

## Cp-2018-30\_2<sup>nd</sup>. Revision COVER LETTER

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To Marit-Solveig Seidenkrantz, Editor,

Re: 2<sup>nd</sup> revision of the manuscript **cp-2018-30**

(by Gloria M. Martin-Garcia, Francisco J. Sierro, José A. Flores and Fatima Abrantes)

Dear Editor, we are submitting the new version of our manuscript, that has been reviewed according to the Referees' suggestions.

A point-to-point reply to Referees' comments is detailed in the "2<sup>nd</sup> Response to Ref" files. The main changes in this version of the manuscript are:

The title of the manuscript has been changed into: "***Change in the North Atlantic circulation associated to the mid-Pleistocene transition***", to avoid misleading the reader, as Ref #1 suggests.

The abbreviation of species have been changed as Ref # 2 suggests

Line 47:

The following cites have been added: (McCartney and Talley, 1984; Ruddiman and McIntyre, 1984; Schmitz and McCartney, 1993; Rahmstorf, 1994; Chapman and Maslin, 1999)

Lines 68/69, 70, 89, 100, 102, 150, 156, 157, 177, 283, 313:

The text of these lines has been modified as suggested

Line 71/72:

The text has been changed as follows: "the Earth's climate system underwent a major change, non-linear 100 ky cycles appeared and superimposed over the more linear, orbital ones of 41 and 23 ky."

Lines 121-124:

The age models for sites 980 and 607 have been explained (new lines 141-143)

Line 131:

A detailed list of indicator species has been included in this section

Line 135-141:

The text has been changed as follows (new Lines 175-178: "This estimation of thermal gradients is possible because all the SST records used for this work are based in planktonic foraminifers' census counts. Nevertheless, previous to the comparison, interpolation was applied to obtain records with the same age points."

Line 142:

The wrong paragraph has been deleted

Line 155:

The paragraph has been changed as follows: "Sediments at Site U1385 define a single, very uniform, lithological unit. Calcareous muds and calcareous clays dominate the lithology. The relative proportions of carbonate (23% - 39%) and terrigenous materials show in the sediment color that varies from dark (i.e., more terrigenous) to light (i.e., more calcareous). The average sedimentation rate for the section is of ~10 cmky<sup>-1</sup> (Stow et al., 2012)."

Lines 176-180:

The new paragraph states as follows: “In U1385, this assemblage shows a clear interglacial-glacial pattern only since Termination TVIII, its percentage decreasing gradually during MIS17-16 until the glacial maximum (Fig. 2e). Comparing glacial stages, MIS20 records the highest average relative abundance (16.8%) and MIS14, the lowest (8.7%). Termination TIX records the most abrupt decrease of this assemblage (15% drop), while at TVI it even increases (5% rise). At the beginning of each interglacial, the percentage of this assemblage rises rapidly, suggesting that the AzC strengthens rapidly in the area after Terminations.”

Line 314:

The former reference was wrong; the right one is Martin-Garcia et al. 2015, and has been included in the new version

Looking forward hearing from you soon,  
Yours sincerely

Gloria M. Martin-Garcia (on behalf of all the authors of the paper)

## **RESPONSE TO REVIEWERS**

### **Response to Referee # 1 // report #2**

The manuscript by Martin-Garcia et al. is improved, but I believe that it needs additional revisions. The authors appear to have addressed the majority of my comments, but not all. It is a bit difficult to determine because the cover letter does not contain references to the specific line numbers where the changes have been implemented so that one can easily cross-check. In addition, the manuscript text is still unclear at times due to the awkward use of the English language.

It occurred to me that the title is a bit misleading. If a study examines the role of North Atlantic circulation in the mid-Pleistocene transition, then I would expect that it spans the entire interval of time. Here the records do not begin until after the mid-point (MIS 20). So only half of the event is captured.

The title of the article has been changed into “Change in the North Atlantic circulation associated to the mid-Pleistocene transition” to avoid misleading the reader.

I still think that a mention of the closed sum problem is important. In my mind changes in a dominant assemblage can drive the percentages of a less dominant species. True, this approach is often used. But that does not mean that it does not have uncertainties.

We know that this problem is intrinsic to all ecological and paleoecological studies. A decrease in abundance of individuals of one species will increase the relative abundance of the others, but there is no other way to deal with this. Absolute abundances of the planktonic species cannot be used in paleoecology, because they are determined by other, non-ecological parameters, such as dilution by detrital inputs, etc.

Regarding my comment to Line 251 of the original manuscript (now section 5.3): The authors maintain that there is an increase in NADW formation rate during glacial intervals begin with MIS 22 and ending with MIS 14. They cite Wright and Flower, 2002; Hodell et al., 2008,

Poirier and Billups 2014, Hodell et al., 2015 for this statement (in the text or rebuttal). I have looked at all of these articles and cannot find a single statement to this effect. In fact, Wright and Flower cite Raymo et al., 1997 saying that there is greater suppression of NADW ... from 950 to 350 Ka. Hodell et al 2015 is about the age model for Site U1385, and I don't see a discussion of deep water circulation in that paper, the d13C record is not shown. Hodell and Channel (2016) note that d13C minima increase from MIS 22 to MIS 14, and they cite Raymo for this observation. However, to my reading of this article, they do not say that this is due to an increase in NADW formation.

This interpretation, as we say at the beginning of the section, is based in “a close correlation between the rate of AMOC and benthic d<sup>13</sup>C levels (Zahn et al, 1997; Adkins et al., 2005; Hoogakker et al., 2006)”. From this assumption, we interpret the published d13C data.

D13C, compared with d18O, from sites 980 (Fig 3 in W&F 2002), U1308-607 (fig 10 in Hodell et al. 2008) (Fig 3 in Hodell-Channell 2016), 1063 (Fig 4, 5c, 7d-h in P&B 2014) and U1385 (Fig 4 in Martin-Garcia et al., 2015), document this increase. We do not think there is any doubt respect MIS 14. As for MIS 16, although it was a more prolonged and severe (in ice volume) glacial than MIS 18, 20 and 22, its d13C was not so low as should be expected. Besides, during MIS 16 glacial maximum, d13C was higher than during the previous glacial maxima.

Respect to Hodell et al 2015, the referee is right. D13C from site U1385 appeared in Martin-Garcia et al., 2015, instead in the previously cited paper. The newly reviewed manuscript has the correct reference.

The rest of my comments are in order of occurrence in the manuscript text:

Line 47: add a citation?

The following cites have been added: (McCartney and Talley, 1984; Ruddiman and McIntyre, 1984; Schmitz and McCartney, 1993; Rahmstorf, 1994; Chapman and Maslin, 1999)

Line 68/69: related to the

Line 70: no comma after which

These lines have been modified as suggested

Line 71/72: the climate system did not switch, the 100 kyr cycle started to appear. The 41 and 23 kyr cycles continue to be present

The text has been changed as follows: “the Earth’s climate system underwent a major change, non-linear 100 ky cycles appeared and superimposed over the more linear, orbital ones of 41 and 23 ky.”

Line 80: why glacial? The manuscript seems to address both, glacial and interglacial intervals

Enhanced ice sheets growth and reduced NADW formation are postulated as partly responsible for the change of the climate system phasing (Imbrie et al., 1993). This manuscript explores such possibility by studying variations in the advection of warm and saline water to subpolar latitudes, before/after the occurrence of the first 100 ky cycle. We are not so interested in the potential change of circulation during interglacials before/after because they did not contribute to increase the ice volume.

The comparison with interglacial conditions serves to highlight the change of circulation that occurred during glacials.

Line 89: I would replace the word 'proven' with something like 'shown'

Line 100: of the Quaternary

Line 102 at the surface

In these lines, the text has been changed as suggested

Line 155: No single sentence paragraphs. What is the difference between a calcareous mud and a calcareous clay? Calcareous means biogenic carbonate as well, right? This paragraph needs a bit rewording to make it more clear.

The difference between mud and clay is the grain size.

The paragraph has been changed as follows:

“Sediments at Site U1385 define a single, very uniform, lithological unit. Calcareous muds and calcareous clays dominate the lithology. The relative proportions of carbonate (23% - 39%) and terrigenous materials show in the sediment color that varies from dark (i.e., more terrigenous) to light (i.e., more calcareous). The average sedimentation rate for the section is of  $\sim 10 \text{ cmky}^{-1}$  (Stow et al., 2012).”

Lines 121-124: What about the age models of the other sites? For calculation of the thermal gradient it is really important that the age models are comparable.

New age models were calculated for sites 980 and 607, based on correlations with the LR04 stack. (Lines 141-143)

Line 131: More detail? I think that it would be appropriate to include a brief list of warm versus cold assemblages etc., then refer to the Appendix with more details

A detailed list of indicator species has been included in this section

Line 135-141: How are the SSTs subtracted? Are the records interpolated to the same ages? The method needs more detail.

The method has been explained in more detail.

Lines 175-178: “This estimation of thermal gradients is possible because all the SST records used for this work are based in planktonic foraminifers’ census counts. Nevertheless, previous to the comparison, interpolation was applied to obtain records with the same age points.”

Line 142: SSTs from Site 607 and 980 have been published. Not all SSTs records have been published as you are presenting those from Site 1385 here for the first time?

The reviewer is right, and the wrong paragraph has been deleted

Line 150: replace the two ‘to’ with ‘with’

Line 156: replace ‘keeps’ with ‘stays’

Line 157: specify which ones, ‘some’ is vague

In these lines, the text has been changed as suggested

Lines 167-174: To my eye the variations are subtle. It seems very qualitative

As the NAC assemblage is the dominant one during the whole interval, and its percentage is never lower than 30 %, subtle variations can indicate substantial changes of the surface circulation

Line 177: instead of referring to a particular climate cycle, just say which MIS, or which Termination? Those are labeled in the figure and it is thus easier to find.

The text has been modified as suggested: “since Termination TVIII”

Line 177: ‘since’ is not correct as the records end at MIS 14.

As we are detailing our results, and the study interval has already been defined, it is understood that “since” refers to our record.

Lines 176-180: I am not sure I can follow the sentence at all. MIS 20 is not an interglacial. And, the variations are subtle, what do you mean with ‘fairly’? I would suggest providing the changes of the percentages to give the reader a sense of how much of a change is actually occurring.

The text has been re-written to clarify it.

It states as follows: “In U1385, this assemblage shows a clear interglacial-glacial pattern only since Termination TVIII, its percentage decreasing gradually during MIS17-16 until the glacial maximum (Fig. 2e). Comparing glacial stages, MIS20 records the highest average relative abundance (16.8%) and MIS14, the lowest (8.7%). Termination TIX records the most abrupt decrease of this assemblage (15% drop), while at TVI it even increases (5% rise). At the beginning of each interglacial, the percentage of this assemblage rises rapidly, suggesting that the AzC strengthens rapidly in the area after Terminations.”

Line 244: is a 0.2 per mil difference in d13C values really significant in terms of NADW? There are other factors that determine the d13C values of benthic forams.

Maximal variation of d13C during MIS 15-14, for instance, was 1 per mil. Although it is true that other factors can contribute, we did not find anything that definitely demonstrates that variations in d13C were NOT related with the presence of different masses of water at the bottom.

Line 283: associated with

The text has been modified as suggested

Lines 285-292: see comment above. I cannot find any statements to this effect in the literature cited in this section. The authors seem to base this on a slight increase in benthic foram d13C values at their site? I think the interpretation of the d13C record is a lot more complex as presented in this study. Do these studies really say that there is an increase in NADW during glacial intervals specifically? Or are they referring to a more general increase in NADW over time, which includes interglacial intervals? As noted above, I cannot find d13C records in the Hodell et al 2015 paper, do you mean Hodell and Channel 2016? They describe an increase in d13C values, but I don't think they discuss deep water circulation.

This question was answered above.

Our statements are not only based on the record from U1385, but also on the data shown in the cited articles (although the authors not necessarily discuss deep water circulation)

As for the increase in NADW formation during interglacials, as well as glacials, we are not arguing against it. The issue we address is that the enhanced AMOC during glacials MIS 16 and MIS 14, had consequences in the building of ice sheets, and prolonged the duration of the glacial stages

The cite Hodell et al 2015 was wrong; d13C data from site U1385 appeared in Martin-Garcia et al 2015. The right reference has been added.

Line 313: southern-more or more southern?

The text has been modified as suggested

Line 314: I cannot find any reference to d13C in the Hodell et al. 2015 paper.

The right reference is Martin-Garcia et al. 2015 (Figure 4)

Line 315: How can you tell from your data that the overturning cell was deepening? Hodell and Channel describe that d13C minima get higher between MIS 22 and MIS14 citing Raymo. But I don't think that they say that this is due to more NADW formation. In any case, there could be other factors.

As explained above, this interpretation is based in the correlation between d13C and masses of water. Although it is true that other factors can contribute, we did not find anything that definitely demonstrates that variations in d13C were NOT related with the presence of different masses of water at the bottom.

Assuming this, d13C records from different N Atlantic sites, not only from U1385, show a progressively increased presence of NADW at depths previously occupied by the AABW (Fig 3 in Hodell-Channell 2016; Fig 4, 5c, 7d-h in P&B 2014; Fig 4 in Martin-Garcia et al., 2015)

## **Response to Referee # 2 // report #2**

I have just two technical comments, as follows:

i) I do not like to use only letters for planktonic foraminifera (i.e., *Turborotalita quinqueloba*=Tq). Because of in the manuscript there are several abbreviation related to the different water fronts, the authors can use the classic abbreviation for planktonic forams, ie., *T. quinqueloba*. The same for *Neogloboquadrina pachyderma* left coiled.

The abbreviations of species have been changed as suggested

ii) the authors at chapter 5.1 start for fig. 3f. In my opinion, the first cited figure in a chapter has to be fig. 3a and after fig. 3b, fig. 3c.....

Yes, this order is the most common one. Nevertheless, panels in figure 3 are arranged in what we think is a more logical and intuitive way, as follows (from bottom to top):

1. Data from the bottom (d18O and d13C)
2. Data of species used as indicators (from polar to mid-latitude)
3. SST
4. Thermal gradient obtained from the previous

# Change in the North Atlantic circulation associated to 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 (37°34.285'N, 10°7.562'W; 2585 mbsl). By comparing the obtained results with published records from other North Atlantic sites between 41 and 55 °N, 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



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

36

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

40

## 41 **1 Introduction**

42 Climate in the North Atlantic region is characterized by the continuous poleward  
43 heat flow carried out by the oceanic circulation. The Gulf Stream and the North  
44 Atlantic Current (NAC) transport warm and salty surface water, originated in the  
45 tropical region, towards the polar ocean, the northeast Atlantic, and along the western  
46 European margin, transferring heat and moisture to the atmosphere during the  
47 process [\(e.g., McCartney and Talley, 1984; Ruddiman and McIntyre, 1984; Schmitz  
48 and McCartney, 1993, Rahmstorf, 1994; Chapman and Maslin, 1999\)](#). Surface  
49 circulation and associated heat flow is pumped by the sinking of surface water in the  
50 subpolar region and formation of the North Atlantic Deep-water (NADW). As a matter  
51 of fact, the Atlantic Meridional Overturning Circulation (AMOC) is responsible for  
52 ~50% of the total poleward heat advection (Sabine et al., 2004; Adkins, 2013).

53 The NAC forms the transition zone between the cold and productive waters  
54 located north of the Arctic Front (AF) (eg., Johannessen et al., 1994), and the warm  
55 and oligotrophic waters from the subtropical gyre in the South. Each water mass has  
56 distinct physic-chemical characteristics and specific planktonic foraminiferal  
57 assemblages (eg., Bé, 1977; Ottens, 1991; Cayre et al., 1999). Various studies have  
58 shown that surface water characteristics in the mid-latitude North Atlantic depend on  
59 the strength and position of the NAC and associated oceanic fronts (Calvo et al.,  
60 2001; Naafs et al., 2010; Voelker et al., 2010). During Pleistocene glacials, the AF  
61 migrated southward into mid-latitude North Atlantic (Stein et al., 2009; Villanueva et

62 al., 2001), cold polar waters expanded to lower latitudes and the NAC did not reach  
63 as far North as during interglacials (e.g., Pflaumann et al., 2003).

64 After MIS21, a northwestward shift in the position of the AF began (Hernandez-  
65 Almeida et al., 2013), that culminated at the end of MIS16, in a similar location to  
66 today's (Wright and Flower, 2002). Coinciding with the final stage of this shift, a major  
67 reorganisation of the meridional overturning circulation developed, related to  
68 increased NADW formation that resulted in deeper and southward penetration of this  
69 mass of water (Poirier and Billups, 2014). Both processes could have been related to  
70 the prolongation of glacials that occurred at the end of the mid-Pleistocene transition  
71 (MPT). This was the transitional period during which the Earth's climate system  
72 underwent a major change, non-linear 100 ky cycles appeared and superimposed  
73 over the more linear, orbital ones of 41 and 23 ky.

74 Although there is still no agreement over the initiation of the MPT (e.g., Clark et  
75 al., 2006; Maslin and Brierley, 2015), strong 100 ky cycles are recorded since ~650  
76 ka (Ruddiman et al., 1989; Imbrie et al., 1993; Mudelsee and Schulz, 1997). Related  
77 with the shift in the AF position, warm and salty surface water could reach subpolar  
78 latitudes during glacials, which would have provided the necessary humidity to  
79 prolong the growth of ice sheets, as well as enhanced meridional overturning – both  
80 processes acting as feedback mechanisms partly responsible for the change of the  
81 climate system phasing (Imbrie et al., 1993). The objective of this work is to study the  
82 evolution of glacial circulation in the North Atlantic from MIS20 to MIS14, and explore  
83 its possible relation with the MPT.

84 Over the last glacial cycle, the Iberian margin recorded both peak displacement  
85 events of the AF and periods of greater influence of subtropical water from the Azores  
86 Current (AzC) (eg., Martrat et al., 2007; Eynaud et al., 2009; Salgueiro et al., 2010).  
87 There is also evidence that polar to tropical planktonic foraminifers assemblages co-  
88 occurred in a latitudinal band around 35° – 40°N during the Last Glacial Maximum  
89 (McIntyre et al., 1972), which suggests that the limit between both water masses was  
90 situated slightly southwards than it is today (Fiúza et al., 1998; Peliz et al., 2005). Site  
91 IODP-U1385 (37°34'N) lies within this oscillating boundary, and has been shown an  
92 ideal location to study oceanographic changes in the North Atlantic through glacial-

93 interglacial periods (e.g., Maiorano et al., 2015; Martin-Garcia et al., 2015; Rodríguez-  
94 Tovar et al., 2015; Rodrigues et al., 2017). Analyses of planktonic foraminifer  
95 assemblages are used to identify the different water masses, and results from IODP-  
96 U1385 are compared with published data from other North Atlantic latitudes to reach  
97 basin-wide conclusions.

98

## 99 **2 Materials and Methods**

### 100 **2.1 IODP Site U1385**

101 The Southwestern Iberian margin is a focal location for paleoclimate and  
102 oceanographic research of the Quaternary (Hodell et al. 2013). Site IODP-U1385 was  
103 drilled at the so-called Shackleton Site (37°34.284'N, 10°7.562'W), at 2589 meters  
104 water depth (Fig. 1). At the surface, this area lies under the influence of the *North*  
105 *Atlantic Central Water* (NACW), with a complex circulation pattern; at depth, the  
106 NADW flows between ~2,200 and 4,000 meters, above the *Antarctic Bottom Water*  
107 (AABW).

108 Today's surface water circulation in the North Atlantic (Fig. 1a) consists of two  
109 different branches. The NAC, after reaching the subpolar ocean, drifts southwards  
110 along Europe transporting the Eastern North Atlantic Central Water of sub-polar origin  
111 (ENACWsp), formed north of 46° (Brambilla and Talley, 2008). In the south, the AzC,  
112 of subtropical origin (ENACWst) and formed along the Azores Front (Rios et al.,  
113 1992), drifts eastwards and bifurcates when approaching the continental margin. The  
114 ENACWst is saltier, warmer, less dense than the ENACWsp and overflows it along  
115 Iberia with a decreasing lower limit from south to north until ~42.7 °N (Fiúza et al.,  
116 1998).

117 Sediments at Site U1385 define a single, very uniform, lithological unit.  
118 Calcareous muds and calcareous clays dominate the lithology. The relative  
119 proportions of carbonate (23% - 39%) and terrigenous materials show in the sediment  
120 color that varies from dark (i.e., more terrigenous) to light (i.e., more calcareous). The  
121 average sedimentation rate for the section is of ~10 cmky<sup>-1</sup> (Stow et al., 2012).

122

### 123 **2.2 Foraminiferal study**

124 This study covers a section comprised between 67.2 and 94.6 crmcd (MIS14 -  
125 MIS20). The age model (Hodell et al., 2015) is based on the correlation of the benthic  
126 oxygen isotope record to the global benthic LR04 isotope stack (Lisiecki and Raymo,  
127 2005). For better comparing our results with data from other North Atlantic sites, new  
128 age models were calculated for sites 980 and 607, based on correlations with the  
129 LR04 stack.

130 Sampling was performed every 20 cm, providing a 1.76-ky resolution on average.  
131 A total of 147 samples, 1 cm-thick, were freeze-dried, weighed and washed over a  
132 63- $\mu$ m mesh. The >63  $\mu$ m residue was dried, weighed and sieved again to separate  
133 and weigh the >150  $\mu$ m fraction. Planktonic foraminifers' taxa were identified (Kennett  
134 and Srinivasan, 1983) in aliquots of this last fraction containing a minimum of 300  
135 specimens.

136 The microfaunal analysis focused on species and assemblages that are  
137 associated with North Atlantic surface water masses (Appendices A and B).  
138 Neogloboquadrina pachyderma sinistral (*N. pachyderma sin*) is an indicator of polar  
139 water (Cayre et al., 1999; Pflaumann et al., 2003; Eynaud et al., 2009). *Turborotalita*  
140 *quinqueloba* dwells in cold waters and is usually associated with the AF  
141 (Johannessen et al., 1994; Cayre et al., 1999). *Globigerina bulloides*, *Globigerinella*  
142 *siphonifera (aequilateralis)*, *Globorrotalia inflata*, and *Neogloboquadrina incompta*  
143 (former *N. pachyderma dextral*), form the North Atlantic Current (NAC) assemblage,  
144 as defined by Ottens (1992). Finally, species included in the warm surface  
145 assemblage (Vautravers et al., 2004) are: *Beela digitata*, *Globigerina falconensis*,  
146 *Globigerinella siphonifera (aequilateralis)*, *Globigerinoides ruber*, *Globigerinoides*  
147 *sacculifer*, *Globoturborotalita rubescens*, *Globoturborotalita tenella*, *Orbulina*  
148 *universa*, and *Pulleniatina obliquiloculata*.

149

### 150 **2.3. Estimation of thermal gradients**

151 Thermal gradients in the North Atlantic are reconstructed by calculating the  
152 difference between the Sea Surface Temperature (SST) from two sites. The site 607  
153 was used as start point, and compared with sites 980 for the latitudinal gradient  
154 ( $SST_{607} - SST_{980}$ ), and U1385 for the longitudinal one ( $SST_{607} - SST_{U1385}$ ). In this

155 way, a positive longitudinal gradient means that SST was warmer at site 607 than at  
156 U1385; a negative longitudinal gradient indicates warmer SST off SW Iberia than at  
157 site 607.

158 This estimation of thermal gradients is possible because all the SST records used  
159 for this work are based in planktonic foraminifers' census counts. Nevertheless,  
160 previous to the comparison, interpolation was applied to obtain records with the same  
161 age points.

162

### 163 **3 Results**

164 Except in the eighth climate cycle (MIS19-MIS18), *Neogloboquadrina*  
165 *pachyderma sinistral* does not vary at glacial-interglacial scale, but peak percentages  
166 are associated either with glacial maxima (MIS20) or to deglaciations, both  
167 Terminations and other deglacial events (Fig. 2b), revealing increased advection of  
168 polar water at these times. *N. pachyderma sin* is less abundant during interglacial  
169 conditions than during glacials, but it is important to note that its percentage during  
170 glacials change through the time series. This species is more abundant during  
171 glacials MIS20, MIS18 (when the highest percentages occurred), and the first half of  
172 MIS16, than during late MIS16 and glacial MIS14 (Fig. 2b). After ~650 ka, *N.*  
173 *pachyderma sin* stays below 10%, except during deglacial events MIS15b/a and at  
174 the end of MIS15, as inferred from sharp decreases in  $\delta^{18}\text{O}$  (Fig.2a-b). This suggests  
175 that since mid-MIS16, the polar water only reached the southwest Iberian margin  
176 associated to some deglacial episodes, and not during full glacial conditions or glacial  
177 maxima, in opposition to what happened before ~650 ka.

178 *Turborotalita quinqueloba* shows lower percentage during MIS20 and MIS18,  
179 than since MIS16 (Fig. 2c). Highest values occur at ~650 ka and during MIS15b, the  
180 glacial interval that interrupted interglacial MIS15. The variation of *T. quinqueloba* in  
181 site U1385 does not show an interglacial-glacial pattern, which suggests this site did  
182 not register the migration of the AF through each climate cycle.

183 The NAC assemblage (Ottens, 1992) is the most abundant one at this site (Fig.  
184 2), indicating that the ENACWsp dominates the surface oceanography in the area  
185 through the time series. This assemblage does not keep a similar interglacial-glacial

186 pattern through the whole study interval, but changes its behaviour at ~650 ka.  
187 Previous to ~650 ka, its variation mirrors that of *N. pachyderma sin*, and the highest  
188 values occur during interglacials. In opposition to this, since ~650 ka, the highest  
189 percentages coincide with full glacial conditions (MIS16a and MIS14a), not with  
190 interglacials (Fig. 2d).

191 The Warm Surface (WS) assemblage (Vautravers et al., 2004) is typical of the  
192 subtropical water transported eastwards by the AzC. In U1385, this assemblage  
193 shows a clear interglacial-glacial pattern only since Termination TVIII, its percentage  
194 decreasing gradually during MIS17-16 until the glacial maximum (Fig. 2e). Comparing  
195 glacial stages, MIS20 records the highest average relative abundance (16.8%) and  
196 MIS14, the lowest (8.7%). Termination TIX records the most abrupt decrease of this  
197 assemblage (15% drop), while at TVI it even increases (5% rise). At the beginning of  
198 each interglacial, the percentage of this assemblage rises rapidly, suggesting that the  
199 AzC strengthens rapidly in the area after Terminations.

200

## 201 **5 Discussion**

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

214

### 215 **5.1 North Atlantic circulation during glacials MIS20 and MIS18**

216 During both glacials, progressive cooling is recorded in sites 607 and 980 (Fig. 3f).  
217 Though the cooling is more pronounced at the higher latitude, the SST gradient  
218 between both sites is not very high and decreases largely towards the end of glacial  
219 stages (Fig. 3g). In contrast, the Iberian margin remained relatively warm during most  
220 of MIS20 and a large part of MIS18 (Fig. 3f), which undoubtedly reflects a continuous  
221 flow of the AzC to this region, as also indicated by the WS assemblage record (Fig.  
222 2e).

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

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

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

252

## 253 **5.2 Changes in the North Atlantic circulation starting at MIS17**

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

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

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

271 The latitudinal thermal gradient for most of MIS16, and the whole MIS14, was  
272 notably higher than during MIS20-18 (Fig. 3g). This great SST decrease, between  
273 sites 607 and 980, must be the result of a significant heat loss to the atmosphere and  
274 associated release of water vapour, along the path of the NAC during both MIS16 and  
275 MIS14. This water vapour release provided the necessary moist to continue ice-  
276 sheets growth, opposite to what had happened during previous glacials. Also contrary



277 to glacials MIS20 and MIS18, when the surface water at the subpolar site 980  
278 progressively cooled towards glacial maxima without important millennial-scale  
279 oscillations (Fig. 3f), in glacials MIS16 and MIS14, the surface ocean circulation was  
280 very variable and the AF migrated northward-southward site 980 very frequently (Fig.  
281 3c-d). During short time periods, the NAC reached this subpolar site, conveying heat  
282 to the northern-latitude Atlantic (Fig. 3e). However, this oscillation of the AF never  
283 affected middle latitudes, according to the fairly mild SST, and low percentage of *N.*  
284 *pachyderma sin.*, recorded both in the open ocean and in the continental margin  
285 during MIS16-14 (Fig. 3c,f).

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

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

298

### 299 **5.3 Implications of changes in the North Atlantic circulation associated with the** 300 **MPT**

301 Assuming a close correlation between the rate of AMOC and benthic  $\delta^{13}\text{C}$  levels  
302 (Zahn et al, 1997; Adkins et al., 2005; Hoogakker et al., 2006), we interpret that the  
303 published  $\delta^{13}\text{C}$  data from the sub-polar North Atlantic (Wright and Flower, 2002;  
304 Hodell et al., 2008; Hodell and Channell, 2016) document a long-term increase in the  
305 NADW formation rate, that initiated in MIS22 and culminated in MIS14. Since MIS17,  
306 mid-latitude and subtropical North Atlantic sites registered a progressive increase of

307 | [NADW at depths previously occupied by the AABW \( \$\delta^{13}\text{C}\$  data in e.g., Poirier and](#)  
308 | [Billups, 2014; \*\*Martin-Garcia\*\* et al., 2015\).](#)

309 | The increased production of NADW, during glacials after MIS16 respect to  
310 | previous ones, triggered the advection of relatively-warm NAC towards subpolar  
311 | latitude, providing additional humidity to the area and, thus, enhancing the growth of  
312 | ice sheets, which led to the prolonged and extreme glaciation of MIS16, one of the  
313 | first and most prominent glacials of the “100-ky world”. In addition, the intermittent  
314 | advection of this warm water made ice sheets more vulnerable to internal instabilities,  
315 | with the subsequent release of icebergs registered in the North Atlantic during MIS16  
316 | (e.g., Wright and Flower, 2002; Hodell et al., 2008). The interaction between a more  
317 | intense AMOC and ice sheet instabilities, **registered** by rapid migrations of the AF  
318 | north and south of site 980 (Fig. 3c-d), resulted in punctual events of sharp reduction  
319 | of the NADW formation, like that at ~655 ka that coincided with one of the  
320 | southernmost positions of the AF, according to the record [of \*T. quinqueloba\*](#) in site  
321 | 980 (Wright and Flower, 2002), and was also registered in U1385 by peaks in [this](#)  
322 | [species and in \*N. pachyderma sin.\*](#), [coinciding with](#) very low percentage of NACass  
323 | (Fig. 3b-e). Both this episode and the outstanding one ~650 ka, with the lowest  $\delta^{13}\text{C}$   
324 | value since MIS18 in middle latitudes in coincidence with very high abundance of the  
325 | NACass in high latitudes (Fig. 3b,e), points to an exceptionally vigorous but shallow  
326 | NA overturning cell, underlain by significant volumes of southern-sourced water,  
327 | similarly to the situation at the end of TII (Böhm et al., 2014). This mode of AMOC,  
328 | according to benthic  $\delta^{13}\text{C}$  records, maintained during glacial stages MIS16, MIS15b,  
329 | and MIS14, when the subpolar site 980 recorded > 0.25 ‰ higher  $\delta^{13}\text{C}$  than southern-  
330 | **more** sites (Wright and Flower, 2002; [Martin-Garcia et al., 2015](#); Hodell et al., 2016).

331 | This vigorous AMOC mode recorded in MIS14 was the culmination of a sequence  
332 | of increasing deepening of the overturning circulation cell that initiated in MIS22, and  
333 | was registered by a tendency towards higher benthic  $\delta^{13}\text{C}$ , both in high and mid-  
334 | latitude sites U1308 and U1313, from MIS22 to MIS14 (Hodell and Channell, 2016),  
335 | and was especially noticeable during glacial stages. During MIS20 and MIS18, ice  
336 | sheets collapses (Wright and Flower, 2002) produced a continuous flux of meltwater

337 pulses that kept very weak NADW formation; the deep North Atlantic being occupied  
338 by southern-sourced waters, according to very low benthic  $\delta^{13}\text{C}$  recorded both in  
339 middle and high latitudes (Wright and Flower, 2002; Hodell et al., 2015; 2016). During  
340 these glacials, the almost shutdown AMOC maintained the AF at a southern position  
341 and prevented the northward flux of the necessary moisture for the growth of ice  
342 sheets, which could not work as a positive feedback and extend glacial stages over  
343 obliquity and precessional (41- and 23 ky) cycles, as they worked during MIS16, one  
344 of the first and most prominent glacials of the “100-ky world”.

345

## 346 **6 Conclusions**

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

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

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

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

367 |

368

369 **Appendix A: Planktonic foraminifer species used in this study**

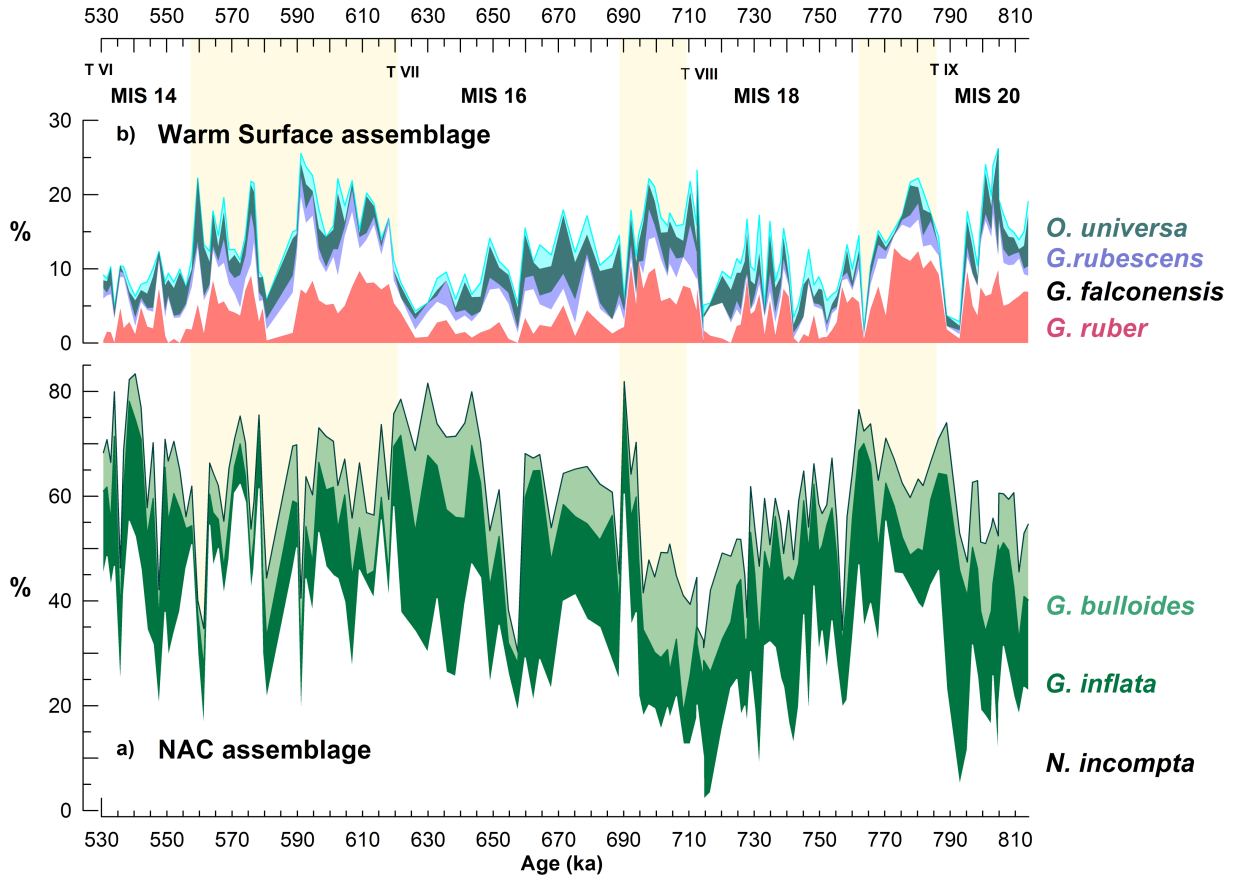
370

Species	Environment	References
<i>Neogloboquadrina pachyderma</i> sinistral (Ehrenberg 1861)	Polar	Pflaummann et al. (1996); Cayre et al. (1999); Schiebel and Hemleben (2017)
<i>Turborotalita quinqueloba</i> (Natland 1938)	Subpolar	Ottens (1991); Schiebel and Hemleben (2017)
<i>Globigerina bulloides</i> d'Orbigny 1826	NA current Transitional	Ottens (1991) Schiebel and Hemleben (2017)
<i>Neogloboquadrina incompta</i> (Cifelli 1961) (Previously known as <i>N. pachyderma</i> dextral)	NA current Portugal current	Ottens (1991) Salgueiro et al. (2008)
<i>Globorotalia inflata</i> (d'Orbigny 1839)	NA current Portugal current Transitional	Ottens (1991) Salgueiro et al. (2008) Schiebel and Hemleben (2017)
<i>Globigerinella siphonifera</i> (d'Orbigny 1839)	Azores current Warm surface Subtropical	Ottens (1991) Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Beela digitata</i> (Brady 1879)	Warm surface Subtropical	Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Globigerina falconensis</i> Blow 1959	Warm surface Subtropical	Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Globigerinoides ruber</i> (d'Orbigny 1839)	Subtropical Warm surface Azores current Subtropical / tropical	Ottens (1991) Vautravers et al. (2004) Salgueiro et al. (2008) Schiebel and Hemleben (2017)
<i>Globigerinoides sacculifer</i> (Brady 1877)	NA transitional Warm surface Tropical	Ottens (1991) Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Globoturborotalita rubescens</i> Hofker 1956	Azores current Warm surface Subtropical	Ottens (1991) Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Globoturborotalita tenella</i> (Parker 1958)	Azores current Warm surface Subtropical	Ottens (1991) Vautravers et al. (2004) Schiebel and Hemleben (2017)

<i>Orbulina universa</i> d'Orbigny 1839	Warm surface Subtropical	Vautravers et al. (2004) Schiebel and Hemleben (2017)
<i>Pulleniatina obliquiloculata</i> (Parker and Jones 1865)	Azores current Warm surface Tropical	Ottens (1991) Vautravers et al. (2004) Schiebel and Hemleben (2017)

371

372



373

374

375 **Appendix B:** Faunal composition of both the NAC, and the warm surface  
 376 assemblages in site U1385 through the study interval. (a) *N. incompta* (white), *G.*  
 377 *inflata* (dark green) and *G. bulloides* (light green). (b) *G. ruber* (red), *G. falconensis*  
 378 (white), *G. rubescens* (lilac), *O. universa* (dark green), and in cyan, other species with  
 379 less than 1.5% each: *G. siphonifera*, *G. tenella*, *B. digitata*, *G. sacculifer* and *P.*  
 380 *obliquiloculata*.

381

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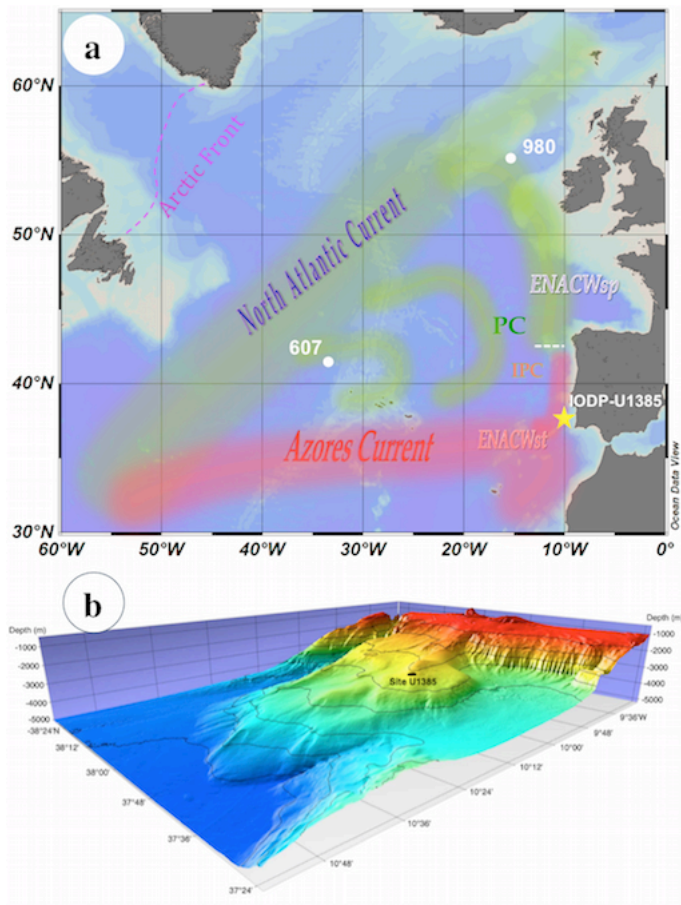
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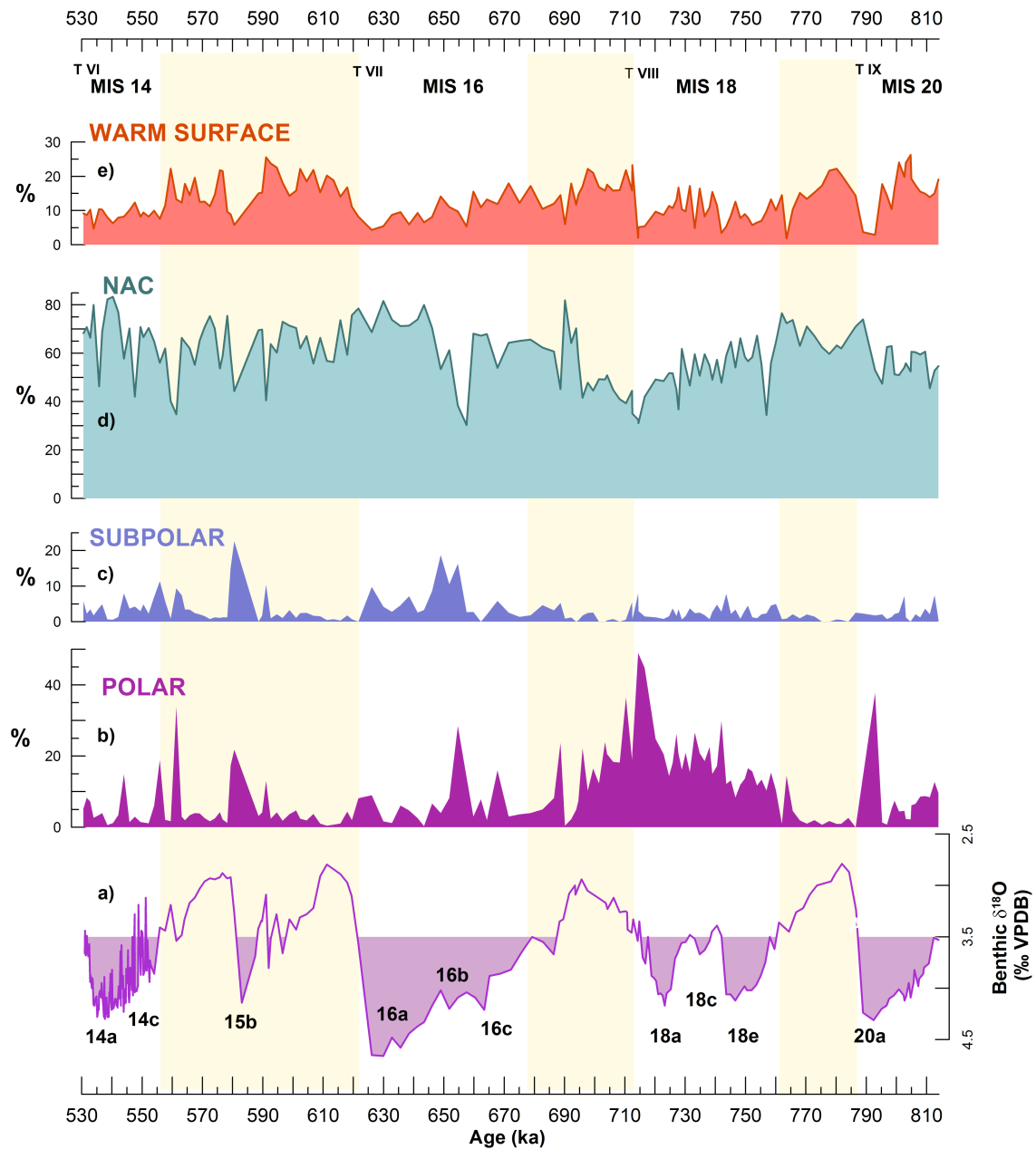


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559 **Figure 1.** (a) Modern surface circulation in the North Atlantic and location of IODP-  
 560 U1385 and other sites discussed in this paper. *ENACWsp* Eastern North Atlantic  
 561 Central Waters of subpolar origin; *ENACWst*, Eastern North Atlantic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

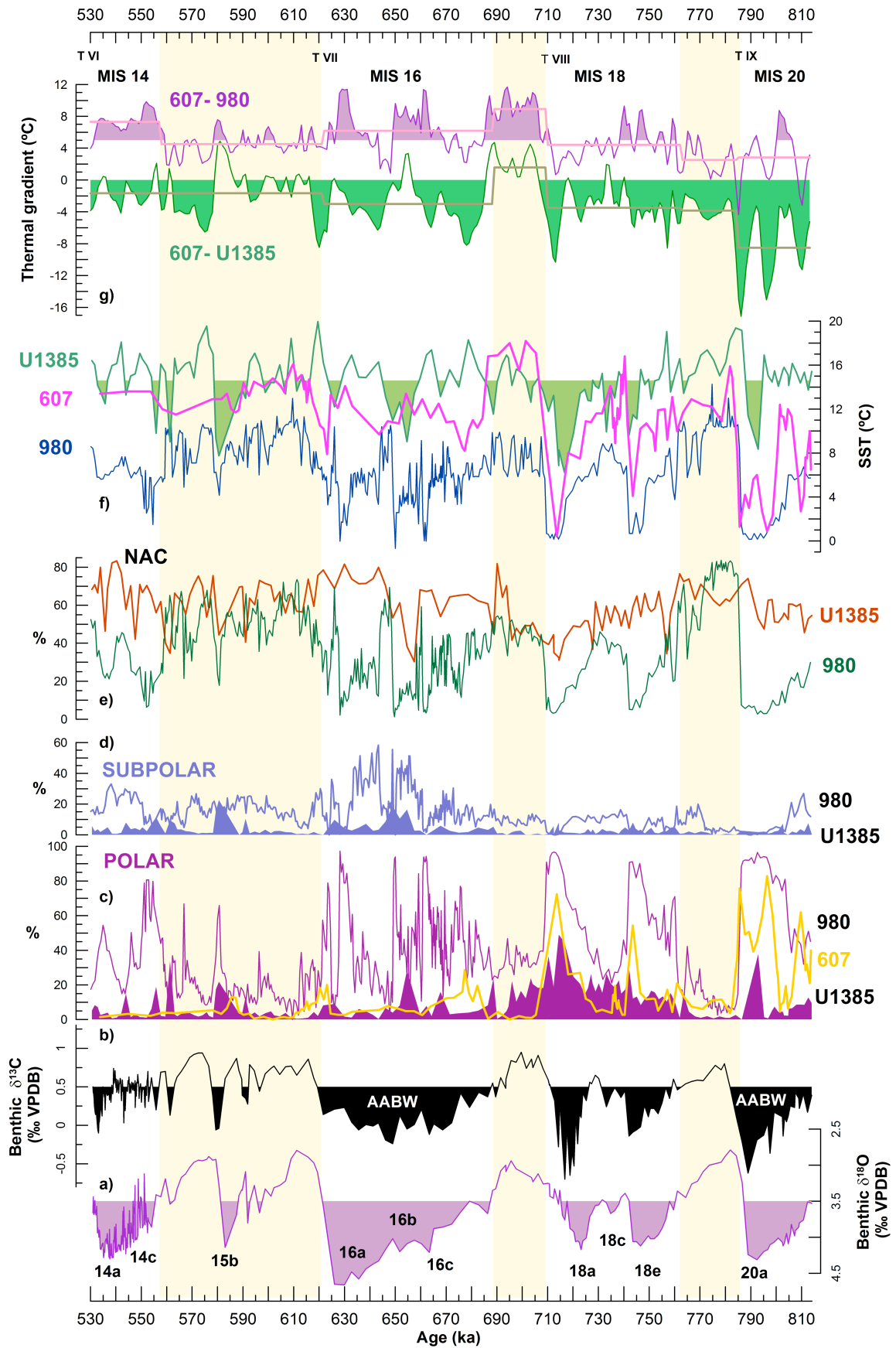
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568 **Figure 2.** Relative abundance of planktonic foraminiferal species and assemblages in  
 569 IODP-U1385 through MIS 14-20, and comparison with benthic isotope data from the  
 570 same site. (a) Benthic  $\delta^{18}\text{O}$  record (Hodell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

573 abundance of: (b) polar species *N. pachyderma* sinistral; (c) subpolar species *T.*  
574 *quinqueloba*; (d) NAC assemblage (as defined by Ottens, 1991); and (e) warm  
575 surface assemblage (as defined by Vautravers et al., 2004). Yellow bands highlight  
576 interglacials. Terminations (T) are marked in roman numerals. IODP-U1385 isotopic  
577 record is from Hodell et al. (2015).  
578



580

581 **Figure 3.** Comparison of records from the mid-latitude (IODP-U1385; ODP-607) and  
582 the subpolar (ODP-980) North Atlantic. Benthic  $\delta^{18}\text{O}$  (a), and  $\delta^{13}\text{C}$  (b) from U1385  
583 (Hodell et al., 2015); filling in (b) enhancing  $^{13}\text{C}$ -depleted values typical for Antarctic  
584 bottom water (AABW) (Adkins et al., 2005). (c) Percentage of *N. pachyderma* sinistral  
585 in sites U1385 (filled), 607 (glod) and 980 (purple). (d) Relative abundance of *T.*  
586 *quinqueloba* for sites U1385 (filled) and 980. (e) Relative abundance of the NAC  
587 assemblage (as defined by Ottens, 1991) in sites U1385 (red) and 980 (green). Site  
588 980 faunal data are from Wright and Flower, 2002; for this work, the NAC  
589 assemblage of site 980 has been calculated using the published census counts. (f)  
590 SST from sites 980 (dark blue; Wright and Flower, 2002), 607 (pink; Ruddiman et al.,  
591 1989), and U1385 (green; Martin-Garcia et al., 2015), with filling enhancing lower  
592 than 14.6 °C, the average SST for the study interval. (g) Longitudinal (green) and  
593 latitudinal (purple) thermal gradients, with the statistical mean for each MIS  
594 represented in superimposed straight lines. Age models for sites 980 and 607 have  
595 been re-calculated using the LR04-stock. Yellow bands highlight interglacials.  
596 Terminations (T) are marked in roman numerals.