

**Planktonic foraminifera response to orbital and millennial-scale climate
variability at the southern Iberian Margin (IODP Site U1385) during Marine
Isotope Stages 20 and 19**

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Abstract

The orbital configuration of Marine Isotope Stage (MIS) 19 provides the best recent analogue to our
present interglacial, and it is marked by millennial-scale climate variability. To evaluate how orbital
and millennial-scale climate changes interact during this interglacial we have conducted a high-
resolution study of planktonic foraminifera assemblages at International Ocean Discovery Program
(IODP) Site U1385, SW Iberian Margin, encompassing late MIS 20 and MIS 19. Estimates of sea
surface temperature (SST), using transfer-functions, are compared with geochemical, XRF

elemental data, biomarker and pollen records from the same site. These results are then compared with SST and ice-rafted debris records from North Atlantic IODP Site U1314 to reconstruct basin-wide palaeoceanographic conditions. During MIS 20, the large size of the ice sheets imparted a strong cooling in the subpolar gyre whereas the Iberian Margin remained under the influence of the subtropical gyre with the development of a high meridional thermal gradient in the North Atlantic. During MIS 20 terminal stadial (794-789 ka) and MIS 19b-a stadial events, the meltwater discharges related to the instability of ice sheets affected both the North Atlantic and the Iberian Margin leading to a weaker thermal gradient. Our data indicate that Termination IX (TIX, ~795-788 ka) was punctuated by short-term warming/cooling phases in the ocean coupled with warming/cooling events on land. A short-term cooling episode, recognized in the ocean and on land, occurred on Termination IX and preceded the beginning of MIS19c. The planktonic foraminifera proxies support a land-ocean decoupling during full interglacial conditions of MIS 19 when SSTs were affected by oceanographic processes rather than atmospheric dynamics. Starting from 780 ka towards MIS 18, the planktonic foraminifera assemblages and SSTs indicate a cooling trend along the Iberian Margin related to a progressive southward migration of polar front.

Key words: North Atlantic, Termination IX, Millennial-scale SST, planktonic foraminifera

1. Introduction

Marine Isotope Stage (MIS) 19 has received much attention in studies of interglacial climate variability because it is considered one of the best analogues for MIS 1 as far as astronomical configuration is concerned (Tzedakis et al., 2009, 2012a; b; Pol et al., 2010; Rohling et al., 2010; Yin and Berger, 2012, 2015; Ferretti et al., 2015; Giaccio et al., 2015). The orbital configurations of both MIS 19 and MIS 1 are characterized by a weak eccentricity-precession forcing, which results

47 in a subdued amplitude of insolation changes (Yin and Berger, 2012, 2015). Millennial-scale
48 climate variability during Pleistocene interglacials is also of interest because of its potential to
49 provide information about climate stability or instability during the Holocene. Several studies
50 carried out in European lacustrine sediments (Giaccio et al., 2015; Wagner et al., 2019) and in
51 marine successions from central and western Mediterranean area (Bertini et al., 2015; Marino et al.,
52 2015; Maiorano et al., 2016; Nomade et al., 2019; Quivelli et al. 2021; Marino et al., 2020) have
53 also highlighted the strong similarity between Termination I (TI) and Termination IX (TIX) and
54 their relationship with the North Atlantic climate oscillations.

55 In the North Atlantic, millennial-scale climate oscillations occurring during Pleistocene interglacials
56 have been linked to oceanic and atmospheric processes related to ice sheet instability (McAyeal,
57 1993; Marcott et al., 2011). Associated with iceberg-discharge events, several extreme cooling
58 events have been recorded by drops in SST and decreases in Ca/Ti (Martrat et al., 2007; Rodrigues
59 et al., 2011; Voelker and de Abreu, 2013; Martin Garcia et al., 2015; Hodell et al., 2013; 2015;
60 Rodrigues et al., 2017). These events have punctuated both interglacial and glacial periods, but with
61 greater amplitude at glacial onsets and terminations (Hodell et al., 2022) and are associated with a
62 strong reduction of the Atlantic Meridional Overturning Circulation (AMOC) and a southern shift
63 of the Subpolar Front (Hodell et al., 2013; 2015, 2022; Rodrigues et al., 2017). Pronounced cooling
64 occurred at TIX as recorded by low alkenone-based SST, which is followed by a large increase in
65 SST toward peak interglacial conditions of MIS 19c (increase of 10°C within 2.5 ka) (Rodrigues et
66 al., 2017).

67 Interglacial MIS 19 has been marked by millennial-scale climate changes with a repeat time of
68 ~5,000 years (Ferretti et al. 2015; Sanchez Goñi et al., 2016). The millennial climate variability
69 (MCV) in the mid- and high- latitude North Atlantic may be triggered by precession-forced low
70 latitude dynamics related to harmonics of precession (Berger et al., 2006; Ferretti et al., 2010;
71 Hernández-Almeida et al., 2012; Ferretti et al. 2015; Sanchez Goñi et al., 2016) that influenced the

72 North Atlantic latitudinal thermal gradient and the northward transport of heat and water vapor from
73 equatorial regions. The increased transport of moisture to the northern high latitudes could have
74 contributed to ice sheet growth during the onset of glacial conditions at the start of MIS 18
75 (Sanchez Goñi et al., 2016).

76 At Site U1385, the existing low-resolution planktonic foraminifera analyses for the time interval
77 including MIS20 and MIS19 did not discuss the millennial-scale variability and focused on long-
78 term palaeoceanographic changes in the North Atlantic circulation during the Middle Pleistocene
79 Transition (Martin-Garcia et al., 2015; 2018; Bahr et al 2018). Here we present new higher
80 resolution record of planktonic foraminifera assemblages and seasonal and annual foraminifera-
81 based SST (Sea Surface Temperature) at orbital and millennial scale to reconstruct sea-surface and
82 subsurface dynamics during late MIS 20- MIS 19 at IODP Site U1385 and their relationship with
83 Northern Hemisphere high latitude ocean-atmosphere dynamics. The study aims to provide insights
84 into i) the late MIS 20 terminal stadial and its oceanographic-atmospheric connection with North
85 Atlantic climate, ii) the high-frequency climate variability across the deglaciation associated with
86 TIX. Moreover, starting from the previously published studies focused on the pollen-based
87 atmospheric processes associated with changes in the marine realm (Hodell et al., 2015; Sánchez
88 Goñi et al., 2016; Rodrigues et al., 2017), our data have been directly compared with the same
89 resolution pollen and isotopic record available at the Site U1385 (Sánchez Goñi et al., 2016) in
90 order to evaluate the effects of air-sea interactions at millennial scale during the studied interval.
91 The overarching aim of the study is to test whether the observed millennial-scale air-sea
92 temperature decoupling based on pollen-alkenone-based SST (Sánchez Goñi et al., 2016) is also
93 recorded by the planktonic foraminifera assemblages. Planktonic foraminifera are amongst the most
94 widely used proxies for paleoceanographic and paleoclimate sea-surface reconstructions. Their
95 distribution and abundance are strongly linked to surface water properties and they represent a good
96 tool to trace the variations of water masses because each water mass is characterized by distinct
97 physical–chemical parameters and specific planktonic foraminiferal assemblages (e.g. Bé, 1977;

98 Ottens, 1991; Cayre et al., 1999). In addition, the distribution of planktonic foraminifera is strictly
99 related to the sea surface temperatures and to other environmental parameters, such as nutrient
100 availability, light intensity, interspecific competition, and salinity (Bé and Tolderlund, 1971; Bé,
101 1977; Hemleben et al., 1989) that can be influenced by both atmospheric and hydrological forcing.

102 The Iberian Margin is very sensitive to variations in North Atlantic atmospheric processes and its
103 oceanographic setting is influenced by changes in the northeastward transport of the different
104 branches of the North Atlantic Current (NAC) towards the European continental margin. Changes
105 in the intensity of the NAC influence the North Atlantic subpolar and subtropical gyres, as well as
106 the position of the Arctic and Subtropical Fronts. Moreover, it is the main driver of the transport of
107 warm, salty surface water from tropical regions to the polar ocean and is responsible for the transfer
108 of heat and moisture to the atmosphere, which can feed the growth of polar ice sheets (e.g.
109 McCartney and Talley, 1982; Ruddiman and McIntyre, 1984; Schmitz and McCartney, 1993;
110 Rahmstorf, 1995; Chapman and Maslin, 1999). To better understand such dynamics during late
111 MIS 20, TIX and MIS 19, the data at Site U1385 have been compared with published (distribution
112 pattern of planktonic foraminifera, isotope stratigraphy) (Alonso-Garcia et al., 2011a; 2011b;
113 Hernández-Almeida et al., 2013; 2015) and unpublished data (seasonal foraminifera-based SST)
114 from IODP Site U1314 located at higher latitude on the Gardar Drift to south of Iceland. The study
115 also benefits from the comparison with the available U1385 XRF elemental data (Hodell et al.,
116 2015) and the biomarker record at the same site (Rodrigues et al., 2017).

117

118 **2. Material and methods**

119 **2.1 Site location and oceanographic setting**

120 IODP Site U1385 was drilled at the “Shackleton site” off the western Iberian Margin (37°34.284'N,
121 10°7.562'W), at 2578 m water depth (Fig. 1). The studied sedimentary section mainly consists of

122 nannofossil muds and nannofossil clays (Expedition 339 Scientists, 2013), with an average
123 sedimentation rates of ~ 11 cm/kyr (Hodell et al., 2015). The stratigraphy of IODP Site U1385 was
124 built upon a combination of chemo-stratigraphic measurements. Core scanning XRF (X-ray
125 fluorescence) was used to measure Ca/Ti of sediment every cm in all holes to define a composite
126 section (Hodell et al., 2015). In this study, we use the high-resolution (every 2 cm) benthic and
127 planktonic oxygen isotope stratigraphy reported in Sánchez Goñi et al. (2016) plotted against the
128 age model obtained by the correlation of the $\delta^{18}\text{O}_b$ to the LR04 stack (Hodell et al., 2013, 2015).
129 Transitions between the different Marine Isotopic Stages (MIS) and sub-stages are defined in
130 Sanchez Goñi et al. (2016) based on significant shifts in the $\delta^{18}\text{O}_b$ record (Fig. 2).

131 Site U1385 (Fig. 1) is currently under the influence of Eastern North Atlantic Central Water
132 (ENACW) at the surface and North Atlantic Deep Water (NADW) at the sea floor. The main
133 surface currents are the Portugal Current (PC) and Azores Current (AzC) (Fig. 1). The PC forms in
134 the Northeastern Atlantic (McCartney and Talley, 1982) as a branch of the North Atlantic Current
135 and brings cold, nutrient-rich water southward along the Iberian Margin from 45° to 30°N (Peliz et
136 al., 2005). The PC involves a subsurface cold, nutrient-rich and less salty water of subpolar origin
137 (Eastern North Atlantic Central Water, ENACWsp) (Peliz et al., 2005). The AzC (Fig. 1) originates
138 in subtropics and flows eastward to the Gulf of Cadiz in large meanders between 35° and 37°N .
139 During winter, the Iberian Poleward Current (IPC) originates from the AzC (Peliz et al., 2005) and
140 moves northward forming a subsurface flow of less ventilated, nutrient-poor warm and saltier
141 waters of subtropical origin (Eastern North Atlantic Central Water, ENACWst) (Frouin et al., 1990;
142 Haynes and Barton, 1990) (Fig. 1). The northern boundary of the AzC forms the Subtropical Front
143 (STF). The surface water masses are influenced by the seasonal migration of the Azores
144 anticyclonic cell and the associated large-scale wind pattern. Between April and October, the
145 northward displacement and strengthening of the Azores high pressure cell and strong northerly
146 trade winds generate coastal upwelling and a relatively cold, nutrient-rich water band forms along
147 the western coast (Fiúza et al., 1982; Fiúza, 1984; Sousa and Bricaud, 1992; Sánchez and Relvas,

2003). The waters involved in the upwelling system are ENACW, either of subpolar or subtropical origin (Sánchez and Relvas, 2003). During the winter, when the Azores high weakens, the surface circulation reverses and a northward flow of warm and saline surface water reaches higher latitudes offshore Portugal (Fiúza et al., 1998; Peliz et al., 2005).

152

153 2.2 Planktonic foraminifera study

Quantitative analyses of planktonic foraminifera assemblages were performed on 160 samples with a spacing of 2 cm, corresponding to an average time resolution of ~250 yr according to the age model of Hodell et al. (2015). This study includes the stratigraphic section between 93.35 and 88.91 corrected meter composite depth (crmcd), which encompasses late MIS 20 and the beginning of MIS 18 (Fig. 2). Samples were washed through a 63 micron sieve and dried. The > 63 µm residue was dried and sieved again to separate the > 150 µm fraction. These residues were split until a representative aliquot containing about 300 specimens was obtained. All specimens were counted in each aliquot and species abundances were quantified as percentages of the total number of planktonic foraminifers. Twenty-one species or species groups were distinguished. To obtain consistency with foraminiferal counts produced by other researchers, *Trilobatus sacculifer* includes *Trilobatus trilobus* and *Trilobatus quadrilobatus* (*sensu* Hemleben et al., 1989; André et al., 2013; Spezzaferri et al., 2015). *Neogloboquadrina incompta* corresponds to those specimens previously referred to as *Neogloboquadrina pachyderma* (dextral) and includes intergradations between *N. pachyderma* (dextral) and *Neogloboquadrina dutertrei* (Darling et al., 2006). *N. pachyderma* only includes the left coiling specimens. In our record *Truncorotalia truncatulinoides* is represented by dextral tests only in agreement with the evidence of a pronounced absence of sinistral coiling specimens during the time interval between MIS 21 and MIS 15 (Kaiser et al., 2019) in the North Atlantic.

The analyses of planktonic foraminifera focused on species that are associated with North Atlantic surface water masses and with the southern Iberian Margin surface waters. *Globigerinoides ruber* is

the most abundant species within the Subtropical Gyre (STG) (Ottens, 1991; Schiebel et al., 2002a; 2002b) and *T. truncatulinoides* is the most abundant species south of Azores Front (AzF) (Ottens, 1991; Schiebel et al., 2002a; 2002b). Both are used to trace the influence of subtropical waters at the site location and the strength of AzC and STG. *G. bulloides* is used as indicator of nutrient-rich conditions related to upwelling conditions in accordance with the findings of Vautravers and Shackleton (2006) and Salgueiro et al. (2008). *N. incompta* and *G. inflata* are reported as the main taxa associated with the PC (Salgueiro et al., 2008, Ottens, 1991). Following its preference for colder conditions, *N. incompta* is generally more abundant along the coast of the Iberian Margin north of 39 °N where the temperatures are lower than those to the south (Salgueiro et al., 2008). In this study, *N. incompta* is used to trace colder, nutrient-rich waters associated with the PC along the Iberian Margin and at the site location (Salgueiro et al., 2008). *G. inflata*, a transitional water taxon (Giraudeau, 1993), is used to evaluate the influence of temperate and oligotrophic transitional water because it occurs in the region influenced by ENACWst along the Iberian Margin (Salgueiro et al., 2008). *N. pachyderma* is used to trace the presence of polar water masses (Cayre et al., 1999; Pflaumann et al., 2003; Eynaud et al., 2009) whereas *Turborotalita quinqueloba* is usually associated with the Artic Front (AF) (Johannessen et al., 1994; Cayre et al., 1999). The latter species also proliferate in areas marked by highly fertile, low-density surface waters (Aksu et al., 2002; Hemleben et al., 1985; Pujol and Vergnaud-Grazzini, 1995; Triantaphyllou et al., 2010) and those influenced by continental runoff (Rohling et al., 1997; Jonkers et al., 2010; Girone et al., 2013; Bartels-Jónsdóttir et al., 2015; Margaritelli et al., 2016). Warm-water taxa (wwt) (Vautravers et al., 2004) include all species dwelling in tropical-subtropical water masses such as *G. ruber*, *T. sacculifer*, *Globoturborotalita rubescens*, *Globoturborotalita tenella*, *Orbulina universa*, *Globigerinella siphonifera*, *Beella digitata*, *Globigerina falconensis* and *Pulleniatina obliquiloculata*.

196

197 2.3 Transfer function and SST reconstruction

198 We used the fossil planktonic foraminifera assemblages to reconstruct the temperatures for the
199 studied interval. Although temperatures for U1314 had been reconstructed previously using this
200 approach for the interval MIS 31-11 (Alonso-García et al 2011a; Hernández-Almeida et al 2012),
201 we re-analyzed the planktonic-foraminifera-based SST estimates at this site and at U1385 using the
202 same methodology for both and the most recent calibration datasets for consistency.

203 For the development of the transfer function, we used the core-top planktonic foraminifera
204 assemblage dataset from the North Atlantic from the ForCens compilation (Siccha and Kucera,
205 2017). Seasonal and annual ocean temperatures at different depths were interpolated for the core top
206 location and extracted from the World Ocean Atlas 2001 (WOA01) (Conkright et al 2002) at 10 and
207 200 m for spring, winter and annual conditions. We include the 200 m depth because it has been
208 shown that fossil planktonic foraminifera assemblages in the North Atlantic are more sensitive to
209 subsurface temperatures at some locations than to 10 m SST (Telford et al 2013). We applied the
210 resulting transfer function to the fossil planktonic foraminifera assemblages from Sites U1385 and
211 U1314. The taxonomy of the fossil samples was harmonized according to the ForCenS database,
212 following criteria suggested by Siccha and Kucera (2017).

213 The modern analogue technique (MAT) (Prell, 1985) is a widely used regression method in
214 paleoceanographic reconstructions. This approach identifies a subset of samples in the calibration
215 data set using similarity measures to reconstruct quantitatively the environmental variable of
216 interest. We selected the optimal number of close analogues determined using squared chord
217 distance (Prell 1985). The performance of the resulting models, coefficient of determination (R^2)
218 and root mean square of prediction (RMSEP), were assessed using cross validation (bootstrapping,
219 999 permutation cycles) (Vaughan and Ormerod, 2005), with a cut-off distance of 850 km to
220 account for the effect of spatial autocorrelation in the modern dataset (Telford and Birks, 2009),
221 following recommendation from other studies in the North Atlantic (Trachsel and Telford 2016).
222 Similarity between the modern and the fossil dataset was evaluated by calculating the chord

223 distance between them (analogue quality) (Overpeck et al., 1985). To evaluate whether temperature
224 at each depth and season were also significant for the downcore assemblage at Sites U1385 and
225 U1314, we used the statistical test developed by Telford and Birks (2011). This method compares
226 the variance in the fossil assemblage explained by the environmental variable of interest with the
227 proportion of variance explained by randomly generated environmental variables. Transfer function
228 development and downcore reconstructions at each depth were performed in R (R core team, 2020)
229 using the packages rioja (Juggins, 2017), raster (Hijmans, 2017), vegan (Oksanen et al., 2018),
230 ggpalaeo (Telford 2019), and ggplot2 (Wickham, 2016).

231

232 **3.Results**

233 **3.1 Planktonic foraminifera assemblages**

234 Planktonic foraminifera at Site U1385 are well preserved and diversified across the studied interval.
235 The assemblages are mainly represented by *N. incompta* that occurs throughout the entire studied
236 interval showing the highest percentages between ~780 ka and ~769 ka (Fig. 2). *N. pachyderma* has
237 a more scattered distribution showing good correspondence to the polar-index % C_{37:4} of Site
238 U1385 (Rodrigues et al., 2017); it occurs during late MIS 20 and late MIS 19 associated with the
239 millennial-scale cooling events during the transition to MIS 18. During late MIS 20 it represents up
240 to 80% of the total assemblage (Fig. 2). *N. dutertrei* is also found along the entire studied section
241 except for the late MIS 20 terminal stadial event (794-789 ka). It occurs with very low percentages
242 never exceeding 8% of the total assemblage. The wwt group shows highest abundance during MIS
243 19c and interstadials of MIS 19 b-a (774-771 ka; 768.7-765.3 ka; 762.9-760.3 ka). The lowest
244 abundances of this group are recorded during the terminal stadial event of MIS 20 (Fig. 2). *T.*
245 *truncatulinoidea* occurs frequently and its pattern follows that of the wwt group trend. *Globigerina*
246 *bulloides* and *T. quinqueloba* are distributed through the entire section: *G. bulloides* shows values

247 ranging between 15% and about 30%. During the MIS 20 terminal stadial event, its values drop
248 below 15% of the total assemblage. *T. quinqueloba* has an average abundance of about 10%, with
249 intervals of maximum relative abundance during the stadial late MIS 19 and between 782 and 784
250 ka, during MIS 19c. *G. inflata* also contributes about 30% to the total assemblage: it has the lowest
251 abundance values during the MIS 20 terminal stadial event and between 780 ka and 769 ka, during
252 MIS 19. The rest of the assemblage is composed of *Globigerinita glutinata*, *Globorotalia scitula*
253 and *N. dutertrei* that combined represent less than 20% of the total assemblages. Among these, *G.*
254 *scitula* is the most abundant with the highest values recorded during the oldest portion of the
255 investigated interval and during MIS 19b. Other less abundant taxa (subordinate taxa in Fig. 2)
256 include *Globigerina falconensis*, *Globorotalia crassaformis* and *P. obliquiloculata*. *G. falconensis*
257 occurs through the entire studied section but generally at very low percentages (lower than 2%),
258 only occasionally showing short-term increases up to 6-7%. The distribution of *G. crassaformis* and
259 *P. obliquiloculata* is very scattered with abundance values lower than 2%. *G. crassaformis* has a
260 more continuous distribution during MIS 20 (with exception of the terminal stadial) and the early
261 interval of MIS 19c.

262

263 3.2 Faunal-Based Sea Surface Temperatures

264 The performance of the MAT regression with five analogues (MAT-K5) for spring, winter and
265 annual temperatures at 10 and 200 m depths using the North Atlantic samples from the ForCens
266 database (Siccha and Kucera, 2017) is shown in supplementary table 1. The cross-validated R^2 of
267 all the models is above 0.95, and the RMSEP is between 0.99 and 1.2 °C. The analogue
268 measurements between the modern and fossil samples at Site U1314 show that they are very similar
269 (Supplementary Fig. 1). For samples at Site U1385, only nine samples between 784 -782 ka and
270 766-761 ka show poor analogue conditions (Supplementary Fig. 1). The reconstructions for each
271 season and depth are highly significant ($p < 0.05$), explaining more variance than the randomly

272 generated environmental variables, and thus they can be considered as important environmental
273 factors driving the planktonic foraminifera assemblages in these two cores for the analyzed interval
274 (Supplementary Fig. 2).

275 At Site U1385, the annual and seasonal SST records show a general trend that is very similar to the
276 Log Ca/Ti and alkenone-based SST profiles. The lowest sea surface and subsurface temperatures
277 are recorded during the MIS 20 terminal stadial event and during the cold events during MIS 19 b-a
278 associated with the onset of glacial conditions. During the MIS 20 terminal stadial event, winter
279 surface and subsurface SSTs show very similar values with a minimum of about 4 °C; during spring
280 season such minima values are registered at the subsurface waters while at surface waters the
281 temperatures are close to 5°C. During TIX, two main warming episodes are recorded in both annual
282 and seasonal temperatures that are marked by increases of up to 8°C in SST. Starting at 787.5 ka
283 and continuing throughout the full interglacial MIS 19c, the temperatures were warm with an
284 average SST of ~15°C in the spring and of ~13°C in the winter. During MIS 19c, the foraminifera
285 SSTs show oscillations in contrast to the relatively stable log Ca/Ti and alkenone-based SST
286 records. The major oscillation, occurring at about 784.5 ka, is marked by a temperature drop of
287 about 5°C.

288 At Site U1314, late MIS 20 is characterized by much lower foraminifera-based temperatures with
289 respect to the Iberian Margin. Such cold conditions are also recorded in the older interval of MIS 20
290 terminal stadial but at about 790 ka the SST records indicate a temperature increase of about 7° C
291 that remained high throughout TIX and the full interglacial MIS19c. During the interglacial phase,
292 warm and stable high SSTs are found with an average spring temperature of ~8°C and of ~ 7°C in
293 the winter. During MIS 19b-a, the Site U1314 seasonal SST profiles are characterized by three
294 minima of temperatures corresponding to the stadial events of MIS 19 b-a. At Sites U1385 and
295 U1314, the MIS 19 b-a interstadials are characterized by SSTs close to those of MIS 19c.

296

297 4.Discussion

298 4.1 Late MIS 20 and deglaciation (Termination IX)

299 The interval from ~805 to 787.5 ka predates the onset of the MIS 19 full interglacial conditions, and
300 represents the latter part of MIS 20 and the MIS 20/19 deglaciation phase (TIX) (Fig. 3). The SST
301 record indicates that the Iberian Margin remained relatively warm until 794 ka (Fig. 3e-g)
302 influenced by a continuous flow of the AzC as suggested by the presence of *G. ruber* (Fig. 4d) and
303 *T. truncatulinoides* (Fig. 4e), in agreement with the findings of Martin-Garcia et al. (2018). The *G.*
304 *inflata* (Fig. 4f) relative abundance record also confirms the evidence of a persistent warm glacial
305 thermocline off Iberia during most of MIS 20 as suggested by Bahr et al. (2018). The drop in the
306 abundance of planktonic foraminifera taxa associated with the AzC (Fig. 4 d - f), the increase in *N.*
307 *pachyderma* (Fig. 4b) and the drop in SSTs of about 8°C (Fig. 3e) marks the beginning of the
308 terminal stadial event at ~794 ka characterised by a reduction of deep water ventilations as
309 supported by a contemporaneous decrease in benthic $\delta^{13}\text{C}$ values (Fig. 3b) (Hodell et al., 2015,
310 2022). This event is also clearly identified by the shift towards low values of Ca/Ti and high Zr/Sr
311 ratios (Hodell et al., 2013, 2015, 2022) (Fig. 3c). Ca/Ti variations reflect relative changes in
312 biogenic carbonate in the sediment; high values of biogenic carbonate are recorded during
313 interglacial and interstadial phases resulting in high Ca/Ti values, while the ratio decreases during
314 glacial and stadial periods (Hodell et al., 2013, 2015, 2022).

315 At the Site U1385, distinct variations in the abundance patterns of planktonic foraminifera
316 assemblages indicate that the terminal stadial was not a homogenous period but was punctuated by
317 three short-term changes in the sea surface circulation, as discussed below.

318 During the first phase labeled 'a' (794-788 ka), high abundances of polar *N. pachyderma* (Fig. 4b)
319 and a sharp decline in *G. ruber* and *T. truncatulinoides* (Fig. 4 d-e) indicate a pronounced cooling of
320 the Iberian Margin region because of the southward shift of the subpolar front. These changes are

321 concomitant with the increase in iceberg discharges in the subpolar North Atlantic, as recorded at
322 Site U1314 (Hernandez-Almeida et al., 2012) (Fig. 4k). *N. pachyderma* is the dominant planktonic
323 foraminifera species during Heinrich events in the North Atlantic Ocean (Heinrich, 1988; Bond et
324 al., 1992), and it is considered to be a tracer of the southward penetration of cold and fresh water
325 masses driven by north Atlantic iceberg discharge events (e.g. Bond et al., 1992). During the
326 middle-late Pleistocene, peaks in *N. pachyderma* abundance in sediment cores from the Iberian
327 Margin (Cayre et al., 1999; De Abreu et al., 2003; Parente et al., 2004; Vautravers and Shackleton,
328 2006; Eynaud et al., 2009; Marino et al., 2014; Martin-Garcia et al., 2015; Naughton et al., 2016)
329 have been also related to north Atlantic iceberg discharges. The arrival of extremely cold and low
330 salinity water at the Iberian Margin is also supported by the concomitant drop of the sea-surface and
331 subsurface temperatures (Fig. 3e-g) and the abrupt increase in the % alkenone C_{37:4} at Site U1385
332 (Rodrigues et al., 2017) (Fig. 4c). This extreme cooling led to a decreased influence of the AzC and
333 the warmer north Atlantic Transitional Water to the southern Iberian Margin as suggested by the
334 drop in the relative abundances of *G. inflata* (Fig. 4f) and *G. ruber* (Fig. 4d). The maximum
335 expansion of semi-desert plants recorded during this cold interval (Fig. 4g, Sanchez Goñi et al.,
336 2016) indicates reduced heat and moisture transport towards Iberia. This fact has been linked to a
337 deflection of the westerly winds due to the atmospheric changes associated with the southward
338 migration of the subpolar front and the slowdown of the AMOC driven by the ice sheet discharges
339 during the terminal stadial event.

340 At ~ 790.2 ka, a short-term increase in *G. inflata* (Fig. 4f) occurred during a time of increasing
341 insolation (Fig. 4n), which may indicate a warming as suggested by the concomitant relative rise in
342 foraminifera- and alkenone-based SST records (Fig. 3d; 3e-g) and drop in *N. pachyderma* and C_{37:4}
343 relative abundances (Fig. 4 b-c). This may indicate a temporary interruption in the arrival of polar
344 waters to the Iberian Margin during the terminal stadial event related to short-term northward shift
345 of subpolar front. During this short relative warming event, labeled "phase b", the AzC seems to
346 play a minor role as indicated by very low abundances of *T. truncatulinoides* and *G. ruber*,

347 suggesting a southernmost position of the AzF. A sharp, very short-lived increase of the polar
348 species (Fig. 4b) concomitant with an abrupt increase of $C_{37:4}$ at about 789.7 ka (Fig. 4 c) and a
349 further cooling of about 4°C in SST record (Fig. 3e), marks the last phase of terminal stadial (phase
350 c) and indicates a renewed intrusion of meltwaters into the region during a persistent cold and arid
351 climate period on land (Sánchez Goñi et al., 2016). The high abundance of semi-desert taxa in the
352 pollen assemblages from Site U1385 (Fig. 4g) corroborates this interpretation (Sánchez Goñi et al.,
353 2016) suggesting that the region was not under the influence of the westerly wind belt that usually
354 transports moisture to the Atlantic margin of the Iberian Peninsula.

355 During TIX, further support for the interpretation of subpolar meltwater intrusion in the North
356 Atlantic at high and middle latitudes comes from increases in Si/Sr at IODP Site U1308 (Fig. 4m)
357 (Hodell et al., 2008) and from $C_{37:4}$ alkenone and quartz abundance at IODP Site U1313 (Naafs et
358 al., 2011). Those records indicate the input of silicate-rich Ice Rafted Detritus (IRD) from North
359 Atlantic and European ice sheets with crystalline bedrock and the occurrence of iceberg melting at
360 least as far south as 41°N (Naafs et al., 2011). However, the absence of detrital carbonate at this
361 time suggests there was no Heinrich event *sensu stricto* (Hemming, 2004) associated with TIX
362 (Hodell et al., 2008). The cold terminal stadial event recorded prior to TIX at Site U1385 and in the
363 wider North Atlantic was probably related to the destabilization of the European Ice sheets as
364 suggested by Rodrigues et al. (2017).

365 At 788.4 ka, a rapid increase of *G. ruber* and *T. truncatulinoides* (Fig. 4 d, e) indicates that during
366 TIX the cold conditions of the terminal stadial were followed by a warming event, labeled as
367 “Event 1”. This event is characterized by a strong rise of sea surface temperatures of about 8°C
368 (Fig. 3 e) indicating a renewed influence of the AzC offshore Portugal. At this time, a very short
369 recovery of Mediterranean forest pollen at the expense of semi-desert communities (Fig. 4g)
370 suggests a weak increase of temperature and humidity on land (Sánchez Goñi et al., 2016). The
371 prominent warming was suddenly interrupted by a new cooling event as indicated by the drop of

about 7°C in the sea surface temperatures, and of about 5°C in the subsurface temperatures (Fig. 3 e-g) and by a sharp increase of *N. pachyderma* (light blue bar in Fig. 4b) and a drop of *G. ruber* abundance values. This cooling event, labeled as “Event 2”, seems to correspond to a 1000-yr-long cooling event on land as indicated by a renewed expansion of semi-desert communities in the pollen assemblages at about 787.5 ka (Fig. 4g), which preceded the onset of the full interglacial conditions (Tajo interglacial) (Sánchez Goñi et al., 2016). This event could be associated with a very short-term cold spell recognized in the western and central Mediterranean Sea, before interglacial warming inception, during TIX (Maiorano et al., 2016; Trotta et al., 2019; Marino et al., 2020; Quivelli et al., 2021). Similar cold and dry events occurring at TIX have been also observed in lacustrine successions from central Italy (Giaccio et al. 2015).

The planktonic foraminifera and pollen assemblage fluctuations recognized at Site U1385 during TIX are closely related and highlight the contemporaneity and strong coupling of regional hydrological and atmospheric changes.

385

4.1.1 Evolution of meridional thermal gradient during MIS20 and Termination IX.

Before the onset of MIS 20 terminal stadial, the SST records indicate relatively warm conditions along the Iberian Margin in contrast with rather low temperatures reconstructed at Site U1314. The planktonic foraminifera-based SSTs (Fig. 3 h-i) indicate surface and subsurface temperatures 16°C lower at Site U1314 compared with the temperatures at Site U1385 (Fig. 3 e-g). The strong meridional thermal gradient between the sites U1314 and U1385 suggests that the Arctic Front was located at a latitude south of Site U1314 but north of Site U1385. Therefore, NAC was diverted southeastwards preventing the arrival of warm waters to the subpolar North Atlantic. However, at ODP Site 980, located eastwards of Site U1314, the *N. pachyderma* abundance values (Fig. 4 l) remained lower during part of the glacial phase as a consequence of the eastwards deflection of the

396 NAC, resulting in a delay in cooling because of the gradual south-eastward migration of the AF
397 during the mid-Pleistocene glacial stages (Alonso-Garcia et al. 2011b, Barker et al., 2021).

398 At Site U1314 winter and spring subsurface seawater temperatures indicate slightly warmer
399 conditions than on the surface (fig. 3 h-i). Hernández-Almeida et al. (2015) also observed higher
400 subsurface temperatures during times of IRD deposition using trace metal analyses (Mg/Ca) of
401 planktonic foraminifera during episodes of weak AMOC. The accumulation of subsurface warming,
402 during ice-rafting events at northern latitudes, is related to the development of a halocline that
403 creates an inverse thermocline with cold waters on top and warm water from the NAC underneath
404 (Hernández-Almeida et al., 2015). With the onset of terminal stadial, the thermal gradient between
405 Sites U1314 and U1385 was reduced because of the arrival of cold water along the Iberian Margin
406 and the reduced influence of AzC. The first warming phase occurring during the terminal stadial
407 event at Site U1385, labeled phase b in Fig. 3, corresponds to an abrupt rise in surface and
408 subsurface SST at Site U1314 (Fig. 3 h- i) and a minimum thermal gradient between the Iberian
409 Margin and high-latitude North Atlantic. The warming phase was accompanied by a progressive
410 increase of benthic $\delta^{13}\text{C}$ values (Fig. 3k) suggesting improved deep- water ventilation and
411 strengthening of the NAC that transports heat northward to the location of Site U1314, thereby
412 leading to a lower north-south thermal gradient (Fig. 4 h-i). During TIX, the simultaneous increase
413 of benthic $\delta^{13}\text{C}$ values at Site U1385 and U1314 (Fig. 3b, 3k) during the warming phase b and
414 Event 1 indicates that the increasing influence of the warmer AzC to the Portuguese Margin was
415 accompanied by an increase in deep water ventilation in the North Atlantic probably related to
416 strengthening of the AMOC. The prominent increase of AzC-related fauna (*T. truncatulinoides* and
417 *G. ruber*) during Event 1 compared to previous warm phase suggests lower rates of meltwater
418 released to the ocean, as the deglaciation progressed, causing a higher northward heat transport and
419 displacement of the STG. At Site U1314, the drop of *N. pachyderma* abundances (Fig. 4j) is further
420 evidence of the northern position of the polar front at this time while the increased abundances of *G.*

421 *inflata* (Fig. 5j) indicate the increasing influence of warm-temperate transitional water at high
422 latitudes.

423

424 **4.2 MIS 19 and full interglacial conditions**

425 The beginning of full interglacial conditions, at 787.5 ka is marked by the reactivation of AzC that
426 persisted throughout all of MIS 19c, and interstadials including those that occur on the MIS 19b-a
427 as indicated by high abundances of *G. ruber* (Fig. 4d). In agreement with the patterns of planktonic
428 $\delta^{18}\text{O}$ and Ca/Ti (Fig. 3a, 3c), the increase of warm water taxa in the foraminifera assemblages
429 seems to be the response to the arrival of warm waters (Fig. 5c) and high sea surface temperatures
430 to the Iberian Margin (Fig. 5b). On land the full interglacial, named Tajo interglacial, is defined as
431 the interval of highest forest expansion with maximum abundances of Mediterranean forest
432 sclerophyllous taxa (Fig. 5i), suggesting the establishment of Mediterranean climate conditions
433 characterized by marked seasonality (warm and dry summers and wet winters) (Sánchez Goñi et al.,
434 2016).

435 Between 787.5 ka and ~780 ka the co-occurrence of high abundance of wwt and *G. inflata* (Fig. 5c,
436 5e) and the presence of *T. sacculifer* defines an interval with persistent seasonal low-nutrient and
437 predominantly stratified surface water conditions (Salgueiro et. 2008, 2010). This may be related to
438 the strengthening of AzC and increase in the influence of warm transitional water masses that flow
439 north of the Azores where *G. inflata* proliferates in accordance with its ecology related to non-
440 upwelling, transitional and oligotrophic, conditions (Giraudeau, 1993). The lower abundance of *N.*
441 *incompta* (Fig. 5f) during this interval indicates a weak influence of the colder PC in agreement
442 with findings based on calcareous nannoplankton assemblages at Site U1313, which indicate the
443 arrival of warmer waters up to 41°N (Emanuele et al., 2015). The highest surface and subsurface
444 temperatures (Fig. 3h-i) and the highest abundances of *G. inflata* recorded at Site U1314 (Fig. 5j)

445 concur to indicate that early MIS19c was the warmest interval of the substage when warm NAC
446 prevailed at high latitudes.

447 The occurrence of *G. bulloides* (Fig. 5h) in the assemblages at IODP Site U1385 indicates that
448 seasonal upwelling occurred during this warm interval. Similar to today, the seasonal upwelling
449 along the Portuguese coast was induced by the northerly trade winds (Fiúza et al., 1982) that blow
450 during summer, favoring the proliferation of *G. bulloides* (Salgueiro et al., 2008). During the older
451 interval of MIS19c (787.5 ka – 780 ka) the occurrence of *T. quinqueloba*, indicative of cold and
452 high fertility environments, could also be associated with the seasonal upwelling as this species can
453 proliferate during upwelling conditions (Sautter and Sancetta, 1992; Schiebel et al., 2004; Davis et
454 al., 2016; Hernández-Almeida et al., 2011).

455 At Site U1385, the warming trend was interrupted by a short-term cold event (Event 3 in Fig. 5)
456 occurring at about 784.5 ka when the annual and seasonal SST records (Fig. 3e-g) display a
457 prominent drop of temperatures of about 5°C with a minimum of sea surface annual temperature of
458 about 13°C. This short climate change did not affect the climate on land because it does not
459 correspond to any of the main Mediterranean forest contractions recorded by pollen assemblages
460 during substage MIS19c (black asterisks in Fig. 5i) (Sánchez Goñi et al., 2016). Sánchez Goñi et al.
461 (2016) found that MIS 19 was punctuated by forest contraction episodes indicative of millennial-
462 scale cooling and drying conditions in southwestern Iberia during the maximum forested phase of
463 MIS 19 as a result of the reinforcement and northward shift of the westerlies during winter.
464 However, the cooling, recorded in SSTs, is mainly recognized by high abundances of *T.*
465 *quinqueloba* and coincides with the maximum expansion of Mediterranean forest pollen indicative
466 of the establishment of marked seasonal climate conditions on land characterized by warm and dry
467 summers and wet winters (Sánchez Goñi et al., 2016). We cannot exclude that the seasonal
468 fertilization related to continental nutrient input during winter precipitation on land increases the
469 abundance of *T. quinqueloba*, during MIS 19c, in accordance with the ecological affinities of the

470 species (Bartels-Jónsdóttir et al., 2015; Jonkers et al., 2010; Rohling et al., 1997). On the contrary,
471 during the cooling events reported for the terrestrial reconstruction, the foraminifera-based SST
472 record does not register any temperature drop, suggesting a land-ocean decoupling as evidenced by
473 pollen and alkenone-based SST during the interglacial interval at Site U1385 (Sánchez Goñi et al.,
474 2016). The cold land–warm ocean decoupling at orbital- and millennial-scale time scales indicate
475 repeated periods of intensified northward transport of heat from equatorial regions and associated
476 water vapor triggered by precession-forced low latitude climate changes (Ferretti et al. 2015;
477 Sanchez Goñi et al., 2016). This moisture increase, during the decrease of summer insolation, could
478 have contributed to growth of the ice sheet during the onset of MIS 18 (Sanchez Goñi et al., 2016).

479 The decoupling of SST with land dynamics that are closely related to atmospheric processes
480 suggests that SST was influenced by oceanographic processes rather than atmospheric dynamics.
481 The upwelling regime along the Iberian Margin may have a strong affect on the relative abundances
482 of planktonic foraminifera indicative of upwelling (Fig. 5c). The reduction of wwt during dry and
483 cooling climate events on land could be an ecological response of these taxa to eutrophication
484 events related to a larger wind-induced upwelling season. During the early MIS 19c, the high
485 abundance of *G. bulloides* during the forest contraction event 4 (782 ka) and event 6 (778 ka) (black
486 asterisks in Fig. 5i) supports this hypothesis. *G. bulloides* is considered the main component of the
487 planktonic foraminifera assemblage associated with upwelling conditions in this region (Salgueiro
488 et al., 2008) and during these events it shows the highest abundances (Fig. 5h) throughout the full
489 interglacial interval. Higher wind activity in spring-summer would have facilitated the
490 destabilization of the water column and intensified upwelling and/or a longer upwelling season
491 related to diminished influence of the winter westerlies in Iberia. The intensified upwelling
492 conditions lead to higher concentration of nutrient in the sea waters, thereby inhibiting the
493 proliferation of warm and oligotrophic taxa. The SST remain high because, at this time, the AzC is
494 active, and the site is under the influence of ENACWst and consequently, during the upwelling

495 season, the upwelled waters had subtropical origin. The occurrence of the tropical taxon *T.*
496 *sacculifer* during this time interval further supports the interpretation of persistently warm SSTs.

497

498 **4.3 Late MIS 19 and glacial inception**

499 From ~780 ka onwards, the annual and seasonal temperatures at Site U1385 show a large variability
500 and a drop of average temperatures of about 1.5-1°C (Fig. 3). In the assemblages, a gradual
501 decrease occurs in the abundance of *G. inflata* (Fig. 5e) that is accompanied by an increase in *N.*
502 *incompta* (Fig. 5f), further indicating cooler temperatures. *N. incompta* is the major component of
503 the PC assemblage along the Iberian Margin today (Salgueiro et al., 2008), with the highest
504 abundances north of 39°N where the water temperature is colder than in the south year-round
505 (Salgueiro et al., 2008). At Site U1385, cooler temperatures favored the replacement of *G. inflata*
506 by *N. incompta* because the PC brought cold nutrient-rich water from the northern latitudes. The
507 increase in percentages of heathlands pollen assemblages indicates the establishment of a cool and
508 less seasonal climate regime on land characterized by lower annual precipitations during the
509 summer (Sánchez Goñi et al., 2016). Evidence of more persistent cool and nutrient-rich waters are
510 also found at Site U1313, where the presence of these waters has been related to the intensification
511 of the cooler NAC forced by variations in high-latitude summer insolation (Emanuele et al., 2015).
512 From ~780 ka onwards, the drop in the abundances of *G. inflata* in the assemblages (Fig. 5j), at site
513 U1314, could also be related to cooling of the NAC. Cooler climate conditions are also recorded in
514 the western Mediterranean basin starting from ~778 ka, as suggested by calcareous plankton and
515 pollen assemblages (Toti et al., 2020).

516 The increase of *N. incompta* and benthic $\delta^{18}\text{O}$ values during late MIS 19c, in combination with the
517 decrease of alkenone-based (Fig. 3d) (Rodrigues et al., 2017) and foraminifera-based temperatures
518 (Fig. 3e-g) at IODP Site U1385 is interpreted as a change in the climate regime in the southern
519 Iberian Margin, probably related to ice sheet expansion at high latitude. The slight increase of *N.*

520 *pachyderma* abundances at ODP Site 980 (Fig. 4l) starting at ~780 ka further supports the onset of
521 progressive cooling that affects the entire North Atlantic. However, the AzC was still seasonally
522 influencing the Iberian Margin because the high abundance of *G. ruber* (Fig. 4d) indicates seasonal
523 transport of warm, salty waters to the site and the high percentages of *G. bulloides* indicates
524 seasonal coastal upwelling (Fig. 5h). These data support an increase in the meridional thermal
525 gradient that coincides with the maximum $\delta^{13}\text{C}$, reflecting a vigorous deep water ventilation and the
526 arrival of moisture to the high northern latitudes, which in turn started building-up the ice sheets at
527 the MIS 19c/b transition (~775 ka).

528 From about 771 ka, the wwt abundance record (Fig. 5c) shows high frequency variability
529 corresponding to stadial-interstadial oscillations that are in good agreement with the oscillations in
530 the planktonic $\delta^{18}\text{O}$ curve (Fig. 5a) and with the log Ca/Ti record during MIS 19b-a (Fig. 3b). The
531 stadials are characterized by drops in wwt abundances and increases of subpolar *T. quinqueloba*
532 (Fig. 5g) suggesting cooling of surface and subsurface waters during the prominent drops in
533 planktonic foraminifera-based (Fig. 3e-g) and alkenone-based SSTs (Fig. 3d) (Rodrigues et al.,
534 2017). The first of those stadial events occurred between 771 ka and 769 ka as recorded by the
535 increase of *N. incompta* and *T. quinqueloba* (Fig. 5f-g) and the sharp decrease of wwt (Fig. 5c),
536 indicating a sustained influence of cold water transported by the PC. The drop in *G. ruber* (Fig. 4d)
537 abundances suggests a diminished influence of the AzC at Site U1385 related to a southern
538 displacement of AzF. This interpretation is supported by the temperature drop at Site U1314 (Fig.
539 3h-i). The records from North Atlantic Site U1313 also support a southward migration of the NAC
540 and consequent increase in the influence of cooler waters at this time (Emanuele et al., 2015). The
541 gradual increase in abundances of *N. pachyderma* and subpolar *T. quinqueloba* during the
542 subsequent stadials of MIS 19b-a are consistent with the *N. pachyderma* abundance record at the
543 ODP Site 980 (Fig. 4i) and at Site U1314 (Fig. 4j) which suggest that the subpolar front rapidly
544 oscillated from its southward position during the stadials to northward positions during the

545 interstadials. At Site U1385 this change is also supported by the trends of lower SST (Fig. 3e-g) and
546 higher $C_{37:4}$ values (Fig. 4c) while, on land, the Mediterranean forest reductions along with semi-
547 desert community expansions (Fig. 4g) suggest a shift towards colder and drier winter episodes
548 (Sánchez Goñi et al., 2016). The low north-south thermal gradient (Fig. 4h-i) suggests that the ice
549 discharges in the North Atlantic and the related meltwater affected both the subpolar gyre and
550 Iberian Margin and, therefore, the SSTs became more similar across different latitudes.

551 The interstadials were marked by a sudden rise of annual and seasonal SST that show values very
552 close to those recorded during MIS 19c (Fig. 3e-g). The prominent increase in the abundance of *G.*
553 *ruber* and *T. truncatulinoides* (Fig. 4d, e) indicates an intensification of the STG and AzC in this
554 sector of the Iberian Margin which played a major role in warming the sea surface, while seasonal
555 coastal upwelling favored the proliferation of *G. bulloides*. Interstadial climate conditions were
556 comparable with the Tajo interglacial phase both in the sea and on land where the pollen
557 assemblages indicate the establishment of Mediterranean climate related to a greater influence of
558 the westerlies that bring moisture to the Iberian Margin (Sánchez Goñi et al., 2016). Overall, the
559 climate variability during MIS 19b-a along the Iberian Margin is a response to repeated shifts of
560 westerlies along with the relative position of AzF and Polar Front. These findings are consistent
561 with the climate patterns in the North Atlantic (Channell et al., 2010; Kleiven et al., 2011; Tzedakis
562 et al., 2012a, b; Emanuele et al., 2015; Ferretti et al., 2015; Sánchez Goñi et al., 2016; Alonso-
563 Garcia et al., 2011a, 2011b), Antarctic EDC ice core record (Jouzel et al., 2007; Pol et al., 2010),
564 and with the millennial-scale climate oscillation recorded in western and central Mediterranean sites
565 (Maiorano et al., 2016; Nomade et al., 2019; Marino et al., 2020; Toti et al., 2020) and in lacustrine
566 sediments from central Italy (Giaccio et al., 2015; Regattieri et al., 2019) during MIS 19 a-b.

567 Our findings indicate that during the MIS 19/18 glaciation, the Iberian Margin experienced the
568 influence of cooler water related to progressive southern migration of subpolar front. This
569 reconstruction is consistent with the increasing trend of benthic $\delta^{18}\text{O}$ values at IODP Site U1385,

570 accounting for both colder deep sea water temperatures and continental ice sheet growth. Evidence
571 of the progressive southern migration of the Polar Front is also indicated by the increasing trend of
572 *N. pachyderma* and benthic $\delta^{18}\text{O}$ at Site U1314. An increase in the global ice volume starting from
573 late MIS 19c and culminating in the onset of glacial MIS 18 is also supported by a similar trend of
574 benthic $\delta^{18}\text{O}$ at IODP Site U1313 (Fig. 5k) (Ferretti et al., 2015).

575 **Conclusion**

576 By analysis of planktonic foraminifera from the Iberian Margin (Site U1385) we documented
577 orbital and millennial-scale paleoceanographic and climate changes during MIS 20 and MIS 19.
578 These changes were mainly controlled by shifts of the AzF and Polar Front as indicated by the
579 faunal and stable isotope records. The combination of planktonic foraminifera and available pollen
580 data from the same site permitted identification of the role of atmospheric versus marine processes
581 in these changes.

582 During MIS 20, the expanded ice sheets resulted in a strong cooling in the SPG whereas the Iberian
583 Margin remained relatively warm under the influence of the AzC. During the TIX terminal stadial
584 event (between 794 ka and 789 ka), fluctuating pulses of cold and fresh water during iceberg
585 discharges into the North Atlantic lowered the sea surface and subsurface temperatures at the
586 Iberian Margin at the same time as the establishment of cold, arid climate conditions on land. The
587 establishment of full interglacial conditions during MIS 19c was preceded by short-term
588 fluctuations in AzC assemblages and SSTs resulting in successive warming/cooling phases in the
589 ocean coupled with warming/cooling events on land. Between 787.5 and 780 ka, the greater
590 influence of the southern AzC and warm transitional waters define the climatic optimum of MIS
591 19c. During this interval the SST trend diverges from the vegetation changes inferred from pollen
592 suggesting a land-sea decoupling. Thus, the planktonic foraminifera climate proxies indicate that
593 during the interglacial phase the sea surface temperatures were dominated by oceanographic rather
594 than atmospheric processes, supporting the land-ocean decoupling inferred from pollen and

595 alkenone-based SSTs at Site U1385. During the cool and dry millennial-scale events on land,
596 greater wind activity in spring-summer would have caused an intensification in upwelling and/or
597 seasonal upwelling as indicated by increased *G. bulloides* during a time of relatively high SST when
598 the site was under the influence of the AzC. The repeated northward transport of heat from lower to
599 high latitude and increase moisture flux during cold conditions on land could have contributed to
600 growth the ice sheets at the onset of MIS 18. The full interglacial conditions started to deteriorate at
601 ~780 ka when *N. incompta* increases at the expense of *G. inflata*, indicating cooler SSTs and the
602 establishment of a cool, less seasonal climate regime on land. The MIS 19 b-a interval was
603 characterized by high frequency variability corresponding to stadial-interstadial oscillations related
604 to shifts of the polar and subtropical fronts coupled with warm-wet/cold-arid climate oscillations on
605 land. From the glacial inception (MIS 19c/b towards MIS18) a cooling trend along the Iberian
606 Margin indicates the progressive southward migration of the polar front, supported by the gradual
607 increase of *N. pachyderma* and *T. quinqueloba*. During these stadial events the SST gradient was
608 reduced because the ice discharges affected both the SPG and Iberian Margin and the SST became
609 more similar across latitudes.

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953

954 **Figure captions**

955 Fig. 1 – Modern surface circulation in the North Atlantic and location of the sites discussed in the
956 text. PC: Portugal Current; IPC: Iberian Poleward Current; ENACWsp: Eastern North Atlantic
957 Central Waters of subpolar origin; ENACWst: Eastern North Atlantic Central Water of subtropical
958 origin; SPG: Subpolar Gyre; STG: Subtropical Gyre; AF: Artic Front.

959 Fig. 2 - Cumulative abundances of planktonic foraminifera at IODP Site U1385 plotted against the
960 $\delta^{18}\text{O}$ plankton and $\delta^{18}\text{O}$ benthos (Hodell et al., 2015; Sánchez Goñi et al., 2016) vs age.

961 Fig. 3 – Faunal-based Sea Surface Temperatures at IODP Site U1385 and Site U1314 through MIS
962 20 and MIS 19 compared with geochemical data from the same sites and alkenone and pollen data
963 from the site U1385. (a) Benthic $\delta^{18}\text{O}$ record at Site U1385 (Hodell et al., 2015; Sánchez Goñi et
964 al., 2016). (b) Benthic $\delta^{13}\text{C}$ record at IODP Site U1385 (Hodell et al., 2015; Sánchez Goñi et al.,
965 2016). (c) Log Ca/Ti record at IODP Site U1385 (Hodell et al., 2015). (d) Alkenone-based SST
966 curve at IODP Site U1385 (Rodrigues et al., 2017). (e-g) Annual and seasonal SST at Site U1385 at
967 10m and 200m depth. (h-i) seasonal SST at IODP Site U1314 at 10m and 200m depth. (j) Benthic
968 $\delta^{18}\text{O}$ record at Site U1314 (Alonso-Garcia et al., 2011; Hernandez-Almeida et al., 2012). (k)
969 Benthic $\delta^{13}\text{C}$ record at Site U1314. Light grey bands highlight stadial phases. Dark grey band
970 highlight MIS 20 terminal stadial. Light yellow band indicates the climate optimum according to
971 the planktonic foraminifera assemblages. Light pink band indicates warming event during terminal
972 stadial. Dark pink band indicates warming Event 1. Light blue band highlights Event 2, the cold
973 event preceding the full interglacial conditions.

974 Fig. 4 – Climate and paleoceanographic phases trough MIS 20 and MIS 19 at IODP Site U1385
975 based on planktonic foraminiferal proxies. (a) Benthic $\delta^{18}\text{O}$ record at Site U1385 (Hodell et al.,
976 2015; Sánchez Goñi et al., 2016). (b) Abundance pattern of *N. pachyderma* at Site U1385. (c) $\text{C}_{37:4}$
977 based freshwater pulse record at IODP Site U1385 (Rodriguez et al., 2017). (d-e) Abundance
978 patterns of planktonic foraminifera species (*G. ruber* and *T. trucatulinoides*) related to AzC and

979 STG. (b) Abundance pattern of *G. inflata* at Site U1385. (g) pollen taxa abundances relevant for the
980 climate variability on land (Sánchez Goñi et al., 2016). (h-i) Seasonal thermal gradient between
981 IODP Site U1385 and IODP Site U1314. (j) Abundance pattern of *N. pachyderma* at IODP Site
982 U1314 (Alonso-Garcia et al., 2011; Hernandez-Almeida et al., 2013). (k) IRD fluxes from Site
983 U1314 (Alonso-Garcia et al., 2011; Hernandez-Almeida et al., 2012). (l) Abundance pattern of *N.*
984 *pachyderma* at Site 980 (Wright and Flower, 2002). (m) Si/Sr record at IODP Site U1308 (Hodell et
985 al., 2008). (n) Mean summer insolation (JAS) (65° N) from Laskar et al. (2004). Light grey bands
986 highlight stadial phases. Dark grey band highlight MIS 20 terminal stadial. Light yellow band
987 indicates the climate optimum according to the planktonic foraminifera assemblages. Light pink
988 band indicates warming event during terminal stadial. Dark pink band indicates warming Event 1.
989 Light blue band highlights Event 2, the cold event preceding the full interglacial conditions. Black
990 asterisks indicate Mediterranean forest contractions (the numeration of these events is according to
991 Sánchez Goñi et al., 2016), blue asterisk indicates the cooling event before the onset of the Tajo
992 interglacial according to Sánchez Goñi et al., 2016.

993 Fig. 5 – Climate and paleoceanographic phases trough MIS 20 and MIS 19 at IODP Site U1385
994 based on planktonic foraminiferal proxies. (a) Benthic $\delta^{18}\text{O}$ record at Site U1385 (Hodell et al.,
995 2015; Sánchez Goñi et al., 2016). (b) Spring SST at Site U1385 at 10m and 200m depth. (c-h)
996 Abundance patterns of selected planktonic foraminifera species at IODP Site U1385. (i) Pollen taxa
997 abundances of Mediterranean forest taxa (green line) and Heathlands (brown line) (Sánchez Goñi et
998 al., 2016). (j) Abundance pattern of *G. inflata* at IODP Site U1314 (Alonso-Garcia et al., 2011;
999 Hernandez-Almeida et al., 2013). (k) Benthic $\delta^{18}\text{O}$ record at IODP Site U1313 (Ferretti et al.,
1000 2015). Light grey bands highlight stadial phases. Dark grey band highlight MIS 20 terminal stadial.
1001 Light pink band indicates warming phase c during terminal stadial. Dark pink band indicates
1002 warming Event 1. Light blue band highlights Event 2, the cold event preceding the full interglacial
1003 conditions. Blue arrow indicates Event 3, the cooling event during MIS19c according to planktonic

1004 foraminifera-based SST. Black asterisks indicate Mediterranean forest contractions (the numeration
1005 of these events is according to Sánchez Goñi et al., 2016) and dashed lines their correlation with
1006 major drop in wwt assemblages. Blue asterisk indicates the cooling event before the onset of the
1007 Tajo interglacial according to Sánchez Goñi et al., 2016.

1008 **Supplementary figure captions**

1009 Supplementary Table 1 - Performance of cross-validated (bootstrapping, 999 permutation cycles)
1010 MAT regression with five analogues (MAT-K5) for seasonal and annual temperatures at 10 and 200
1011 m depth, with a cut-off distance of 850 km.

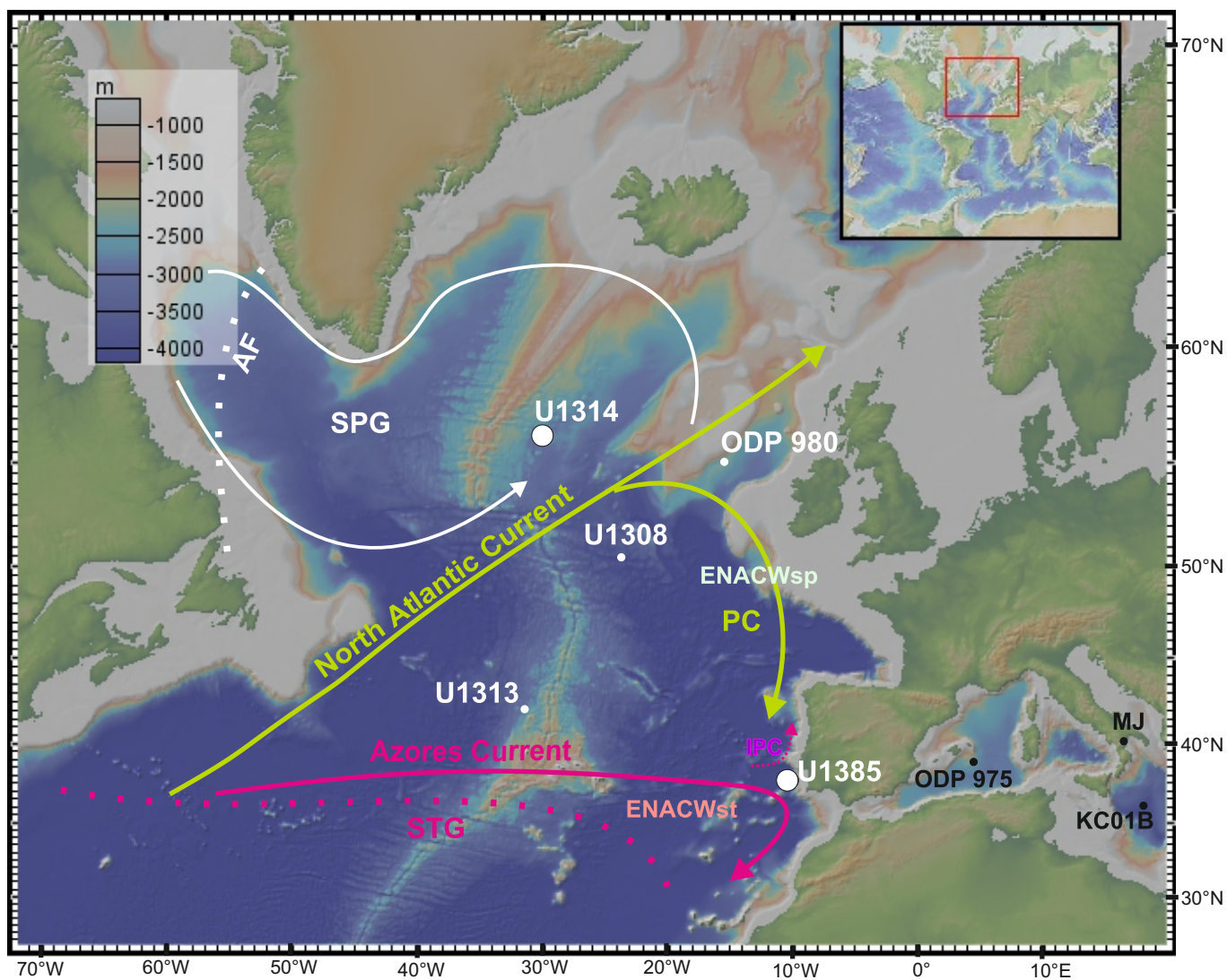
1012 Supplementary Fig. 1 - Squared residual lengths between fossil planktonic foraminifera
1013 assemblages from sites A) U1314 and B) U1385 and the modern training set for the North Atlantic
1014 through time.

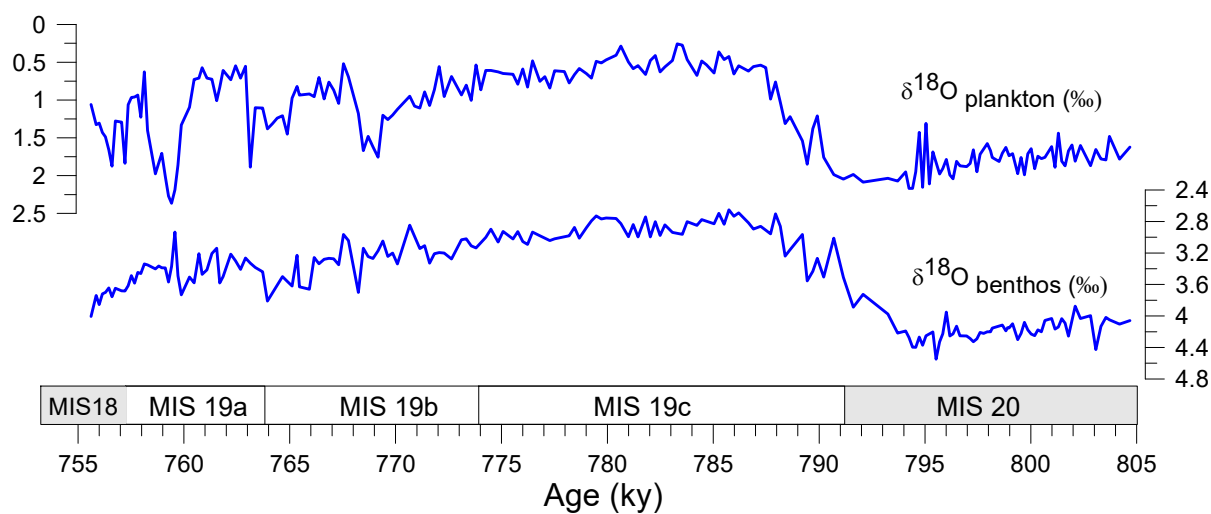
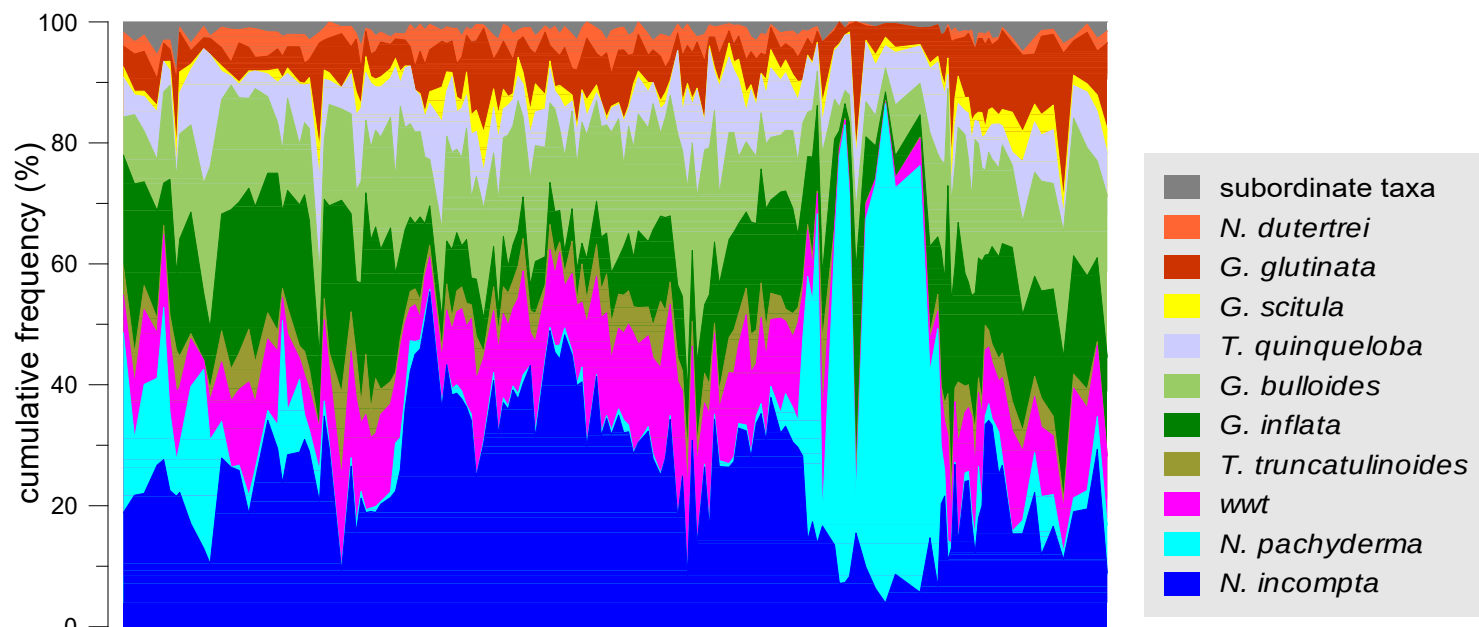
1015

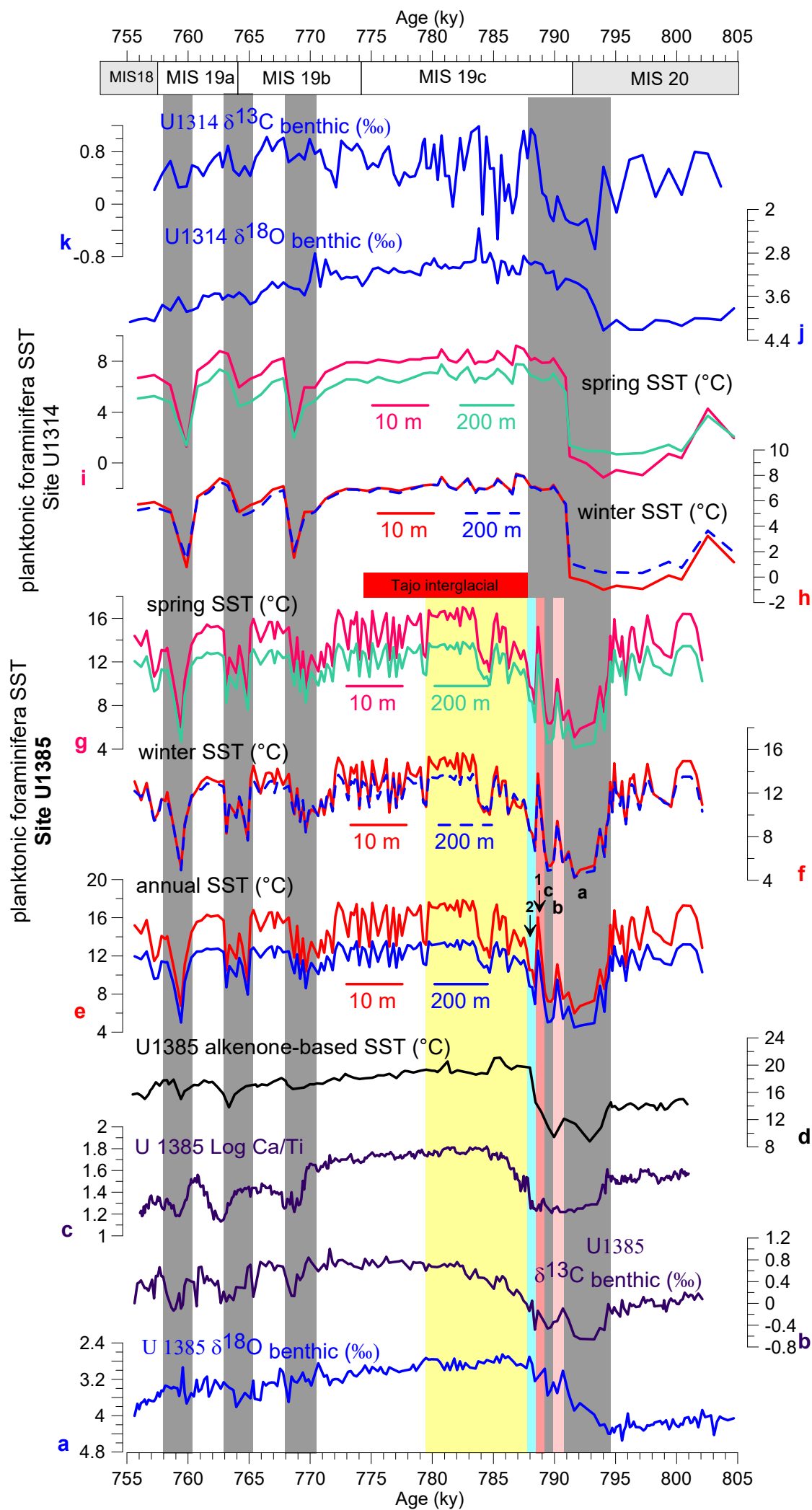
1016 Supplementary Fig. 2 - Variance of the reconstructed SST for each season and depth at sites A)
1017 U1314 and B) U1385. Environmental variables with a $p < .05$ are significant for the downcore
1018 assemblage.

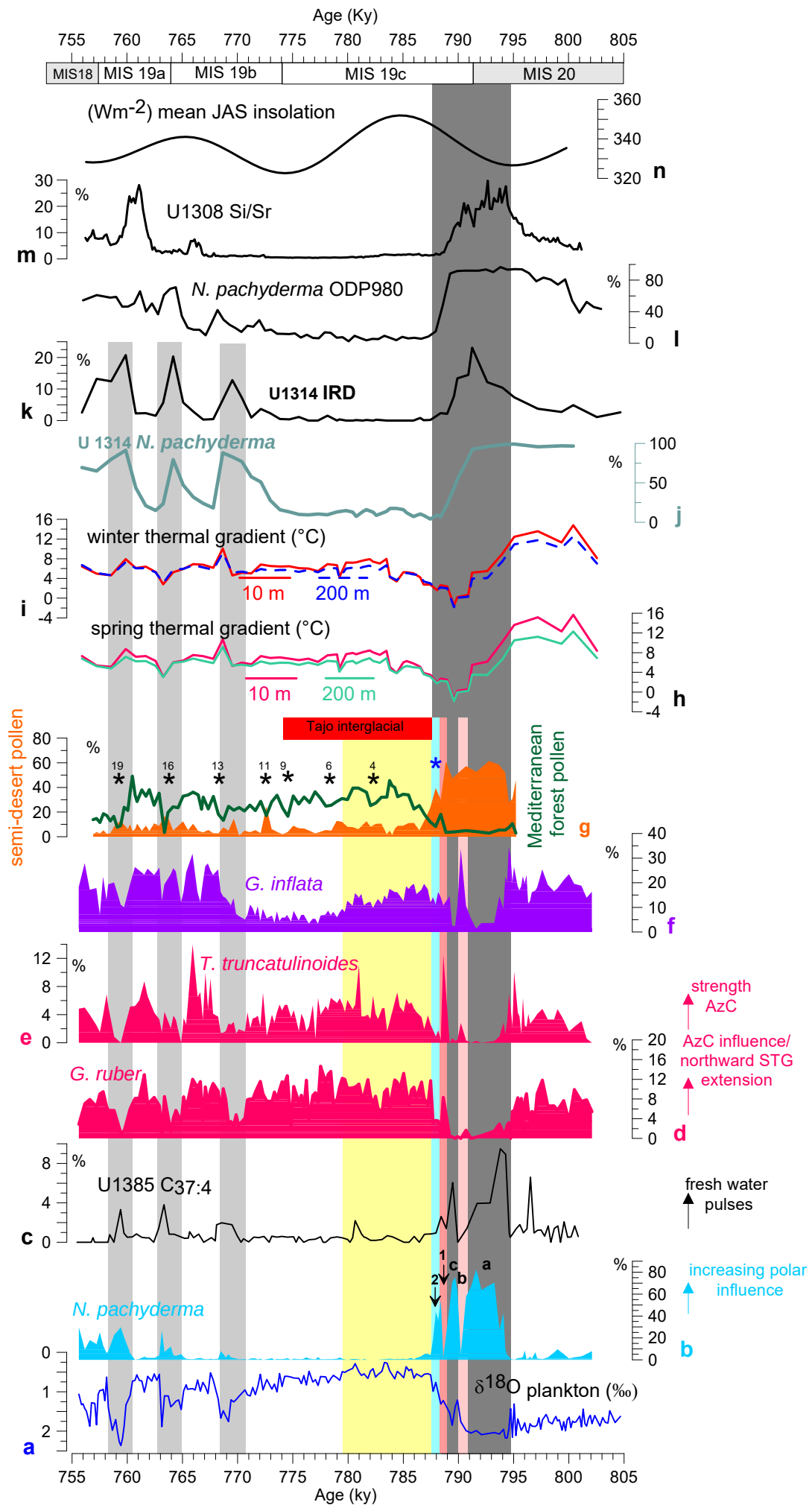
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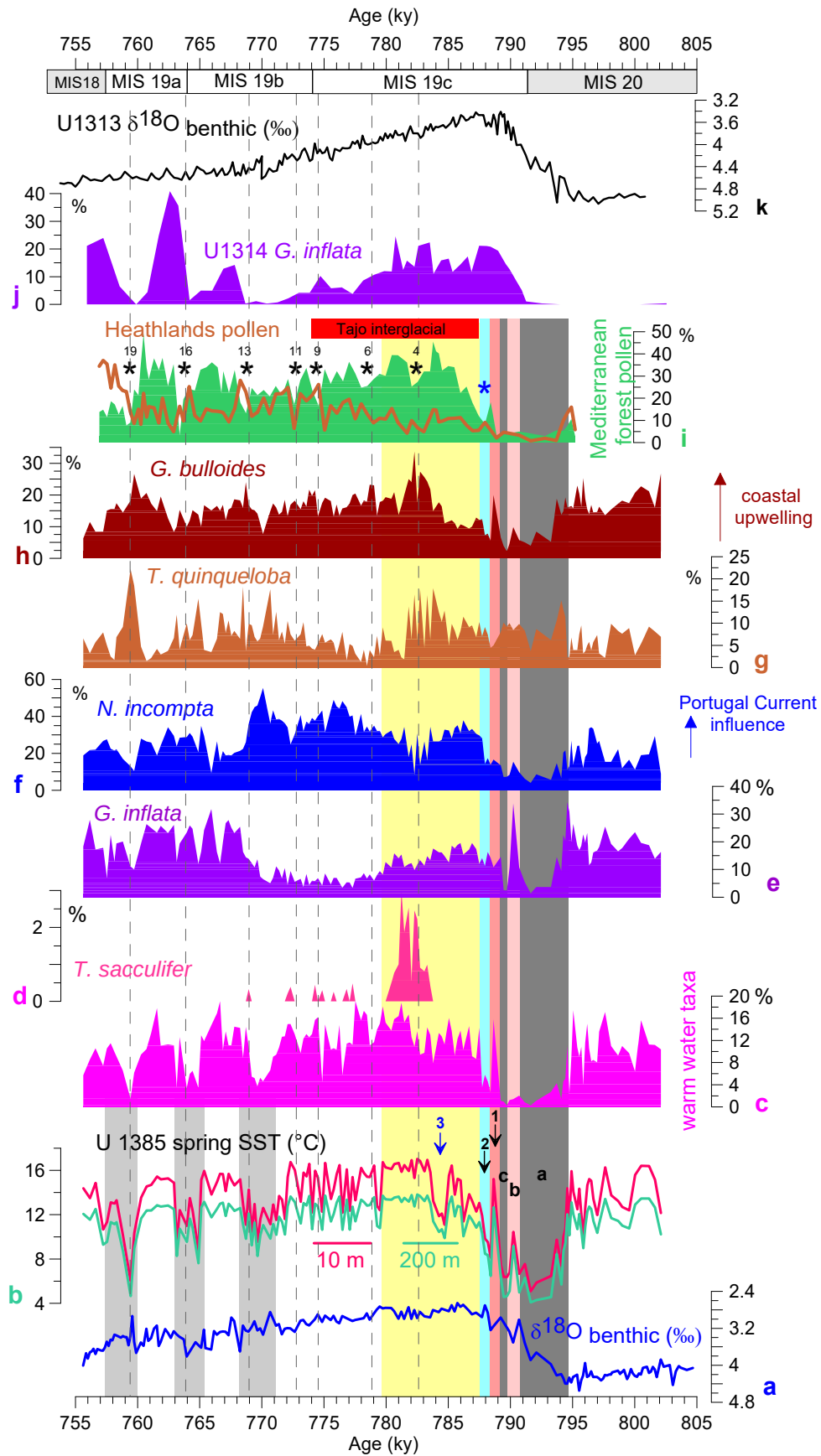
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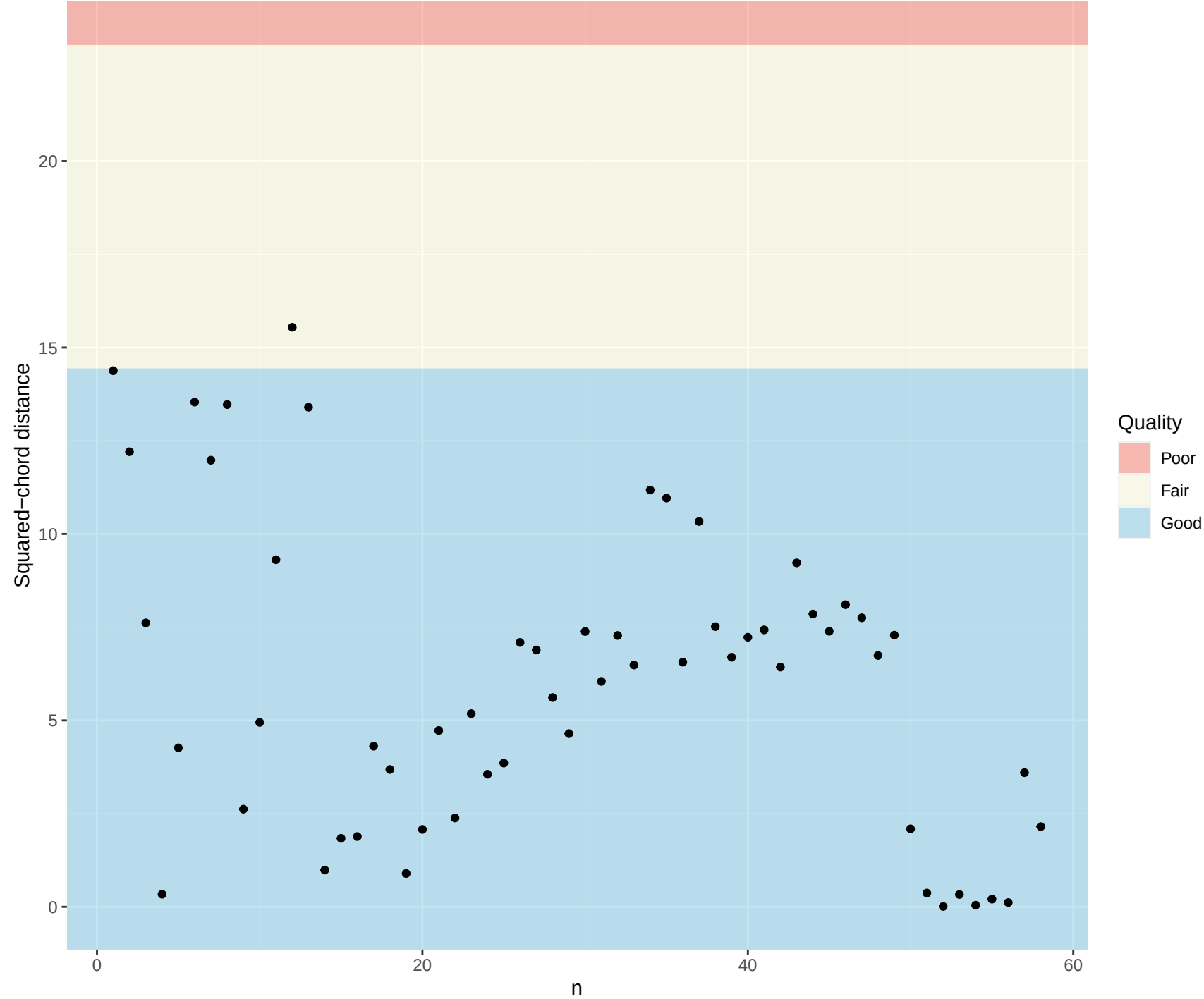




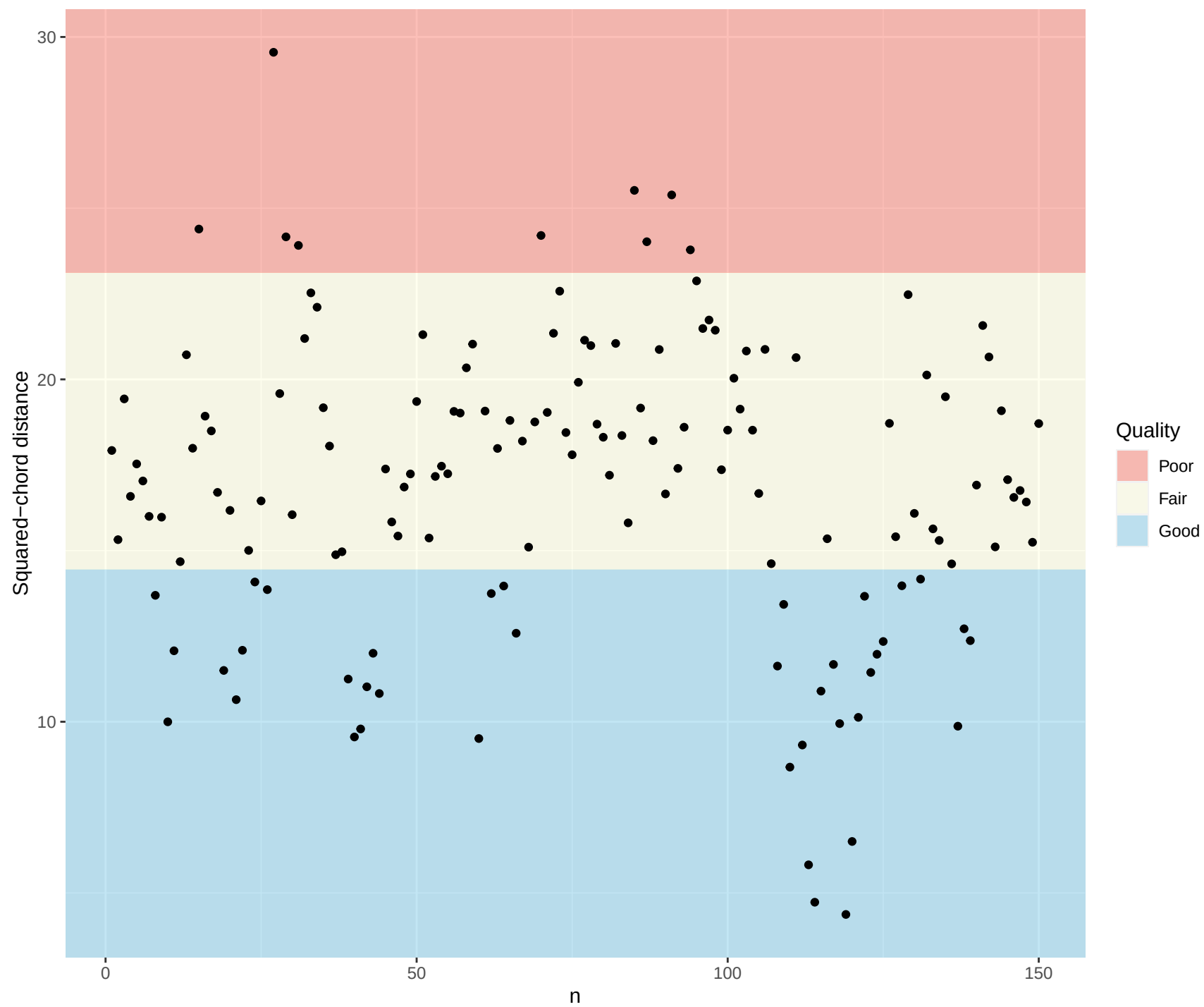


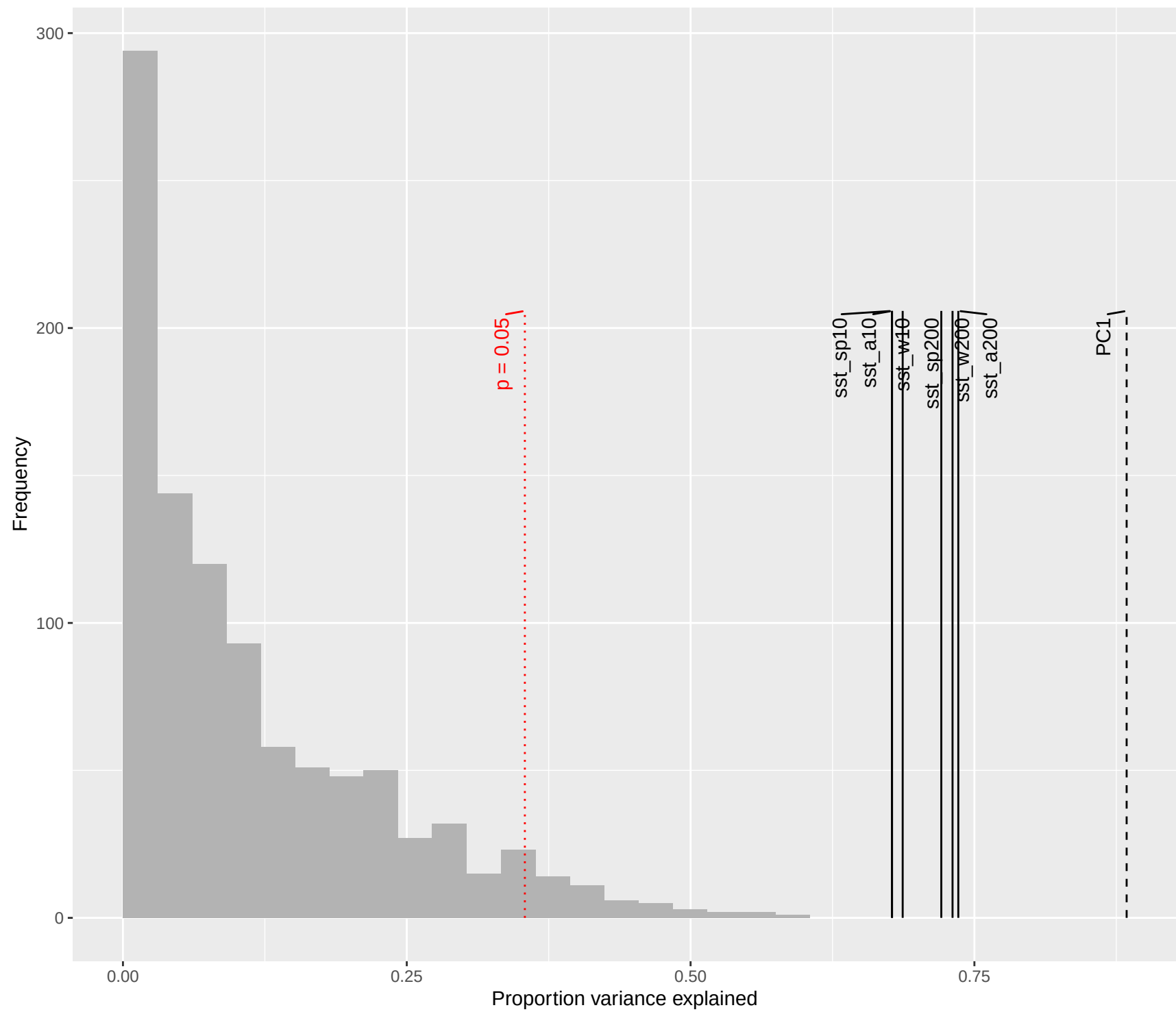


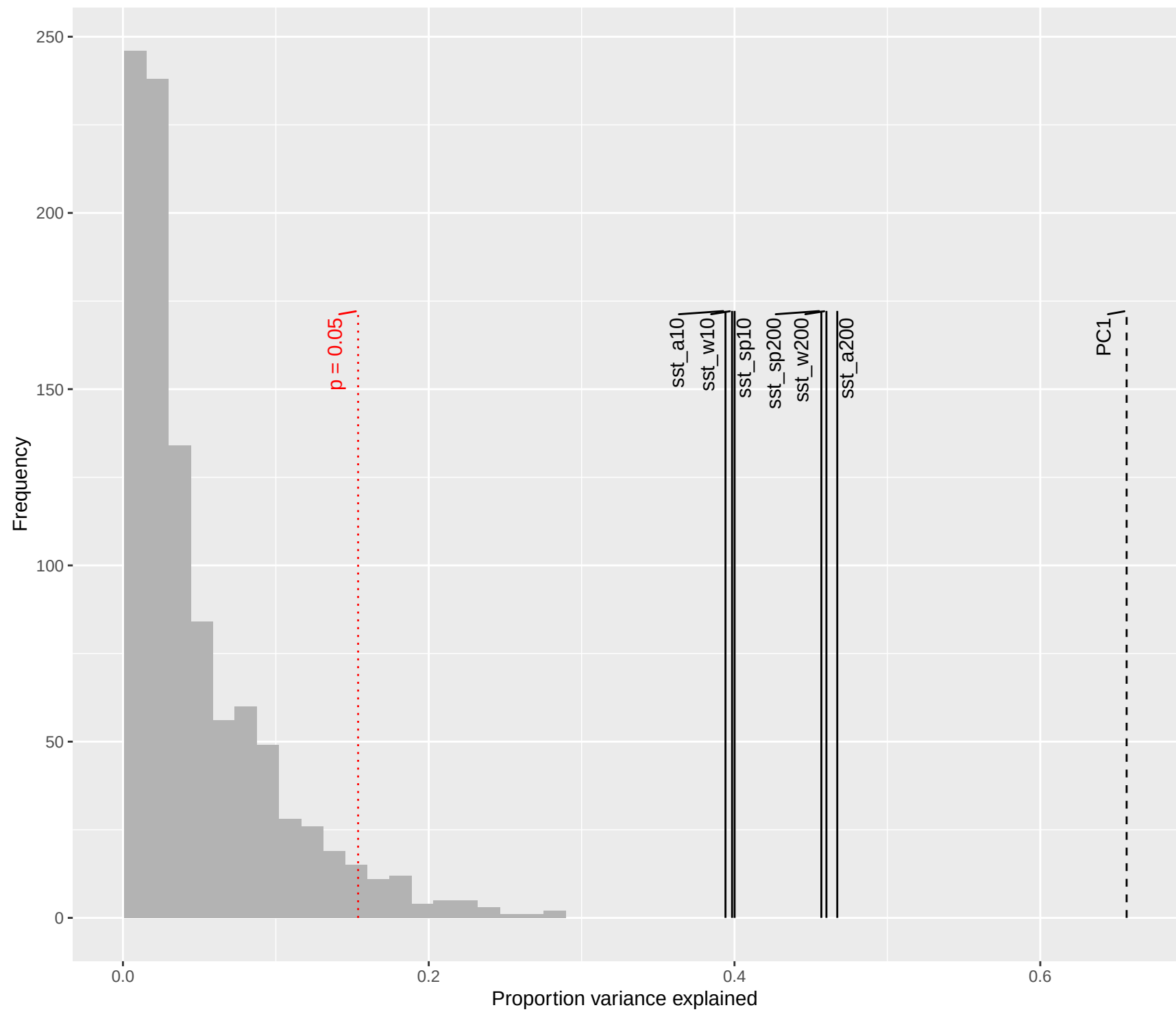
Analogue distance ForCenS NAT – U1314



Analogue distance ForCenS NAT – U1385







Performance MAT-K5

season/depth	RMSEP (cv)	R2 (cv)	Avg.Bias	Max.Bias	Skill
SSTsp 10m	1,033	0,989	0,076	0,519	98,920
SSTsp 200m	1,246	0,960	0,079	1,925	95,951
SSTw 10m	1,020	0,990	0,049	0,415	98,946
SSTw 200m	1,200	0,963	0,073	1,618	96,250
SSTa 10m	0,992	0,990	0,081	0,811	98,948
SSTa 200m	1,225	0,960	0,069	1,854	95,976