the north compared to the south of the AF (Table 3). This likely results from changing food availability in the different water masses, as indicated by the sea surface chlorophyll concentrations (cf. Antoine et al., 1996). The Azores Frontal Zone is an oligotrophic region, with slightly more productive waters to the north, as already deduced from macroplankton and micronekton faunas (Fasham et al., 1985; Angel, 1989).

In January 1999 even 'deep dwelling' species such as *G. inflata* and *G. truncatulinoides* (Hemleben et al., 1985, 1989) were most frequent in the upper 200 m of the water column (Fig. 5). The distribution of *G. truncatulinoides* closely mirrored the main jet of the AC (cf. Alves and de Verdière, 1999) with a concentration of >20 specimens m^{-3} (Fig. 4). Therefore, we assume that *G. truncatulinoides* is transported by the AC into the Azores region (cf. Weyl, 1978). This is in contradiction to the assumption of local reproduction (Lohmann and Schweitzer, 1990). Strong evidence for current-transported *G. truncatulinoides* comes also from the eastern Caribbean Sea, where specimens are injected from the Sargasso Sea through the Anegada and Mona Passages into the Venezuela Basin (Schmuker, 2000). This could make *G. truncatulinoides* an appropriate tool to reconstruct subsurface currents within the tropical to transitional oceans.

5.2. Planktic foraminifers in surface sediments

The large-scale planktic foraminiferal distribution in surface sediments of the North Atlantic has been extensively studied (e.g., Schott, 1935; Ericson et al., 1954; Kipp, 1976; Pflaumann et al., 1996; Prell et al., 1999). As with faunal compositions in the water column, the planktic foraminiferal assemblages in surface sediments differ from north and south of the Azores Islands (Table 4, Fig. 6). In general, the correlation between the depth habitat of living planktic foraminifers (Fig. 5) and their distribution across the AF (Table 3) is also displayed in the surface sediments (Fig. 6). The shallow dwelling species *G. ruber* (white) is abundant in surface sediments across the AF (Prell et al., 1999), with only a slight decline at central site 579. Other shallow-dwelling species which have been found to dwell in the subsurface waters, such as *G. sacculifer* and *G. falconensis*, are most frequent in the

surface sediment at the central site 579 and may have been imported from western waters by the AC. Intermediate to deep-dwelling species *G. scitula* and *G. truncatulinoides* are confined in their distribution by the AF (Fig. 6). Ubiquitous species like *G. bulloides* and *G. glutinata*, although of high ecological significance, yield little information on the position of the AF (Table 4).

In the North Atlantic, the northern limit of the modern occurrence of *G. truncatulinoides* is at about 60°N (Prell et al., 1999). Major faunal portions of *G. truncatulinoides* occur along the northern edge of the subtropical gyre in the Sargasso Sea and south of the Azores Islands (Bé, 1977; Pujol, 1980). The abundance of *G. truncatulinoides* (dextral) decreases to the south of the AF, while its sinistral variety increases (Fig. 6). However, the pronounced seasonal changes in the regional distribution and water depth range of *G. truncatulinoides* (Table 3, Figs. 4 and 5), in addition to displacement of specimens by currents and mixing processes (Berger, 1971) within the AF region, make it difficult to interpret the distribution of this species within the surface sediment with respect to the position of the AC (Fig. 6). Although the coiling direction of *G. truncatulinoides* (ratio of dextrally vs. sinistrally coiled specimens) allows to distinguish between water masses on a large scale (Ericson et al., 1954), this method is not suited to reconstruct the position of the AC on a regional scale (1–2° latitude) as it is done here. Stable oxygen isotope ratios ($\delta^{18}O$) yield further information about the population dynamics of *G. truncatulinoides* (cf. Deuser et al., 1981; Durazzi, 1981; Hemleben et al., 1985; Mulitza et al., 1997; 1998), and may help to unravel the position of the late Quaternary AC.

G. scitula is a deep-dwelling cosmopolitan species which is most frequent in the temperate regions of the world oceans (Frerichs, 1971; Bé, 1977; Bé and Hutson, 1977; Hemleben et al., 1989). In the surface sediments of the North Atlantic, *G. scitula* reaches its maximum abundance in the Azores region to the north of the AF (Fig. 6; cf. Prell et al., 1999). A similar distribution has been observed across the Kuroshio Oyashio-boundary, where *G. scitula* is restricted to the colder and more nutrient rich Oyashio side of the water mass boundary (Bradshaw, 1959). As its high frequency is restricted to sediments to the north and below the modern AC (Figs. 1 and 6), changes in *G.*

scitula abundance can be used as an indicator of the AF position.

T. humilis changes its life habitat on an ontogenetic term between the surface ocean and the deeper water column (Hemleben et al., 1989). This habit is typical for deep-dwelling species (e.g., *G. truncatulinoides*) and makes it rather difficult to assign this species to a particular hydrographic regime. However, *T. humilis* shows the same distribution pattern as the subtropical to tropical species *G. sacculifer* and *G. falconensis* (Bé, 1977) and is possibly carried by the Gulf Stream and AC from the Sargasso Sea into the Azores region (cf. Ruddiman, 1968). Hence, the maximum occurrence of these species is assumed to follow the main jet of the AC.

5.3. Planktic foraminifers in the late quaternary

Differential fluctuations of planktic foraminiferal species at site 580 (Fig. 1) during the late Quaternary (since ~ 290 ka BP) allow a first discussion of the persistence of the Azores Front Current System. Despite a low sedimentation rate (~ 1.1 cm ka $^{-1}$) and a rather low sampling resolution of $\sim 11,000$ years, the most significant trends and peaks in the planktic foraminiferal distribution may be assigned to climatic changes. The studied site is located just to the south of the modern Azores Current, and changes in the fossil fauna point towards a southward shift of the AFCS during glacial times. This is demonstrated in particular by an increase in the relative abundance of *G. scitula* (Figs. 3 and 6), which nowadays is found only in water masses to the north (ENAW). This may imply that a transitional water mass similar to the ENAW was present in the Azores region during glacial times, despite a significant southward shift of the polar front and a compressed circulation pattern in the glacial North Atlantic (McIntyre et al., 1976). In contrast, the frequency of *G. sacculifer*, *G. ruber* (white), and *T. humilis* (Fig. 6), species that are delivered by the AC, was highest during interglacial times at site 580, indicating a stronger and more southern AC during interglacial compared to glacial times (cf. Duplessy, 1999). However, to decipher the ancient AFCS, the geographical coverage of core investigation should be extended to the south of site 580 (Fig. 1), and a higher stratigraphical resolution is needed. Unfortu-

nately, cores with a distinctly higher sedimentation rate than that studied here (~ 1.1 cm kyear $^{-1}$), are not available from this region to date. Future investigations will concentrate on high-resolution studies on the present core material.

6. Conclusions

The seasonal and regional distribution of living planktic foraminifers displays the general hydrographic structure of the modern Azores Front Current System. During winter, the Azores Current transports high numbers of *G. truncatulinoides* and *T. humilis* across the Azores region within the surface water. During summer, the shallow dwelling foraminiferal fauna is dominated by *G. ruber* (white), and *G. sacculifer* marks the main jet of the Azores Current. Because the Azores Front is most pronounced below the thermocline, it affects mainly deep-dwelling species such as *G. scitula*, which is abundant only to the north of the Azores Front.

In the surface-sediment, *G. scitula* is significantly more frequent to the north of the Azores Front than to its south. The co-occurrence of *G. sacculifer*, *G. truncatulinoides*, and *T. humilis*, delineates the Azores Current and displays a distinct seasonality.

Over the last ~ 290 ka, increased numbers of *G. scitula* in the faunal assemblage indicate a southward shift of the Azores Front during glacial times and the presence of transitional water masses south of the Azores islands. Decreased numbers of *G. sacculifer*, *G. ruber* (white), and *T. humilis* occurring at the same time may be explained by a southward shift and a weakening of the Azores Current. A more detailed study of the ancient Azores Front Current System, both in terms of geographic expansion and stratigraphic resolution, will lead to better understanding of glacial/interglacial changes in North Atlantic circulation.

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