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The Azores Front since the Last Glacial Maximum

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Abstract

The spatial distribution of warm surface water in the Atlantic Ocean reflects the state of the thermohaline circulation. The Azores Current/Front, which is a recirculation of the Gulf Stream, marks the northeastern boundary of the North Atlantic subtropical gyre. Its position is therefore diagnostic of the width of the Atlantic warm water sphere. Here we report high resolution stable isotope and faunal abundance records of planktonic foraminifera in a sediment core from the Gulf of Cadiz (southwest Spain) which reflects shifting of the Azores Front since the Last Glacial Maximum (LGM). Today, the Azores Front does not penetrate into the Gulf of Cadiz, even though the front resides at the same latitude as the Gulf of Cadiz in the Atlantic. Our results indicate that the Azores Front is a robust feature of the Atlantic surface circulation, and that is present both in interglacial times and during the LGM at roughly the same latitude. However, during the LGM prior to 16 ka BP and during the Younger Dryas, the Azores Front did penetrate eastward into the Gulf of Cadiz.

Keywords: Palaeoceanography; foraminifera; Stable isotopes; Azores Front; Last Glacial Maximum

1. Introduction

Close to the Azores Islands lies the Azores Front (AF) (see Fig. 1). It marks the boundary between the European and African surface water masses [1,2] and extends across the Atlantic between latitudes of 30° and 40°N from the Newfoundland GrandBanks to the coast of Morocco [1]. South of the Azores, the AF coincides with the Azores Current, a strong eastward flow that is generated by water mass transformation in the Gulf of Cadiz (GoC), southwest of Spain [3]. The AF marks a zone of strong hydrographic transition, in terms of both temperature (~ 4 °C) [1] and water column structure [4], and it is characterised by locally intense upwelling [5,6].

The plankton assemblage changes substantially across the AF, particularly below the seasonal thermocline, as a result of higher overall productivity and a deeper Deep Chlorophyll Maximum north of the front [2,4,7,8]. The local thermal and ecological signature of the AF/AC close to the Azores Islands allows evidence of its past behaviour to be preserved in the sediment record. The AC/AF is strongest in the spring [6] and shows random variability in strength

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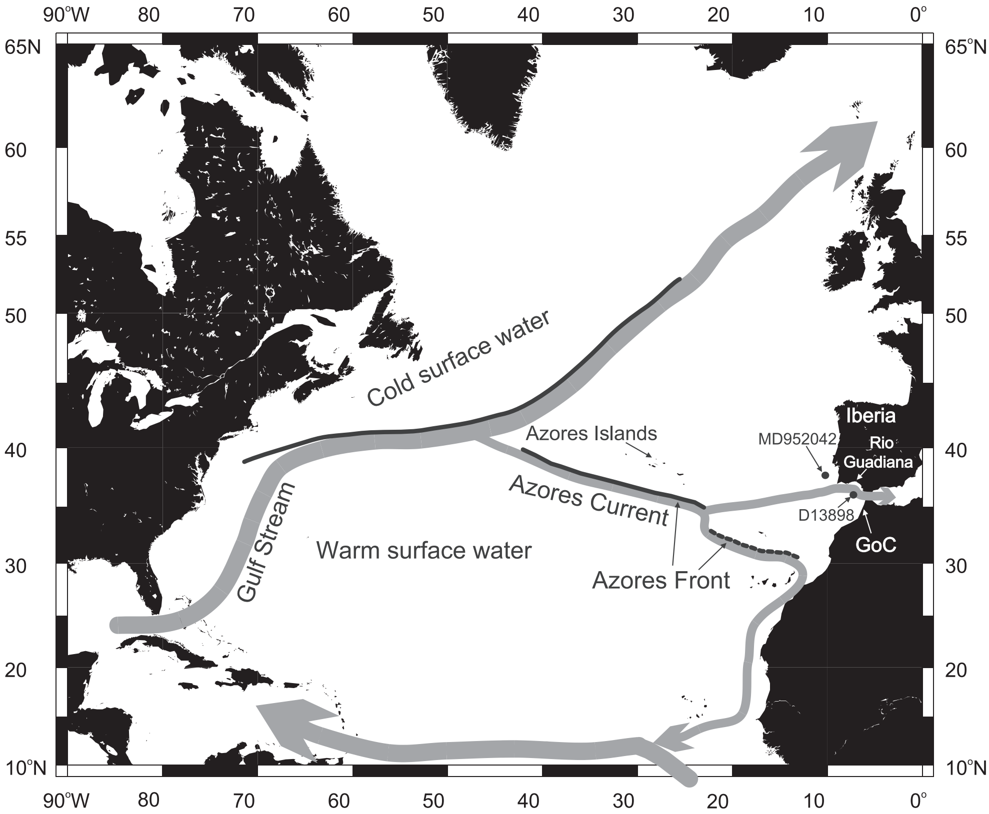

Fig. 1. General surface circulation in the North Atlantic today. Core locations are shown.

and position throughout the year as a result of meandering [9]. The sediment record will therefore record the long-term average position of the AF meander belt, rather than that of the AF itself.

Towards the East Atlantic Margin, the geographic positions of the AC and AF are separated. The AC flows into the Gulf of Cadiz to replace water lost during water mass transformation. The AF resides further to the south, between the Canary Islands and Madeira [10]. A high-resolution circulation model captures observations made during the CANIGO project and so offers comprehensive insight into the oceanography of the area between the Azores and the Strait of Gibraltar [11]. The model shows the AC continuing eastwards from the Azores to the Strait of Gibraltar, while the AF (a sharp ~ 4 °C transition at the Azores) degenerates into two weaker transitions, one lying to the west of the GoC but not penetrating into it ($\sim 1°$) and one lying further to the south ($\sim 3°$) (see Fig. 2). The southern branch coincides with a second zone of increased velocity, which turns south to flow between the Canary Islands and North Africa.

We here report stable isotope (C and O) and planktonic foraminiferal assemblage records for a core from the GoC in comparison with core MD952042 from offshore southern Portugal [12], to investigate the history of the Azores Current/Azores Front in the GoC region.

2. Modern planktonic foraminiferal assemblage

Both the GoC and the southern Portuguese margin have mean summer temperatures of 22 °C, and similar mean winter temperatures (16 °C for the GoC, 15 °C for southern Portugal) [13].

Plankton tows in the Gulf of Cadiz indicate that the dominant foraminiferal species is *Globigerina bulloides*, which makes up between 30% and 54% of the individuals in the study area. *Globigerinoides*

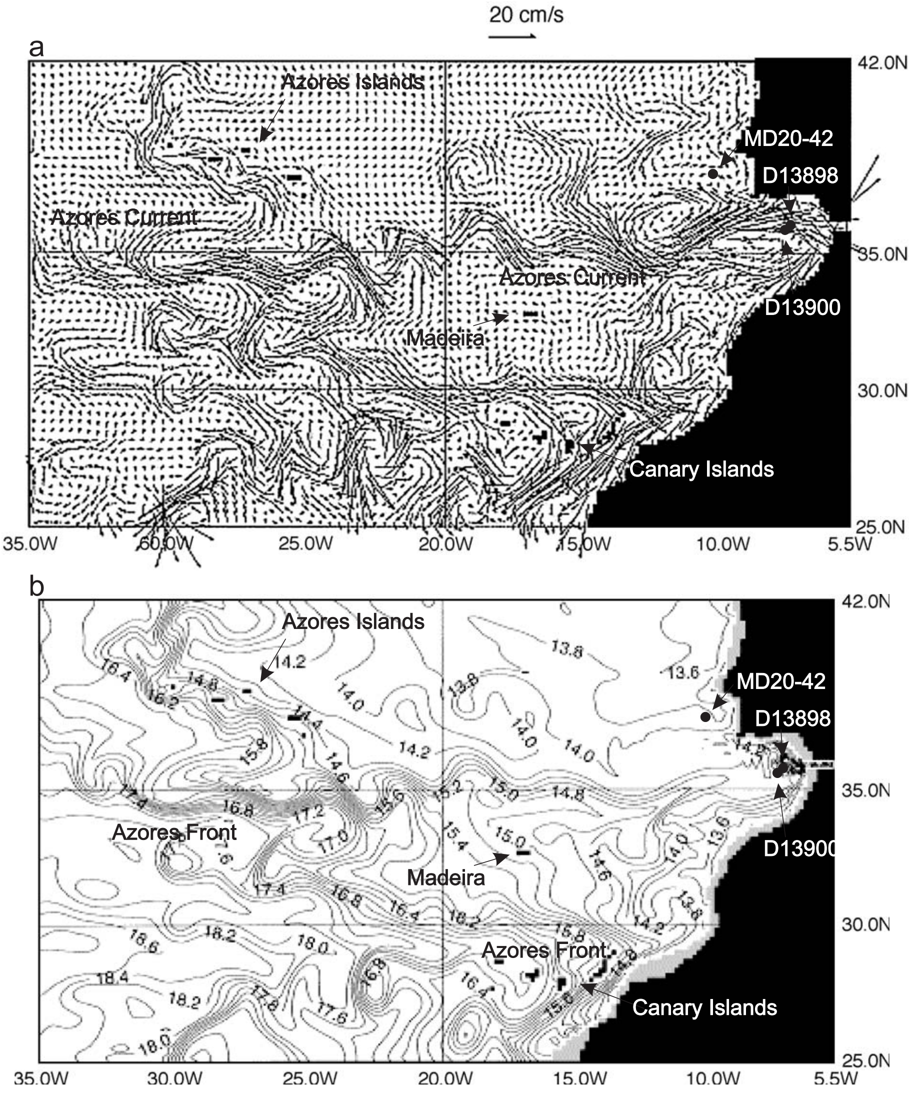

Fig. 2. Present day oceanographic setting from CANIGO regional model [11]. (a) Velocity at 36.6 m depth (after [11]). (b) Temperature at 202 m depth (after [11]).

ruber, *Globorotalia inflata*, *Globigerinella siphonifera* and *Globigerinoides sacculifer* are also common, each contributing 5–15% of the living fauna [14]. Core top records indicate a similar dominance of *G. bulloides* (30%) and *G. ruber* and *G. sacculifer* together make up ~ 23% of dead fauna [15]. Also present in low abundances in plankton tows and core tops are *Turborotalita quinqueloba*, *Globigerinita glutinata*, *Globigerinita humilis*, *Globigerinoides tenellus*, *Globorotalia hirsuta*, *Globorotalia scitula*, *Globorotalia truncatulinoides*, *Neogloboquadrina pachyderma* dextral and *Orbulina universa* [14–16].

A similar planktonic foraminiferal assemblage is found in core tops from the Portuguese margin, though it is more dominated by *G. bulloides* (25–75%) [17,18]. *N. pachyderma* (d) is more common than in the GoC (15–40%) and *G. ruber* and *G. sacculifer* are generally less abundant north of Cape St. Vincent [17]. Other important species (5–15%) are

G. inflata, *G. siphonifera* and *O. universa*. This assemblage is comparable to that reported in plankton tows immediately north of the AF [2] and in the BIOTRANS sector off northwest Iberia [19,20] indicating that a fairly consistent bioprovince extends from north of Iberia to the AF.

3. Modern distribution of G. scitula

G. scitula is generally placed with the temperate–sub-polar assemblage [21], as in the Atlantic it is uncommon in the low latitudes and found in relatively high abundance north of 35–40° [22]. It is also frequent in temperate regions elsewhere, such as the Indian Ocean [23,24] and the North Pacific [25–27]. Though *G. scitula* is consistently found in the Mediterranean during the last glaciation, it is not found in this region today [28], which also seems to indicate a preference for cool surface water conditions.

High abundances of *G. scitula* have been recorded in upwelling cells in the Panama Basin [29] and associated with periods of upwelling in the Central Pacific [30]. Kuroyanagi et al. (2002) [27] have shown that *G. scitula* is part of the Spring bloom fauna when the surface waters are at their most mixed, which also indicates an association with poorly stratified/enhanced productivity settings. In the modern North Atlantic *G. scitula* reaches its maximum abundance around the Azores Islands [22], and plankton tows indicate that it is present in high abundances north of and within the Azores Front where frontal upwelling causes high productivity, but in very low abundances to the south [2]. Bradshaw (1959) [25] shows peak numbers of *G. scitula* occurring in a narrow band on the northern margin of the Kuroshio Current, in close analogy to that found at the AF in the Atlantic. This is confirmed by the observation of peak abundances of *G. scitula* between the sub-polar front and the Kuroshio Front/Extension [27]. Peak abundances of *G. scitula* are thus routinely associated with environments exhibiting seasonal or oceanographic vertical mixing at temperate latitudes. Where temperature is found to be an inadequate explanation, high abundance of *G. scitula* in the sediment record is therefore likely to be reflecting enhanced vertical mixing (upwelling).

4. Material and methods

We present high-resolution data for core D13898, to assess changes in the regional oceanography of the GoC between the LGM and present. This is a ~ 16 m long core recovered using the SOC Giant Piston Corer from water depths of ~ 1250 m in the central part of the Gulf of Cadiz. D13898 is positioned on the most distal and muddy parts of the Gulf of Cadiz sediment drift and consists of homogenous and massive, brown coloured, clay rich mud with no sand/silt layers or other evidence for turbidite activity apparent. The chronostratigraphic framework for D13898 is based on 10 AMS radiocarbon dates performed on >6 mg of shallow-dwelling (i.e. excluding all *Globorotaliids*, *G. siphonifera* and *G. calida*) planktonic foraminiferal tests picked from the >150 μm fraction. The radiocarbon analyses were undertaken via the NERC Radiocarbon Laboratory (NERC-RCL), at the University of Arizona NSF-AMS facility. The datings have been calibrated using the Calib 4.3 program, and the Bard et al. (1998) "glacial" polynomial [31,32] in the case of the oldest two (see Table 1). As the aim of this study is to compare the Gulf of Cadiz records to that of MD952042, the chronostratigraphy is "tuned" to that of MD952042 by correlation of tie-points concerning global events such as the deglaciation and Heinrich Events.

For the planktonic foraminiferal abundance study, samples were disaggregated, washed and sieved to remove all material finer than 150 μm. Where neces-

Table 1
Stratigraphic position of radiocarbon datings

Sample depth (cm)	Conventional radiocarbon age	1σ	Mean calendar age
0	5227	42	5597
100	8615	55	9317.5
220	11642	89	13303.5
300	12796	73	14927
380	14716	86	17039
480	16480	120	19068.5
608	17600	110	20358
834	19340	120	22360.5
1234	23010	180	27176[a]
1628	24040	200	28667[a]

Conversion from conventional to calendar years is done with the Calib4.3 program. No reservoir correction has been used.

[a] Conversion done using Bard et al. (1998) glacial polynomial.

sary, samples were split into suitable aliquots of at least 300 individuals. The data are presented as percentages of total planktonic foraminiferal number.

The specimens selected for stable isotope analyses were washed and sonicated in methanol to remove surface contamination. Stable isotope analyses were carried out on 7–15 individuals of *N. pachyderma* (d) between sizes of 150 and 212 μm or 6–15 individuals of *G. bulloides* sized between 190 and 210 μm. Stable isotope analyses were carried out using a Europa Geo 2020 mass spectrometer with individual acid-bath preparation. The carbon and oxygen isotope ratios are expressed as δ values, in per mils (‰), relative to the Vienna Peedee Belemnite standard [33,34].

5. Framework for interpretation of stable isotope data

Oxygen isotope records are dominated by changes in global ice volume, because the preferential sequestration of the lighter (^{16}O) isotope into ice sheets causes relative ^{18}O enrichment in the oceans. As the records discussed have been synchronised, global ice-volume effects will be equally represented at any given time.

Detailed comparisons are made only between records based on the same species, thus avoiding any bias from metabolic (“vital”) effects so that offsets between records represent genuine differences in the environmental conditions. These differences concern the combined influences in changes in temperature and the freshwater cycle. Higher temperatures cause more light oxygen to be incorporated into calcite, giving negative δ^{18}O shifts. Fresh water has a light δ^{18}O, and influxes of fresh water will be recorded as negative excursions in the oxygen isotope record. Conversely, evaporative loss causes the waters to become heavier in δ^{18}O. It is unlikely that amounts of isotopically light fresh water large enough to cause more than transient excursions were supplied to the GoC in the past, as there are no major rivers to supply it and the GoC is open to the Atlantic in the west. Though the Heinrich Events caused significant freshening in the North Atlantic, there is no closed circulation in the GoC to cause this fresh water to remain as a cap over large time periods. Meltwater of this nature therefore also can be considered to be capable of providing transient freshening only. The open setting makes large offsets between cores due to evaporative loss unlikely. Large isotopic offsets between the records discussed in this study are therefore predominantly the result of spatial differences in temperature.

The ^{18}O record represents mean thermal conditions and therefore can be expected to accurately reflect the mean position of the Azores Front. The waters upwelled by the front, however, are transported perpendicularly away from the center of the front in vertical circulation cells that may be up to 100 km wide in the open ocean [6]. In addition upwelled water is exported from the axis of the Azores Current on both the northern and the southern side by eddies formed as meanders “pinch out” and collapse [9]. The carbon incorporated into the analysed tests will reflect the complexity these processes will cause within the ^{13}C signal. The ^{13}C record for a shallow dwelling species positioned close to the AF would therefore be anticipated to show relatively negative values and high variability. The considerable width over which the upwelled water is transported will also tend to damp and smooth transitions caused by migration of the AF.

In today’s western Mediterranean, *G. bulloides* is a spring–summer species that grows at the base of the photic zone feeding on phytoplankton produced during the spring bloom, and temperature is considered a much less important factor in governing its distribution than food availability [35]. It is the dominant species in plankton tows at ~ 100 m from Sicily to the westward edge of the GoC [14] and is reported in high abundances in core tops from the GoC [15]. East of the Azores, *G. bulloides* is found in high abundances at less than 100 m depth during August and is absent in January, as is the case in the Mediterranean [2]. Isotopic records for a species will be biased towards the season and environment of maximum test production, and as this seems to be constant throughout the study area, *G. bulloides* can be considered to be a useful marker for conditions at relatively shallow water levels in spring to summer.

N. pachyderma (d) is found only in low abundances in the Mediterranean today, and is not present in significant numbers in plankton tows [14] or core tops [15] from the GoC. It is found in high abundance further north in the adjacent North Atlantic [19,20], and has been widely described as a temperate to subpolar species (e.g. Refs. [36,37]). *N. pachyderma* (d) is a dominant species during the last glaciation in both the Mediterranean and the GoC [15,35]. In the Mediterranean, *N. pachyderma* (d) is generally considered to be a mesopelagic species that thrives at the Deep Chlorophyll Maximum, and it typically reflects stable (deep) conditions that are "set" in winter [35,38–40]. Similar habitats at depth have been observed for *Neogloboquadrinids* in the Atlantic [41–45], Pacific [40,46,47] and Southern Oceans [48].

6. Results

In the D13898 record, *N. pachyderma* (d) consistently shows heavier δ^{18}O than *G. bulloides* (Fig. 3A). This is consistent with *N. pachyderma* (d) dwelling at greater depth, and therefore lower temperature, and this isotopic configuration can be considered robust. At 23.5 ka BP and during the deglaciation the *N. pachyderma* (d) and *G. bulloides* records show similar δ^{18}O. The increase in δ^{18}O at 23.5 ka BP is close in age to Heinrich Event 2 (H2; 24 ka BP [49]) and probably represents this event in D13898. Strong cooling associated with the Heinrich Events have been found in alkenone records (which, like *G. bulloides*, are indicative of spring conditions) from the Alboran Sea [50]. It is likely that the stronger response of *G. bulloides* compared to *N. pachyderma* (d) during H2 is due to the latter being representative of different seasonal conditions (winter) and living at greater depth. H1 (17 ka BP [49]) does not appear to be strongly represented in D13898.

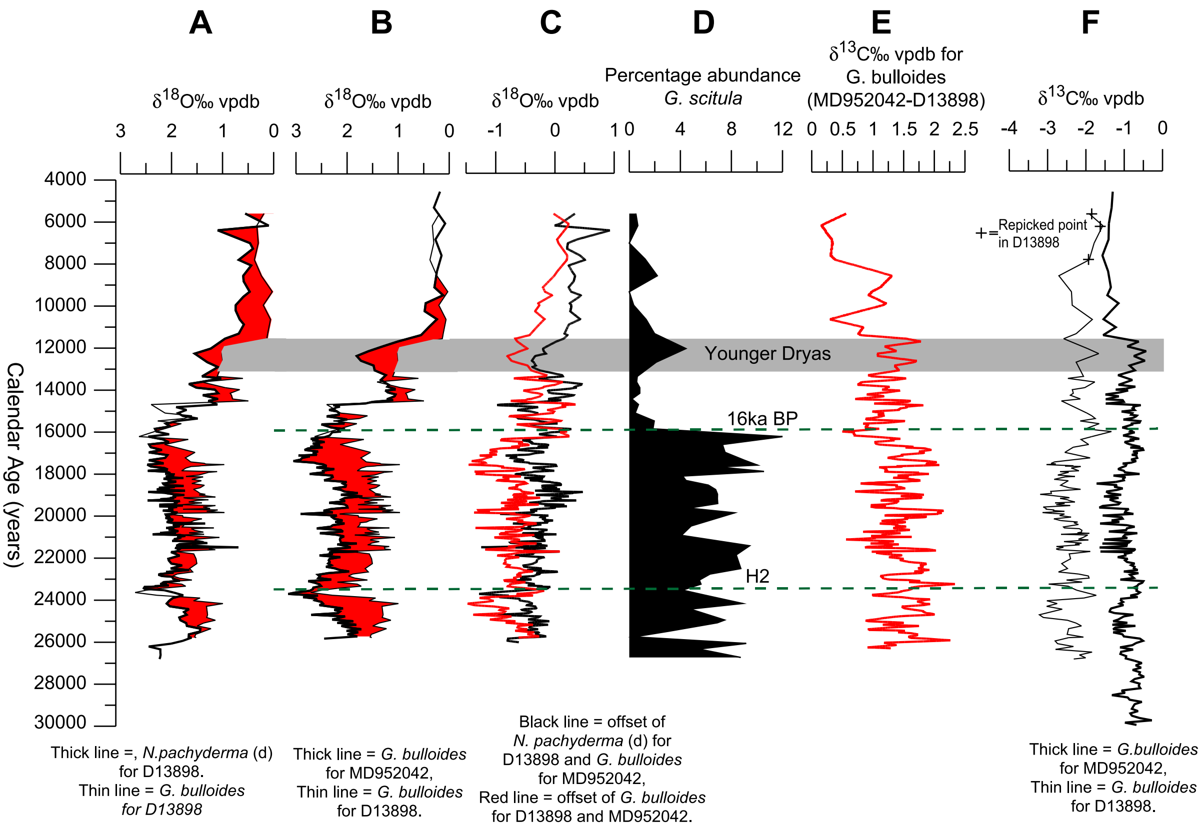

Fig. 3. (A) Offset of δ^{18}O between the *N. pachyderma* (d) and *G. bulloides* records of D13898. (B) Offset of δ^{18}O between the *G. bulloides* record of D13898 and the *G. bulloides* record of MD952042. (C) Offsets of *G. bulloides* and *N. pachyderma* (d) for D13898 and *G. bulloides* for MD952042. (D) Percentage abundance of *G. scitula*. (E) Offset of carbon isotope values between *G. bulloides* records of MD952042 and D13898. (F) δ13C for *G. bulloides* in D13898 and MD952042.

A strong isotopic gradient is seen between the $\delta^{18}O_{G.\ bulloides}$ records of MD952042 and D13898 prior to 16 ka BP and during the Younger Dryas (Fig. 3B). This strong isotopic gradient is also found between the $\delta^{18}O_{N.\ pachyderma}$ (d) record for D13898 and $\delta^{18}O_{G.\ bulloides}$ for MD952042. During the last glacial period and Younger Dryas, both records for D13898 show lighter $\delta^{18}O$ values than the $\delta^{18}O_{G.\ bulloides}$ record of MD952042. The isotopic gradient between the GoC and the Portuguese margin is therefore not confined to the surface waters but is also found in slightly deeper water masses (around the DCM).

Throughout the last 26 ka, D13898 shows significantly lighter $\delta^{13}C_{G.\ bulloides}$ than MD952042 (Fig. 3D,E). The records compared in Fig. 3D and E are for the same species, so that differences cannot be ascribed to "vital effects" and are unlikely to be due to differing seasons of growth. The lighter values in D13898, relative to MD952042, therefore suggest a higher rate of ^{12}C resupply to surface waters in the Gulf of Cadiz compared to the Portuguese margin. In many records (e.g. Ref. [51]) high resupply of light carbon to surface waters has been related to vertical mixing during coastal upwelling. Though coastal upwelling is known to occur along the Portuguese margin, it does not occur in the Gulf of Cadiz to the south of the Guadiana estuary [52,53]. Though the two $\delta^{13}C_{G.\ bulloides}$ records are similar in shape, the offset between the records is very variable, with Holocene offsets of ~ 0.25‰ and glacial offsets up to 1.75‰ (Fig. 3D,E). In the absence of upwelling, the ^{12}C resupply to surface waters must have been provided by another mechanism, which has undergone significant variation throughout the last 26,000 years.

In our faunal abundance data (Fig. 4), D13898 shows downcore variations consistent with the thermal history of the Last Glacial Maximum and the Last Deglaciation, in agreement with other records from the GoC (e.g. Ref. [15]). The general warming of the North Atlantic subsequent to 15 ka is reflected by an increase in the abundance of *G. ruber* and *G. sacculifer* and a decrease in the abundance of *N. pachyderma* (d). The Younger Dryas and Bölling-Allerød are also reflected in these records. However, we concentrate specifically on the record for *G. scitula*, a deep dwelling species (100–700 m water depth; [2]), whose abundance changes seem to be inadequately explained by temperature alone. It is common (4–10%) prior to 16 ka BP, but is rare throughout the rest of the core with the exception of the Younger Dryas and a small peak at ~ 9 ka BP (Fig. 3C). The

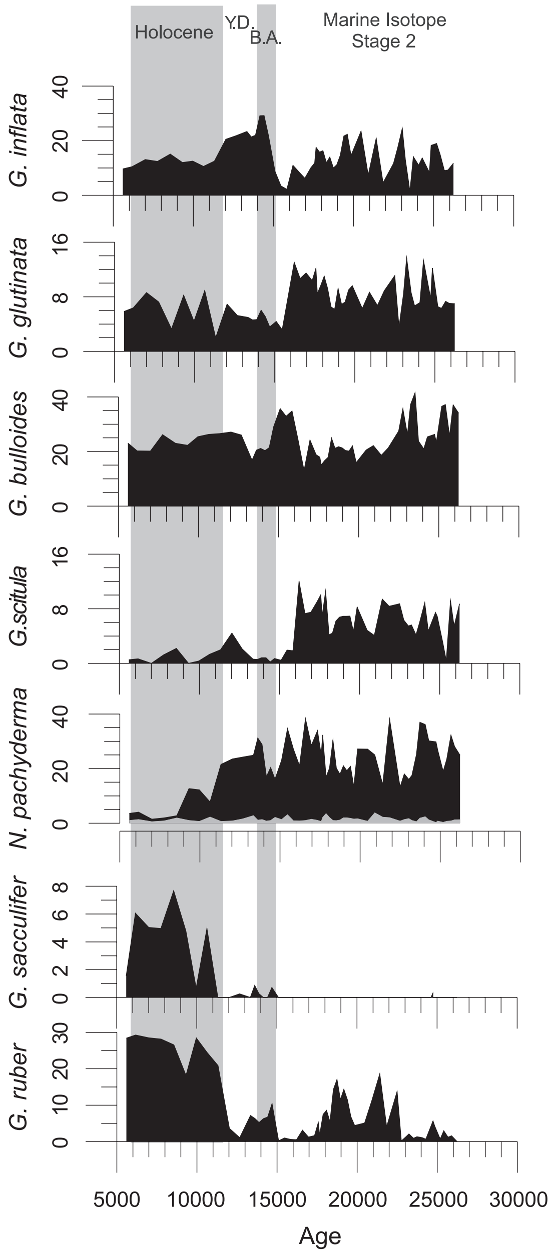

Fig. 4. Faunal assemblage data for D13898. Age is in calendar years. Y.D. and B.A. represent Younger Dryas and Bölling-Allerød respectively. In the *N. pachyderma* plot, the dextral form is shown in black and the sinistral form is shown overlayed in grey.

decrease in abundance at 16 ka BP predates Termination 1a by $\sim$ 2000 years. It does however coincide closely with the disappearance of the $\delta^{18}O_{G.\ bulloides}$ offset between D13898 and MD952042 (Fig. 3B). As argued before, offsets between two closely spaced records from an open ocean setting predominantly reflect temperature contrasts. Hence, we interpret the $\delta^{18}O_{G.\ bulloides}$ difference between D13898 and MD952942 as a temperature gradient. Its disappearance at 16 ka BP seems to be associated with a cooling of the surface waters at D13898. *G. scitula* is often considered to be an indicator for cold surface conditions [21], and would be expected to increase in association with the cooling at D13898 noted above. Instead, a decrease is observed, and the collapse of the *G. scitula* population needs to be considered in view of changes in the regional hydrographic context. Significant changes in the *G. scitula* population are not found in MD952042 [18], further indicating that the variability found in D13898 reflects changes in local hydrography.

7. Discussion

The abundance peak of *G. scitula* on the northern flank of the AF has considerable fossilisation potential and therefore has been proposed as a useful indicator for the presence of the AF [2]. As the abundance record of *G. scitula* in D13898 can neither be ascribed to temperature variation or coastal upwelling, which does not penetrate far into the GoC as a result of the configuration of its coastline [52,53], we consider the presence or absence of this species in core D13898 as a marker for past presence or absence of the AF at this location.

The intervals with peak abundances of *G. scitula* coincide with times when the oxygen isotope offset between D13898 and MD952042 is persistent and of considerable magnitude (Fig. 3). This suggests that there was a large thermal gradient between the two locations. The magnitude of the isotopic offset between D13898 and MD952042 indicates that the site of D13898 was on average 4–5 °C warmer than that of MD952042 during this time, using a value for changes in the oxygen isotope ratio of 0.23‰ $°C^{-1}$ [54] and assuming that the isotopic contrast was entirely related to temperature. Such a contrast would be consistent with the magnitude of the thermal transition across the AF today ($\sim$ 4 °C, see Fig. 2b). High abundances of *G. scitula* and relatively high (isotopic) temperatures in the D13898 record prior to 16,000 years and during the Younger Dryas therefore suggest that the AF resided close to the D13898 location. Subsequent to the withdrawal of the AF at 16 ka BP, the $\delta^{18}O$ offset between *N. pachyderma* (d) and *G. bulloides* in D13898 is absent, indicating a poorly stratified water column during the deglaciation.

The AF is known to be a location of vigorous upwelling [9] and if it resided near the location of core D13898, this should be represented in the carbon isotope record. Greater resupply of light carbon to the surface waters would be expected to characterise the signals in D13898 prior to 16 ka BP and during the Younger Dryas. The offset between the D13898 and MD952042 $\delta^{13}C$ records for *G. bulloides* is highly variable, but it is generally enhanced during the glacial period than relative to the Holocene (Fig. 3d). Just before 16 ka BP, the offset declines significantly and then increases again toward glacial values in the Younger Dryas. This pattern supports our interpretation of the $\delta^{18}O$ differences and the *G. scitula* abundance data.

The presence of strong stratification at D13898 prior to 16 ka indicates that the AF is not statistically positioned at this location and the strong thermal gradient between D13898 and MD95-2042 suggests that the AF is statistically positioned to the north of D13898. However, the presence of probably upwelled light carbon and abundant *G. scitula* in the D13898 record indicate that this location is close enough to be influenced by the AF. D13898 is therefore interpreted to be positioned within the southern part of the AF meander belt.

8. Conclusions

The presence of a large $\delta^{18}O$ offset between D13898 and MD952042 strongly suggests that an enhanced thermal gradient existed between the Gulf of Cadiz and the Portuguese margin prior to 16 ka BP. At the same time, the Gulf of Cadiz shows high abundances of *G. scitula*, a species that peaks in abundance at the Azores Front and so offers an indicator for the presence or absence of the Azores Front in the study area. Furthermore, these times were also characterised by enhanced resupply of light carbon to surface waters in the Gulf of Cadiz, a likely reflection of frontal upwelling. During the Younger Dryas, the enhanced thermal gradient between the Gulf of Cadiz and the Portuguese margin returns. At this time, there is a marked increase in the abundance of *G. scitula* and a return of frontal upwelling in the Gulf of Cadiz. It is therefore proposed that prior to 16 ka BP the Azores Front resided in the Gulf of Cadiz, and it briefly returned during the Younger Dryas. This is most simply explained by extension of the AF eastward along the AC beyond the point at which the relationship between these two features degenerates today. It is therefore proposed that the Azores Front resided at similar latitude to today during the LGM.

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