Role of the North Atlantic circulation in the mid-Pleistocene transition

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Abstract

The southwestern Iberian margin is highly sensitive to changes in the distribution of North Atlantic currents, and to the position of oceanic fronts. In this work, the evolution of oceanographic parameters from 812 to 530 ka (MIS20-MIS14) is studied based on the analysis of planktonic foraminifer assemblages from site IODP-U1385 (37º34.285´N, 10º7.562´W; 2585 mbsl). By comparing the obtained results with published records from other North Atlantic sites between 41 and 55 ºN, basin-wide paleoceanographic conditions are reconstructed. Variations of assemblages dwelling in different water masses indicate a major change in the general North Atlantic circulation during MIS16, coinciding with the definite establishment of the 100-ky cyclicity associated to the Mid-Pleistocene Transition. At surface, this change consisted in the re-distribution of water masses, with the subsequent thermal variation, and occurred linked to the northwestward migration of the Arctic Front (AF), and the increase in the North Atlantic Deep Water (NADW) formation respect to previous glacials. During glacials prior to MIS16, the NADW formation was very weak, which drastically slowed down the surface circulation; the AF was at a southerly position and the North Atlantic Current (NAC) diverted southeastwards, developing steep south-north, and east-west, thermal gradients and blocking the arrival of warm water, with associated moisture, to high latitudes. During MIS16, the increase in the

meridional overturning circulation, in combination with the north-westward AF shift, allowed the arrival of the NAC to subpolar latitudes, multiplying the moisture availability for ice-sheets growth, which could have worked as a positive feedback to prolong the glacials towards 100-ky cycles.

Keywords: Mid-Pleistocene Transition (MPT); North Atlantic circulation; North Atlantic Current (NAC); Planktonic foraminifers; Iberian margin; IODP-U1385; Glacials.

1 Introduction

Climate in the North Atlantic region is characterized by the continuous poleward heat flow carried out by the oceanic circulation. The Gulf Stream and the North Atlantic Current (NAC) transport warm and salty surface water, originated in the tropical region, towards the polar ocean, the northeast Atlantic, and along the western European margin, transferring heat and moisture to the atmosphere during the process. Surface circulation and associated heat flow is pumped by the sinking of surface water in the subpolar region and formation of the North Atlantic Deep-water (NADW). As a matter of fact, the Atlantic Meridional Overturning Circulation (AMOC) is responsible for ~50% of the total poleward heat advection (Sabine et al., 2004; Adkins, 2013).

The NAC forms the transition zone between the cold and productive waters located north of the Arctic Front (AF) (eg., Johannessen et al., 1994), and the warm and oligotrophic waters from the subtropical gyre in the South. Each water mass has distinct physic-chemical characteristics and specific planktonic foraminiferal assemblages (eg., Bé, 1977; Ottens, 1991; Cayre et al., 1999). Various studies have shown that surface water characteristics in the mid-latitude North Atlantic depend on the strength and position of the NAC and associated oceanic fronts (Calvo et al., 2001; Naafs et al., 2010; Voelker et al., 2010). During Pleistocene glacials, the AF migrated southward into mid-latitude North Atlantic (Stein et al., 2009; Villanueva et al., 2001), cold polar waters expanded to lower latitudes and the NAC did not reach as far North as during interglacials (e.g., Pflaumann et al., 2003).

After MIS21, a northwestward shift in the position of the AF began (Hernandez-Almeida et al., 2013), that culminated at the end of MIS16, in a similar location to today´s (Wright and Flower, 2002). Coinciding with the final stage of this shift, a major reorganisation of the meridional overturning circulation developed, related to increased NADW formation that resulted in deeper and southward penetration of this mass of water (Poirier and Billups, 2014). Both processes could have been related with the prolongation of glacials that occurred at the end of the mid-Pleistocene transition (MPT). This was the transitional period during which, the Earth´s climate system underwent a major change, switching from a linear orbital (41 and 23 ky cycles) response, to a non-linear 100 ky forcing. Although there is still no agreement over the initiation of the MPT (e.g., Clark et al., 2006; Maslin and Brierley, 2015), strong 100 ky cycles are recorded since ~650 ka (Ruddiman et al., 1989; Imbrie et al., 1993; Mudelsee and Schulz, 1997). Related with the shift in the AF position, warm and salty surface water could reach subpolar latitudes during glacials, which would have provided the necessary humidity to prolong the growth of ice sheets, as well as enhanced meridional overturning – both processes acting as feedback mechanisms partly responsible for the change of the climate system phasing (Imbrie et al., 1993). The objective of this work is to study the evolution of glacial circulation in the North Atlantic from MIS20 to MIS14, and explore its possible relation with the MPT.

Over the last glacial cycle, the Iberian margin recorded both peak displacement events of the AF and periods of greater influence of subtropical water from the Azores Current (AzC) (eg., Martrat et al., 2007; Eynaud et al., 2009; Salgueiro et al., 2010). There is also evidence that polar to tropical planktonic foraminifers assemblages co-occurred in a latitudinal band around 35º – 40ºN during the Last Glacial Maximum (McIntyre et al., 1972), which suggests that the limit between both water masses was situated slightly southwards than it is today (Fiúza et al., 1998; Peliz et al., 2005). Site IODP-U1385 (37º34´N) lies within this oscillating boundary, and has been proven an ideal location to study oceanographic changes in the North Atlantic through glacial-interglacial periods (e.g., Maiorano et al., 2015; Martin-Garcia et al., 2015; Rodríguez-Tovar et al., 2015; Rodrigues et al., 2017). Analyses of planktonic foraminifer assemblages are used to identify the different water masses, and results from IODP-

U1385 are compared with published data from other North Atlantic latitudes to reach basin-wide conclusions.

2 Materials and Methods

2.1 IODP Site U1385

The Southwestern Iberian margin is a focal location for paleoclimate and oceanographic research on the Quaternary (Hodell et al. 2013). Site IODP-U1385 was drilled at the so-called Shackleton Site (37º34.284´N, 10º7.562´W), at 2589 meters water depth (Fig. 1). At surface, this area lies under the influence of the *North Atlantic Central Water* (NACW), with a complex circulation pattern; at depth, the NADW flows between ~2,200 and 4,000 meters, above the *Antarctic Bottom Water* (AABW).

Today´s surface water circulation in the North Atlantic (Fig. 1a) consists of two different branches. The NAC, after reaching the subpolar ocean, drifts southwards along Europe transporting the Eastern North Atlantic Central Water of sub-polar origin (ENACWsp), formed north of 46º (Brambilla and Talley, 2008). In the south, the AzC, of subtropical origin (ENACWst) and formed along the Azores Front (Rios et al., 1992), drifts eastwards and bifurcates when approaching the continental margin. The ENACWst is saltier, warmer, less dense than the ENACWsp and overflows it along Iberia with a decreasing lower limit from south to north until ~42.7 ºN (Fiúza et al., 1998).

Sediments at Site U1385 define a single lithological unit with a high sedimentation rate (~10 $cmky^{-1}$), very uniform and dominated by calcareous muds and calcareous clays, with varying proportions of biogenic carbonate (23% - 39%) and terrigenous sediments (Stow et al., 2012).

2.2 Foraminiferal study

This study covers a section comprised between 67.2 and 94.6 crmcd (MIS14 - MIS20). The age model (Hodell et al., 2015) is based on the correlation of the benthic oxygen isotope record to the global benthic LR04 isotope stack (Lisiecki and Raymo, 2005).

Sampling was performed every 20 cm, providing a 1.76–ky resolution on average. A total of 147 samples, 1 cm-thick, were freeze-dried, weighed and washed over a 63-μm mesh. The >63 μm residue was dried, weighed and sieved again to separate and weigh the >150 μm fraction. Planktonic foraminifers' taxa were identified (Kennett and Srinivasan, 1983) in aliquots of this last fraction containing a minimum of 300 specimens.

The microfaunal analysis focused on species and assemblages (Appendices A and B) that are associated with North Atlantic surface water masses.

2.3. Estimation of thermal gradients

Thermal gradients in the North Atlantic are reconstructed by calculating the difference between the Sea Surface Temperature (SST) from two sites. The site 607 was used as start point, and compared with sites 980 for the latitudinal gradient (SST_{607} – SST_{980}), and U1385 for the longitudinal one (SST_{607} – SST_{U1385}). In this way, a positive longitudinal gradient means that SST was warmer at site 607 than at U1385; a negative longitudinal gradient indicates warmer SST off SW Iberia than at site 607.

SST records from all sites have been previously published (Ruddiman et al., 1989; Wright and Flower, 2002; Martin-Garcia et al., 2015) and are based in planktonic foraminifers´ census counts.

3 Results

Neogloboquadrina pachyderma sinistral (Nps) is an indicator of polar water (Cayre et al., 1999; Pflaumann et a., 2003; Eynaud et al., 2009). Except in the eighth climate cycle (MIS19-MIS18), Nps does not vary at glacial-interglacial scale, but peak percentages are associated either to glacial maxima (MIS20) or to deglaciations, both Terminations and other deglacial events (Fig. 2b), revealing increased advection of polar water at these times. Nps is less abundant during interglacial conditions than during glacials, but it is important to note that glacial Nps´ percentages change through the time series. Nps is more abundant during glacials MIS20, MIS18 (when the highest percentages occurred), and the first half of MIS16, than during late MIS16 and glacial MIS14 (Fig. 2b). After ~650 ka, Nps keeps below 10%, except during some deglacial events, as inferred from sharp decreases in $\delta^{18}O$ (Fig.2a-b). This suggests that since mid-MIS16, the polar water only reached the southwest Iberian margin associated to some deglacial episodes, and not during full glacial conditions or glacial maxima, in opposition to what happened before ~650 ka.

Turborotalita quinqueloba (Tq) dwells in cold waters and is usually associated with the AF (Johannessen et al., 1994; Cayre et al., 1999). Its percentage in U1385 is lower before MIS16 than since then (Fig. 2c). Highest values occur at ~650 ka and during MIS15b, the glacial interval that interrupted interglacial MIS15. The variation of Tq in site U1385 does not show an interglacial-glacial pattern, which suggests this site did not register the migration of the AF through each climate cycle.

The NAC assemblage (Ottens, 1992; Appendix A) is the most abundant one at this site (Fig. 2), indicating that the ENACWsp dominates the surface oceanography in the area through the time series. This assemblage does not keep a similar interglacial-glacial pattern through the whole study interval, but changes its behaviour at ~650 ka. Previous to ~650 ka, its variation mirrors that of Nps, and the highest values occur during interglacials. In opposition to this, since ~650 ka,, the highest percentages coincide with full glacial conditions (MIS16a and MIS14a), not with interglacials (Fig. 2d).

The Warm Surface (WS) assemblage (Vautravers et al., 2004; Appendix B) is typical of the subtropical water transported eastwards by the AzC. In U1385, this assemblage shows a clear interglacial-glacial pattern only since the seventh climate cycle (Fig. 2e). During glacials previous to MIS16, the WS assemblage is fairly abundant (MIS18), and even more abundant than during interglacials, like in MIS20, when it reaches the highest percentages of the whole study interval. During MIS16, its percentage decreases as the glacial advances, and in MIS14, values are low since the glacial inception. At the beginning of each interglacial, its percentage rises rapidly, suggesting that the AzC strengthens rapidly in the area after Terminations.

5 Discussion

The location of sites 607 and 980 along the main core of the NAC towards the high latitudes of the North Atlantic (Fig. 1a), allowed us to monitor past changes in the northward heat transport, using planktonic foraminifer assemblages and SST reconstructions from both sites. By contrast, planktonic foraminifer assemblages at site U1385 are more influenced by the advection of heat to the northeastern Atlantic through the easternmost branches of the NAC, and especially by the AzC, that originates in the tropics and flows towards Iberia following the northern margin of the subtropical gyre (Fig. 1a). In consequence, with these three strategic sites, we can monitor changes in the main circulation systems of the NE Atlantic during the mid-Pleistocene, and estimate the heat advection to the north (SST gradient between sites 607 and 980) and to the northeast Atlantic (SST gradient between sites 607 and U1385) (Fig. 3f-g).

5.1 North Atlantic circulation during glacials MIS20 and MIS18

During both glacials, progressive cooling is recorded in sites 607 and 980 (Fig. 3f). Though the cooling is more pronounced at the higher latitude, the SST gradient between both sites is not very high and decreases largely towards the end of glacial stages (Fig. 3g). In contrast, the Iberian margin remained relatively warm during most of MIS20 and a large part of MIS18 (Fig. 3f), which undoubtedly reflects a continuous flow of the AzC to this region, as also indicated by the WS assemblage record (Fig. 2e).

At the subpolar latitude of site 980, the presence of polar water increased rapidly since glacial inceptions, as informed by very high percentages of Nps during MIS20, MIS18e, and MIS18a (Fig. 3c). As glacial conditions progressed, the heat flow along the main core of the NAC reduced largely, and even interrupted at glacial maxima MIS20a and MIS18a, as can be inferred from the low temperatures registered in the Azores region (site 607, Fig. 3f). This reduced advection of warm water from the tropics to subpolar latitudes triggered the southward migration of the AF, that surpassed 50 ºN during both MIS20, MIS18e, and MIS18a (Wright and Flower, 2002), and favoured the advection of polar water as far south as site 607, as informed by the Nps record (Fig. 3c).

While the northward flow of heat decreased progressively along both glacials, the heat flow towards the Iberian margin continued in the early part of glacial MIS18 and, especially, during MIS20, indicating a very active AzC during both glacials. This current advected warm water eastward, and deflected northward along the Iberian margin, similarly to today´s IPC (Fig. 1a), probably overflowing the polar water mass, as the co-occurrence of polar and subtropical fauna suggest (Fig. 2b,e). The advection of the warm AzC to site U1385 was only interrupted at Terminations TIX, TVIII, and at deglaciation MIS18e/d, when massive surges of very cold and low-salinity surface waters reached the area, which was registered by peaks of the polar species Nps and sharp decreases in the WS assemblage (Fig. 2b,e). This interpretation is corroborated by the negative longitudinal thermal gradient between sites 607 and U1385 (Fig. 3g), which indicates that, an important fraction of the heat reaching the Iberian margin did not flow through the site 607 region.

The very low SST at the mid-latitude site 607, and the low latitudinal thermal gradient, during glacial maxima MIS20a, MIS18e and MIS18a (Fig. 3f-g), suggests either a complete shut-down of the NAC core flux, or a southward or southeastward diversion of this current,.as glacial conditions progressed. Nevertheless, the low thermal gradient between sites 607 and U1385 (Fig. 3g) implies that the SW Iberian margin was always under the influence of the warmer AzC.

5.2 Changes in the North Atlantic circulation starting at MIS17

Both latitudinal and longitudinal thermal gradients (Fig. 3g) inform of drastic rearrangement of North Atlantic circulation starting at MIS17. SST at site 607 was much warmer than during MIS19, although both interglacials were similar, according to $\delta^{18}O$ (Fig. 3a,f). This points to a reactivation of the NAC during MIS17, and a displacement of this current westward site 607. Such reactivation would be the result of increased NADW formation, that reached higher rates than during the previous interglacial, as suggested by the ~0.2‰ higher $\delta^{13}C$ in MIS17 than in MIS19 (Fig. 3b). On the other hand, the very high latitudinal thermal gradient (Fig. 3g) suggests that this current did not reach subpolar latitudes, as it did during the following interglacial, MIS15, when this gradient was much lower.

The unusually high longitudinal thermal gradient registered during MIS17 was due to the prolonged deglaciation of MIS18, that continuously advected polar water along the Iberian margin (Martin-Garcia et al., 2015), resulting in very cold SST and high Nps percentages, at site U1385 (Fig. 3).

MIS16 was a very prolonged glacial with extensive ice sheets; nevertheless, polar waters did not extend to the mid-latitude ocean, as suggested by the low percentages of Nps in sites 607 and U1385 (Fig. 3c).

The latitudinal thermal gradient for most of MIS16, and the whole MIS14, was notably higher than during MIS20-18 (Fig. 3g). This great SST decrease, between sites 607 and 980, must be the result of a significant heat loss to the atmosphere and associated release of water vapour, along the path of the NAC during both MIS16 and MIS14. This water vapour release provided the necessary moist to continue ice-sheets growth, opposite to what had happened during previous glacials. Also contrary to glacials MIS20 and MIS18, when the surface water at the subpolar site 980 progressively cooled towards glacial maxima without important millennial-scale oscillations (Fig. 3f), in glacials MIS16 and MIS14, the surface ocean circulation was very variable and the AF migrated northward-southward site 980 very frequently (Fig. 3c-d). During short time periods, the NAC reached this subpolar site, conveying heat to the northern-latitude Atlantic (Fig. 3e). However, this oscillation of the AF never affected middle latitudes, according to the fairly mild SST, and low percentage of Nps, recorded both in the open ocean and in the continental margin during MIS16-14 (Fig. 3c,f).

In the mid-latitude ocean site 607, SST during MIS16 and MIS14 were very different from those recorded in MIS20 and MIS18 (Fig. 3f). While in the older glacials SST decreased towards glacial maxima, this trend is not observed during MIS16 and MIS14, and warm SST was recorded also during glacial maxima.

Although warmer SST were recorded through the mid-latitude North Atlantic, a negative thermal gradient still prevailed during MIS16-14, between sites 607 and U1385 (Fig. 3g), indicating a continuous heat flow toward southwest Iberia. This suggests that, this region remained under the influence of the subtropical AzC during most part of glacials MIS16 and MIS14, as it also did during MIS20, based on the mild SST registered at that time (Fig. 3f). Contrary to previous glacials, the NAC kept vigorous in site U1385 during MIS16, except at ~655 ka, and MIS14, and increased its strength as glacials advanced (Fig. 2d).

5.3 Implications of changes in the North Atlantic circulation associated to the MPT

Assuming a close correlation between the rate of AMOC and benthic $\delta^{13}C$ levels (Zahn et al, 1997; Adkins et al., 2005; Hoogakker et al., 2006), data from the sub-polar North Atlantic (Wright and Flower, 2002; Hodell et al., 2008) document a long-term increase in the NADW formation rate, that initiated in MIS22 and culminated in MIS14. This enhanced the southward flux of the NADW and, since MIS17, mid-latitude North Atlantic sites registered a relative decrease of the AABW during glacials, and subtropical sites recorded the presence of NADW at depths previously occupied by the AABW (e.g., Poirier and Billups, 2014; Hodell et al., 2015).

The increased production of NADW, during glacials after MIS16 respect to previous ones, triggered the advection of relatively-warm NAC towards subpolar latitude, providing additional humidity to the area and, thus, enhancing the growth of ice sheets, which led to the prolonged and extreme glaciation of MIS16, one of the first and most prominent glacials of the "100-ky world". In addition, the intermittent advection of this warm water made ice sheets more vulnerable to internal instabilities, with the subsequent release of icebergs registered in the North Atlantic during MIS16 (e.g., Wright and Flower, 2002; Hodell et al., 2008). The interaction between a more intense AMOC and ice sheet instabilities, recorded by rapid migrations of the AF north and south of site 980 (Fig. 3c-d), resulted in punctual events of sharp reduction of the NADW formation, like that at ~655 ka that coincided with one of the southernmost positions of the AF, according to the Tq record in site 980 (Wright and Flower, 2002), and was also registered in U1385 by peaks in Nps and Tq, and very low percentage of NACass (Fig. 3b-e). Both this episode and the outstanding one

~650 ka, with the lowest $\delta^{13}C$ value since MIS18 in middle latitudes in coincidence with very high abundance of the NACass in high latitudes (Fig. 3b,e), points to an exceptionally vigorous but shallow NA overturning cell, underlain by significant volumes of southern-sourced water, similarly to the situation at the end of TII (Böhm et al., 2014). This mode of AMOC, according to benthic $\delta^{13}C$ records, maintained during glacial stages MIS16, MIS15b, and MIS14, when the subpolar site 980 recorded > 0.25 ‰ higher $\delta^{13}C$ than southerner sites (Wright and Flower, 2002; Hodell et al., 2015, 2016).

This vigorous AMOC mode recorded in MIS14 was the culmination of a sequence of increasing deepening of the overturning circulation cell that initiated in MIS22, and was registered by a tendency towards higher benthic $\delta^{13}C$, both in high and mid-latitude sites U1308 and U1313, from MIS22 to MIS14 (Hodell and Channell, 2016), and was especially noticeable during glacial stages. During MIS20 and MIS18, ice sheets collapses (Wright and Flower, 2002) produced a continuous flux of meltwater pulses that kept very weak NADW formation; the deep North Atlantic being occupied by southern-sourced waters, according to very low benthic $\delta^{13}C$ recorded both in middle and high latitudes (Wright and Flower, 2002; Hodell et al., 2015; 2016). During these glacials, the almost shutdown AMOC maintained the AF at a southern position and prevented the northward flux of the necessary moisture for the growth of ice sheets, which could not work as a positive feedback and extend glacial stages over obliquity and precessional (41- and 23 ky) cycles, as they worked during MIS16, one of the first and most prominent glacials of the “100-ky world”.

6 Conclusions

By studying planktonic foraminiferal assemblages from the Iberian margin (IODP-U1385) for the interval 812–530 ka and comparing them with records from other sites between 41 and 55 ºN, we are able to trace paleoceanographic conditions across the North Atlantic from MIS20 to MIS14 and draw the following conclusions:

Variations of microfaunal assemblages associated to surface currents indicate a major change in the general North Atlantic circulation during this interval, coinciding with the definite establishment of the 100-ky climate phasing. In surface, this change consisted in the re-distribution of water masses and associated SST that happened linked to the northwestward migration of the AF during MIS16, and was related with the increasing NADW formation trend that initiated in MIS22.

Prior to MIS 16, the AMOC rate was very low, especially during glacials, the AF was at a southerly position, and the NAC diverted southeastwards, developing steep south-north and east-west thermal gradients, and blockading the arrival of warm water, with associated moisture, to the high latitude North Atlantic.

During MIS16, the NADW formation increased respect to previous glacials, especially during glacial maxima, which resulted in the north-westward AF shift and enhanced surface circulation, allowing the arrival of the relatively-warm NAC to subpolar latitudes and increasing the moisture availability to continuing the ice sheets growth, which would have worked as a positive feedback to prolong the duration of glacials to 100-ky cycles.

Appendix A: North Atlantic current assemblage (Ottens, 1991)

Globigerina bulloides
Globigerinella siphonifera (aequilateralis)
Globorrotalia inflata
Neogloboquadrina pachyderma dextral

Appendix B: warm surface assemblage (Vautravers et al., 2004)

Beela digitata
Globigerina falconensis
Globigerinella siphonifera (aequilateralis)
Globigerinoides ruber
Globigerinoides sacculifer
Globoturborotalita rubescens
Globoturborotalita tenella
Orbulina universa
Pulleniatina obliquiloculata

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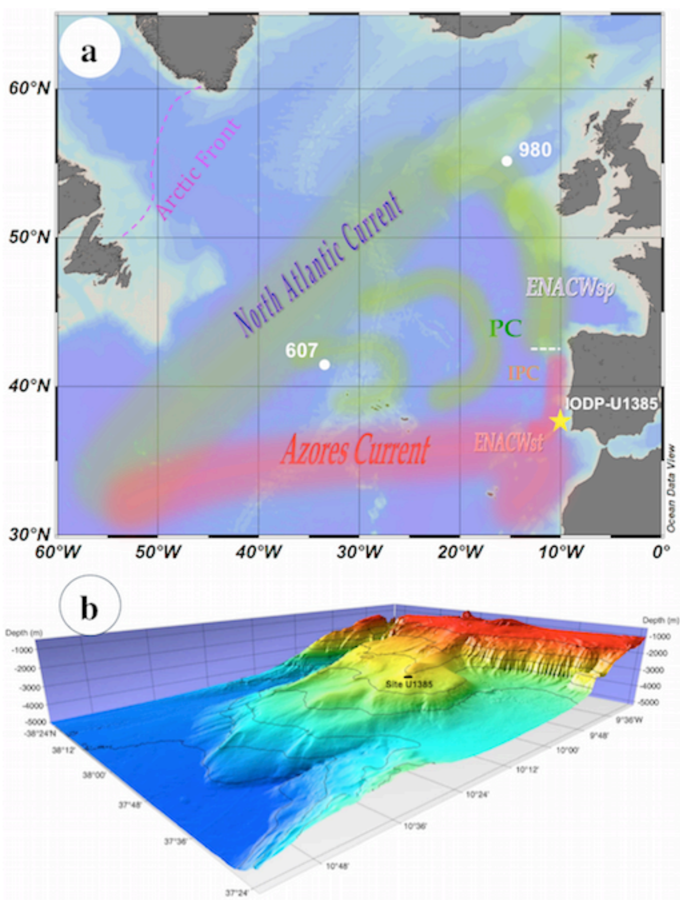


Figure 1. (a) Modern surface circulation in the North Atlantic and location of IODP-U1385 and other sites discussed in this paper. *ENACWsp* Eastern North Atlantic Central Waters of subpolar origin; *ENACWst*, Eastern North Atlantic Central Waters of subtropical origin; *IPC*, Iberian Poleward Current; *PC,* Portugal Current. The white dashed line represents the today´s approximate surface limit between *ENACWsp* and *ENACWst* (Fiúza et al., 1998). (b) Regional bathymetry of the SW Iberian margin, showing site U1385 (Expedition 339 Scientists, 2012).

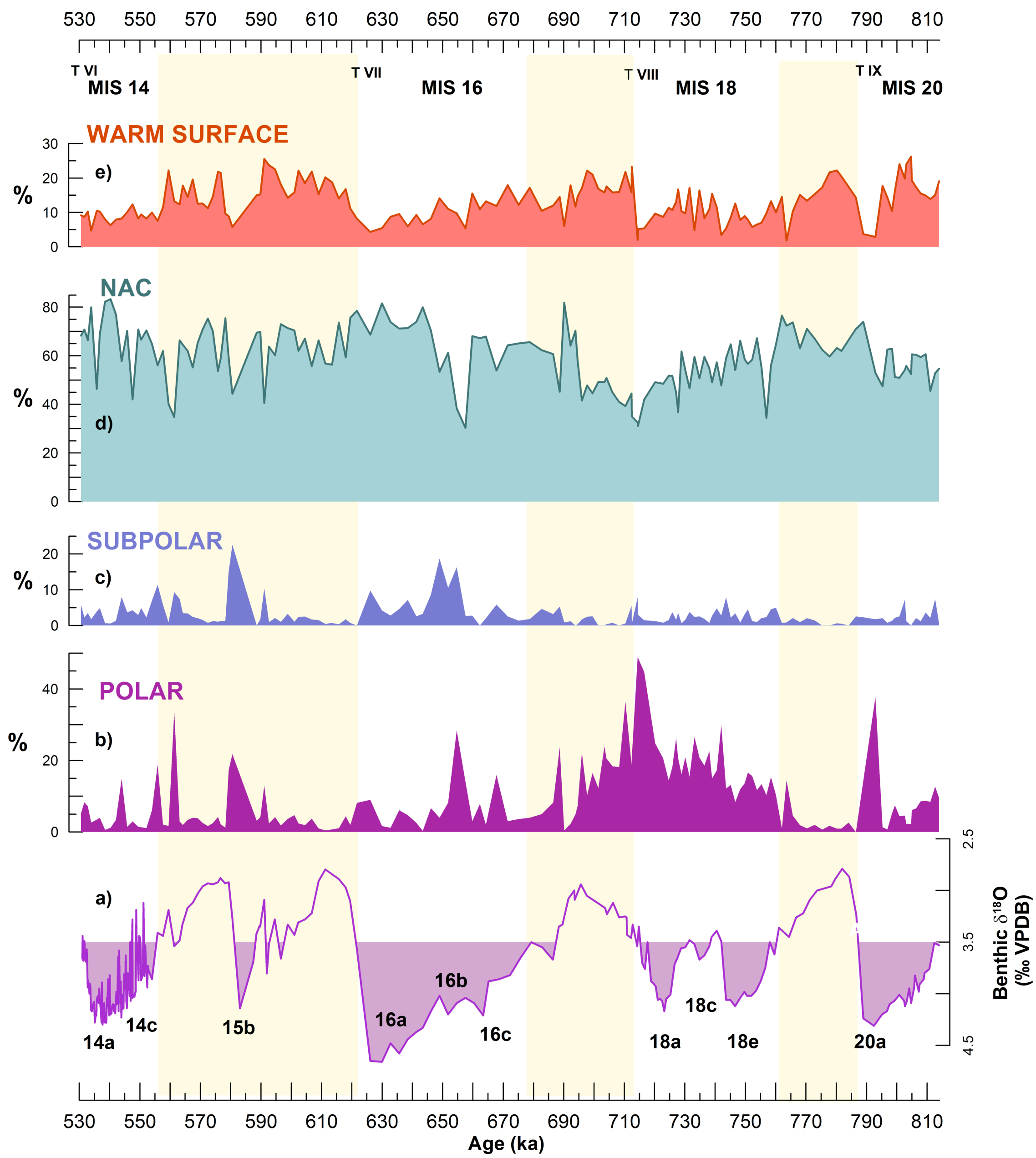
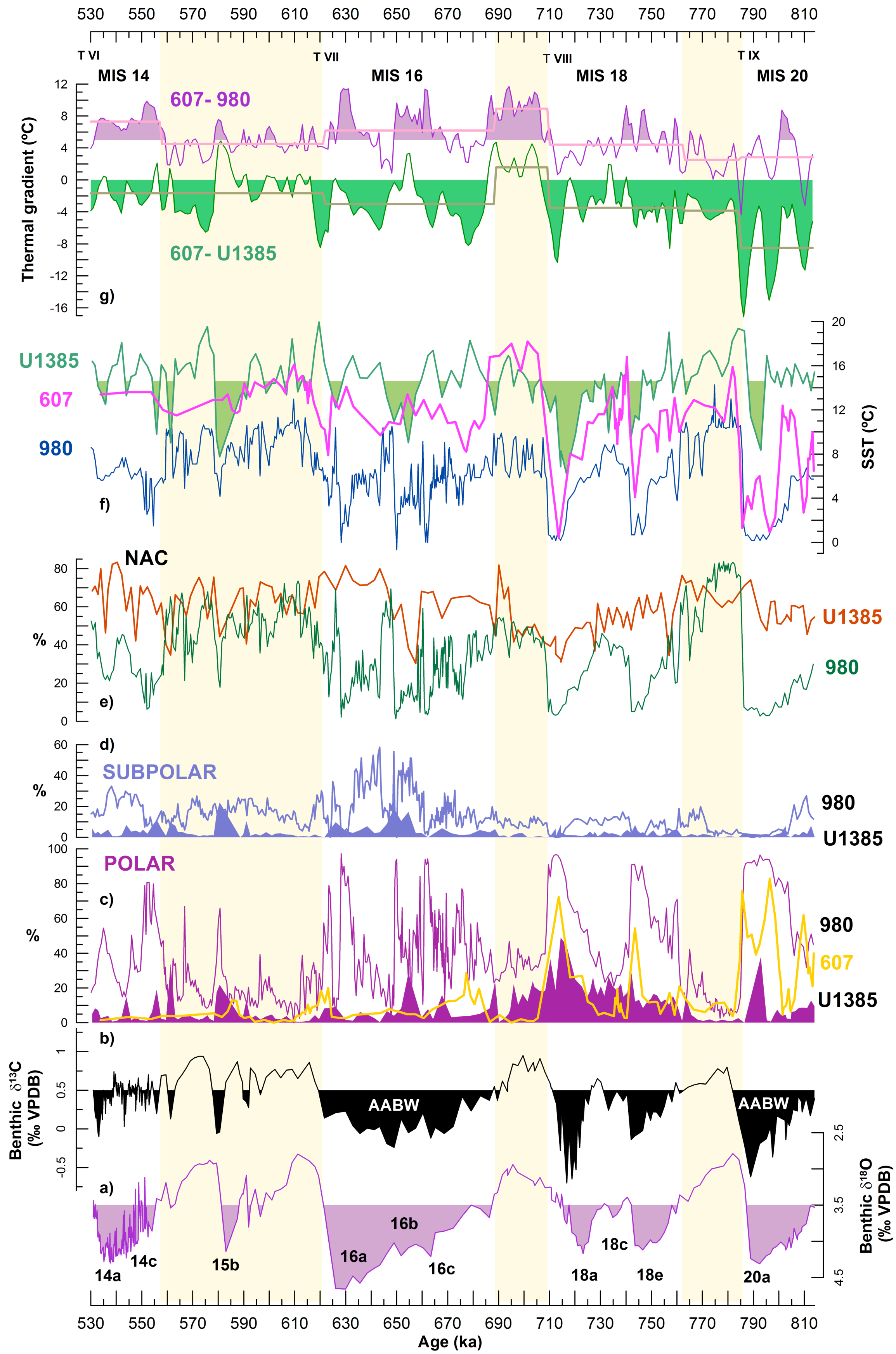


Figure 2. Relative abundance of planktonic foraminiferal species and assemblages in IODP-U1385 through MIS 14-20, and comparison with benthic isotope data from the same site. (a) Benthic $\delta^{18}O$ record (Hodell et al., 2015) with filling enhancing glacial conditions according to the threshold for the North Atlantic (McManus et al., 1999); glacial substages are named according to Railsback et al. (2015). Relative

abundance of: (b) polar species *N. pachyderma* sinistral; (c) subpolar species *T. quinqueloba*; (d) NAC assemblage (as defined by Ottens, 1991); and (e) warm surface assemblage (as defined by Vautravers et al., 2004). Yellow bands highlight interglacials. Terminations (T) are marked in roman numerals. IODP-U1385 isotopic record is from Hodell et al. (2015).



Thermal gradient (ºC)
607- 980
607- U1385
g)
T VI
T VII
T VIII
T IX
MIS 14
MIS 16
MIS 18
MIS 20
U1385
607
980
f)
SST (ºC)
NAC
%
e)
U1385
980
d)
SUBPOLAR
%
980
U1385
POLAR
c)
%
980
607
U1385
b)
Benthic δ13C (‰ VPDB)
AABW
AABW
a)
Benthic δ18O (‰ VPDB)
14a
14c
15b
16a
16b
16c
18a
18c
18e
20a
Age (ka)

554

Figure 3. Comparison of records from the mid-latitude (IODP-U1385; ODP-607) and the subpolar (ODP-980) North Atlantic. Benthic $\delta^{18}O$ (a), and $\delta^{13}C$ (b) from U1385 (Hodell et al., 2015); filling in (b) enhancing ^{13}C-depleted values typical for Antarctic bottom water (AABW) (Adkins et al., 2005). (c) Percentage of *N. pachyderma* sinistral in sites U1385 (filled), 607 (glod) and 980 (purple). (d) Relative abundance of *T. quinqueloba* for sites U1385 (filled) and 980. (e) Relative abundance of the NAC assemblage (as defined by Ottens, 1991) in sites U1385 (red) and 980 (green). Site 980 faunal data are from Wright and Flower, 2002; for this work, the NAC assemblage of site 980 has been calculated using the published census counts. (f) SST from sites 980 (dark blue; Wright and Flower, 2002), 607 (pink; Ruddiman et al., 1989), and U1385 (green; Martin-Garcia et al., 2015), with filling enhancing lower than 14.6 ºC, the average SST for the study interval. (g) Longitudinal (green) and latitudinal (purple) thermal gradients, with the statistical mean for each MIS represented in superimposed straight lines. Age models for sites 980 and 607 have been re-calculated using the LR04-stock. Yellow bands highlight interglacials. Terminations (T) are marked in roman numerals.