# Intermediate water variability of the subtropical Northeastern Atlantic during 490–424 ka (late MIS 13 and MIS 12)

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#### Abstract :

High-resolution foraminiferal stable isotopes and benthic foraminiferal faunal records of IODP Site U1391 drilled off the western Iberian margin were adopted to reconstruct intermediate water variability of the subtropical Northeastern Atlantic during the late Marine Isotope Stage (MIS) 13 and MIS 12. Five faunal turnovers were recognized based on multivariate statistical analyses of benthic foraminiferal census data from the size fraction >125 µm. The dominance of Uvigerina peregrina parva and Melonis barleeanum coincides with high benthic foraminiferal accumulation rates (BFAR), high benthic  $\delta$ 13C and the presence of dark-colour sediments during the final stage of MIS 13, also accompanied by frequent occurrences of Planulina ariminensis, an indicator of Mediterranean Outflow Water (MOW), which indicates MOW-related high oxic and mesotrophic to slightly eutrophic bottom water environments. MIS 12c and MIS 12b are characterized by Bulimina mexicana assemblage, together with low BFAR, high benthic δ13C and the presence of light-colour sediments, revealing mesotrophic and well-oxygenated seafloor conditions associated with the possible advection of Glacial North Atlantic Intermediate Water (GNAIW) to the studied site. A prominent increase in organic matter supply and a slight decrease in dissolved oxygen concentration during MIS 12a were reflected by more abundant Bulimina aculeata, higher BFAR, lower benthic δ13C and the darker-colour sediments relative to MIS 12c-b. A shift in the dominant species and significantly decreased benthic  $\delta$ 13C, suggest an increased influence of southern-sourced waters (SSW) and a decreased influence of GNAIW during MIS 12a. During the early Termination V (TV), infaunal taxa mainly composed of B. aculeata, Bulimina exilis, Nonionella turgida, Brizalina sp. and Uvigerina proboscidea dominate the benthic foraminiferal population, which may be attributed to eutrophic and poorly-oxygenated bottom water environment strongly influenced by SSW. During the late TV, N. turgida rapidly became the predominant taxa, and its predominance was probably the result of further reduction in dissolved oxygen concentration.

#### Highlights

► Intensified Mediterranean Outflow Water during the late MIS 13. ► Strong influence of Glacial North Atlantic Intermediate Water from MIS 12c to 12b. ► Increase influence of southern-sourced waters (SSW) during MIS 12a. ► The Northeastern Atlantic intermediate water filled mostly by SSW during TV.

**Keywords** : MIS 12, foraminiferal faunal turnover, benthic stable carbon isotope, western Iberian margin, intermediate-depth water circulation

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# 1. Introduction

High-amplitude and low-frequency glacial/interglacial climatic cycles (~100 kyr) characterize the post-middle Pleistocene transition period (Clark et al., 2006). Among these glacial/interglacial episodes, Marine Isotope Stage (MIS) 12 is considered as the strongest glacial stage of the last 800 kyr (Lang and Wolff, 2011). Global ice volume was ~15% larger and global sea level was ~20 m lower during MIS 12 than during the Last Glacial Maximum (LGM) (Rohling et al., 1998). Since the important roles that changes in surface hydrography and the deep water formation played in global climate stability were recognized, many studies have involved changes in the North Atlantic

surface water conditions (Hodell et al., 2008; Stein et al., 2009; Voelker et al., 2010; Rodrigues et al., 2011), and the North Atlantic Deep Water (NADW) variability during MIS 12 (Raymo et al., 1990; Oppo et al., 1998; Poli et al., 2000; Rodríguez-Tovar et al., 2015).

However, studies of the North Atlantic intermediate water variability during MIS 12 are relatively scarce, especially from the high-resolution records. The existing high-resolution records on the North Atlantic intermediate worte, variability are mostly limited to the last glacial (Boyle and Keigwin, 1987; Cppo and Fairbanks, 1987; Oppo and Lehman, 1993; Marchitto et al., 1998 Praetorius et al., 2008; Yasuhara et al., 2019). During the LGM, nutrient-deplaced Glacial North Atlantic Intermediate Water (GNAIW) filled 1000-2000 r w ter depths of the North Atlantic and below ~2000 m was occupied by nutrient-rich Southern Ocean Water (SOW) which took the place of NADW formed during by interglacial stages (Boyle and Keigwin, 1987; Oppo and Fairbanks, 1967: Duplessy et al., 1988). Boyle and Keigwin (1987) proposed that GNAIW was produced at the expense of the NADW formation. The shoaling of NADW to form GNAIW during the LGM rearranged the distribution of nutrients and metabolic  $CO_2$  which were concentrated in deep waters rather than in intermediate waters as observed in the modern ocean, and this rearrangement may have affected past atmospheric CO<sub>2</sub> through the changes in oceanic alkalinity (Boyle, 1988). Therefore, knowledge of past variability in intermediate water circulation in the North Atlantic is important for understanding climate changes during the late Pleistocene.

Several studies focused on the glacial/interglacial-timescale variability of the Northeastern Atlantic intermediate water. The benthic  $\delta^{13}$ C record of ODP Site 982 retrieved in the subpolar Northeastern Atlantic revealed that the intermediate-depth water experienced a shift from interglacial Upper North Atlantic Deep Water (UNADW; a mixture of Labrador Sea Water (LSW) and Mediterranean Outflow Water (MOW)) to GNAIW over the last 1.0 Myr (Venz et al., 1999). The benthic foraminiferal record of IODP Site U1391 retrieved off the western Iberian margin suggested that the Northeastern Atlantic intermediate water was filled by intensified MOW during the interglacial stages and that the MOW current was sluggish during the glacial stages since the late Pleistocen (Guo et al., 2017, 2020). However, in addition to the flow intensity, the histor, of intermediate water hydrological changes is less understood. More evidence are needed to reconstruct the changes in the Northeastern Atlantic intermediate water circulation.

The western Iberian margin has become an ideal area of high-resolution paleoceanographic structions since the "Shackleton Site" provided a high-fidelity record of millennial-scale crimate variability for the last glacial cycle (Shackleton et al., 2000). Benthic foraminifera are abundant off the western Iberian margin, and their faunal changes and stable isotope compositions have been used as paleoceanographic proxies (Singh et al., 2015; Guo et al., 2017, 2020). In this study, we present high-resolution foraminiferal stable isotope data and benthic foraminiferal faunal records from the depth interval of 124-128.3 mcd at IODP Site U1391 drilled off the western Iberian margin at 1085 m water depth (Fig. 1a), in order (1) to reveal bottom

water hydrological changes off Portugal, and (2) to explore the possible changes in intermediate water circulation of the subtropical Northeastern Atlantic during the late MIS 13 and MIS 12.

# 2. Regional oceanographic setting

The surface hydrography off the western Iberian margin is characterized by seasonal upwelling and is affected by the southward cool Portugal Current during summer and by the northward warm Iberian Poleward Cu. rent during winter (Haynes and Barton, 1990). Underneath the surface water 'ice the North Atlantic Central Water (NACW). It has two origins (Fiúza et al., 1998): the warmer, saltier, nutrient-poor subtropical origin NACW<sub>st</sub> (100-250 ...) which is formed along the Azores Front at approximately 35°N, and the colder, less laline, nutrient-rich subpolar origin NACW<sub>sp</sub> (250-500 m) which develops ir. t're eastern North Atlantic north of 46°N by winter cooling and deep convection (N<sup>2</sup>Cartney and Talley, 1982). Underlying NACW is the MOW current that fills the Northeastern Atlantic intermediate water between 500 and 1400 m (Ambar and Howe, 1979). MOW derives from Mediterranean Intermediate Water (MIW) and Western Mediterranean Deep Water (WMDW) with a high salinity of 38.4 psu (Bethoux, 1980) and dissolved oxygen concentration of 175 µmol/kg (Wüst, 1961). MIW is formed in the southern Adriatic Sea, the southern Aegean Sea and the Levantine Basin, and spreads into the western Mediterranean Sea through the Strait of Sicily (Candela, 2001), making up to ~70% of the outflowing Mediterranean waters (Millot et al., 2006), and WMDW originates in the Gulf of Lions (Rohling et

al., 1998). The saltier outflowing Mediterranean waters entrain less saline NACW when entering the Gulf of Cádiz through the Strait of Gibraltar, continue westward along the continental slope of Spain and Portugal, and approach buoyancy at about 1000 m near 8°W (Zenk, 1975; Ambar and Howe, 1979; Baringer and Price, 1997). The product water, MOW, turns northward at Cape Sao Vicente, the southwestern corner of the Iberian Peninsula and reaches as far north as 50°N (Iorga and Lozier, 1999). Large density difference between the Mediterran a water and the Atlantic water on the east and west sides of the Strait of Gibra. far 1 takes MOW cascade down several hundred meters in the Gulf of Cádiz and cour the rocky seafloor as a contour current (Kenyon and Belderson, 1973), thus energing large-scale contourite drifts along the Iberian margin (Faugères et al. 1923; Hernández-Molina et al., 2003, 2006; Llave et al., 2006), and contributing to the deposition of Moroccan contourite systems (Lebreiro et al., 2018). As MOV/ moves forward and mixes with NACW, it experiences a dramatic dec. ase in velocity from approximately 3m/s at the Strait of Gibraltar (Ambar and Howe, 1979), to ~0.8-1m/s at Cape Sao Vicente (Cherubin et al., 2000), and to 0.12m/s off the Portuguese margin (Zenk and Armi, 1990). This mixing process makes the MOW salinity (~36.5 psu) much lower and its oxygenation (~190 µmol/kg) slightly higher than its source waters (Fig. 1b; Caralp, 1988; Ambar et al., 2002).

## 3. Materials and methods

#### 3.1 Sediments

IODP Site U1391 (37°21.532' N, 9°24.656' W; water depth 1085 m; Fig. 1a) was drilled off the western Iberian margin, within a large plastered drift on the middle slope terrace of the contourite depositional system (CDS) (Hernándz-Molina et al., 2003), and it is the most distal site drilled during IODP Expedition 339 under the influence of northward MOW (Expedition 339 Scientist, 2012). The research was conducted on Core A 13H-5 to Core B 13H-4 from Site U1391 with a composite succession between 124 and 128.3 mcd (maters of composite depth). The studied interval is dominated by calcareous ..... with minor calcareous sandy mud and calcareous silty mud (Expedition 339 Scientists, 2012). Samples for foraminiferal stable isotope analyses were t.k in at 4 cm interval throughout the 430 cm-long section providing an average resolution of ~600 years. For benthic foraminiferal faunal analyses, the top 5.2 cm was sampled at 4 cm spacing and the rest of the section at intervals of ~8 cn. with an average resolution of ~1300 years. About 30 grams of dried sediments were soaked in water for at least 2 days and then washed over a 63 µm mesh-size screen. The residue was dried and sieved over a 125 µm mesh-size screen.

The number of lithic fragments was determined in the >300  $\mu$ m size fraction. It was normalized by the respective sample's dry weight and expressed as "#/g". The lithic fragments coarser than 250  $\mu$ m are considered ice-rafted debris (IRD) (Voelker

et al., 2006).

#### 3.2 Stable isotopes and stratigraphy

Stable oxygen and carbon isotopes were measured on 6-8 tests of planktonic foraminifera Globigerina bulloides picked from the 250 to 300 µm size fraction and 2-4 tests of Cibicidoides pachyderma or Cibicidoides wuellerstorfi and Uvigerina peregrina parva picked from the >250 µm size fraction reaminiferal tests were poked with a needle and ultrasonically rinsed in few drops of absolute alcohol in order to remove impurities. Measurements were performed using a Finnigan MAT 253 mass spectrometer at Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, with a long-term precision  $^{1}$ , then  $\pm 0.08\%$  for  $\delta^{18}$ O and  $\pm 0.04\%$  for  $\delta^{13}$ C. All isotope data were calibrated to the Vienna PeeDee Belemnite (VPDB) standard. The age model of b: studied section was established based on the correlation of G. bulloide  $\delta^{\circ}$  curve of Site U1391 with planktonic foraminifera Globorotalia inflata  $\delta^{1b}$  Curve of core MD01-2446 (Voelker et al., 2010), using the software package A. alySeries of Paillard et al. (1996). G. inflata and G. bulloides have a similar dwelling depth (Hemleben et al., 1989), so their stable isotope records are comparable. In our previous studies (Guo et al., 2020, 2021), planktonic  $\delta^{18}$ O curve of Site U1385 was used as a tuning target, but in this study we switched the tuning target to core MD01-2446 because core MD01-2446 had a higher-resolution planktonic  $\delta^{18}$ O record during MIS 12 relative to Site U1385, which allowed the establishment of a high-resolution stratigraphic framework.

#### 3.3 Benthic foraminiferal analyses

Benthic foraminifera were picked and counted from the >125  $\mu$ m size fraction (Schönfeld et al., 2012). The sample was split using a microsplitter to obtain a subsample that contains at least 300 specimens when it was enough, or all benthic foraminifers were picked out. All benthic foraminifera were identified to the species level referring to the taxonomic works of Jones (1994), M.iker and Schmiedl (2012) and Holbourn et al. (2013).

Q-mode cluster analysis and non-metrical nultuumensional scaling (nMDS; Euclidean distance measure) analysis were performed on the benthic foraminiferal percentage data to group samples based on their similarities in faunal composition. Cluster analysis was conducted using TLIA software (Version 1.17.16, Grimm, 1987), and nMDS analysis and similarity percentage (SIMPER) analysis were performed using PAST software (Version 3.0; Hammer et al., 2001). SIMPER analysis (Euclidean distance measure: all samples pooled) aimed to determine the taxa which were primarily reponsible for differences in sample groups revealed by cluster analysis and nMLs analysis. Factor analysis was performed on the benthic foraminiferal percentage data to extract the possible environmental factors that controlled the foraminiferal distribution. Prior to analyses, the number of species recognized at Site U1391 were reduced to a practical size with a minimum loss of ecological significance. Genera with a high number of species and low relative abundance of each species were counted together. For example, Textularia, Quinqueloculina, Elphidium, Fursenkoina, Cibicides and Cibicidoides were counted

at generic level. Considering the results of the analyses may be strongly biased by those rare species included (Lutze and Coulbourn, 1984), only those species/taxa whose relative abundance exceeded 3% in at least 2 samples were taken into consideration. This dataset included 60 samples and 26 taxa which accounted for 76.9-99.2% (88.4% on average) of the original data.

The accumulation rates of benthic foraminiferal tests reliably indicate the organic matter flux to the sea floor which determines botton water trophic levels (Rodríguez-Tovar et al., 2015), and they was calculated according to the empirical formula proposed by Herguera and Berger (1991):

## $BFAR = N \times 5F \times DBD$

where BFAR is the benthic foramin<sup>;</sup>.er, l accumulation rate  $(n \text{ cm}^{-2} \text{ kyr}^{-1})$ ; N is the number of benthic foraminifera per gram  $(n \text{ g}^{-1})$ ; SR is the linear sedimentation rate (cm kyr<sup>-1</sup>); and DBD is the dry bulk density of sediment (g cm<sup>-3</sup>; Expedition 339 Scientists, 2013).

# 4. Results

#### 4.1 Age model and sedimentation rates

Comparison of planktonic and benthic  $\delta^{18}$ O records between Site U1391 (Fig. 2a, Guo et al., 2017 and this study) and Core MD01-2446 (Fig. 2b; Voelker et al., 2010) suggests that the studied section spans the time interval from 490.8 to 424.0 ka (Fig. 3). This interval includes the later part of MIS 13a, the glacial MIS 12 and Termination V (TV). The transition of MIS 12/11 was placed at 124.01 mcd based on

the already published age model from Guo et al. (2017, 2020), and the transition of MIS 13/12 was placed near 126.86 mcd because the planktonic  $\delta^{18}$ O value at this depth is comparable to the value at the transition of MIS 12/11 and is lower than the values between them. MIS 13a is identified by low planktonic and benthic  $\delta^{18}$ O values (Fig. 3a, 3b). The glacial MIS 12 is characterized by high  $\delta^{18}$ O values (Fig. 3a, 3b), and it can be further divided into three substages according to the significant fluctuations in the planktonic  $\delta^{18}$ O record. MIS 12a ar 12c are characterized by higher  $\delta^{18}$ O values and are separated by MIS 1. b which is distinguished by comparatively lower  $\delta^{18}$ O values (Fig. 3a). The sta lial-interstadial variation is less significant in the benthic  $\delta^{18}$ O record (Fi , 3b). TV is recognized by a Younger Dryas-like event, which shows a slig' there are in the decreasing trend of planktonic  $\delta^{18}$ O during the transition from MIS 12 to MIS 11 (Fig. 3a). The interval of TV determined at Site U1391 coincid's with the IRD peak at Core MD01-2446 (Fig. 3e; Voelker et al., 2010), on some degree reflecting a robust chronology. Table 1 contains the tie points used to consults the Site U1391 age model.

The sedimentation rates of the studied interval vary between 1.6 and 57.2 cm/kyr, and high sedimentation rates mainly occur within MIS 13a (Fig. 3g). The sedimentation rates during MIS 12 are generally low, 5.0 cm/kyr on average (Fig. 3g), approximating the estimation from Guo et al. (2017, 2020). The mass accumulation rates (MARs) have a similar variation trend to the sedimentation rates with the maximum value within MIS 13a (Fig. 3h).

### 4.2 Benthic foraminiferal records

#### 4.2.1 General characteristics of benthic foraminiferal fauna

A total of 186 benthic foraminiferal species have been identified in this study. Among the total 60 samples, only 5 samples from the top of the section contain less than 300 specimens. The absolute abundance of benthic foraminifera (number of specimens per 50g) varies greatly from 179 to 85179 and the number of species per sample varies between 23 and 69 with the average of 47.

The hyaline forms are the predominant contructures and account for 74.4-99.5% (93.7% on average) of the benthic foramirin ral fauna, mainly including *Bulimina mexicana*, *Bulimina aculeata*, *Uvigen a peregrina parva*, *Melonis barleeanum*, *Cassidulina neoteretis*, *Nonione<sup>11</sup>a turgida*, *Cibicidoides* spp., *Brizalina* sp. and *Bulimina exilis* (>2%, in decreasing order of relative average abundance). The porcelaneous forms (milic<sup>11</sup>ids) account for 0.2-25.6% (4.7% on average) of the benthic foraminiferal formation and mainly consist of *Quinqueloculina agglutinans* and *Sigmoilopsis schlume argeri*. The relative abundance of the agglutinated forms ranges between 0 and 5.0% with an average value of only 1.6%. The agglutinated forms are dominated by *Textularia* sp.

#### 4.2.2 Temporal variations of major benthic foraminifera species/taxa

*B. mexicana* is predominant species of genus *Bulimina* and also the most abundant species of the benthic foraminiferal fauna, accounting for on average 24.9%

of the population at Site U1391. It keeps a high relative abundance during MIS 12c and 12b with the maximum value of 94.5% and the mean value of 52.5% (Fig. 4). Its dominance is replaced by *B. aculeata* during MIS 12a. Although the relative abundance of *B. mexicana* significantly decreases during this time interval, it is still abundant relative to other species and ranks only second to *B. aculeata* with an average relative abundance of 20% (Fig. 4). During the early part of TV, *B. aculeata* shows a slight increase in abundance and reaches the maximum abundance of 42.6% at 426.3 ka (Fig. 4). *B. exilis* occurs in large numbes ard accounts for on average 15.2% of the benthic foraminiferal population (Fig. 4). On the contrary, the abundance of *B. mexicana* drops to a low level (Fig. 4). *D ring* the late part of TV *B. exilis* nearly disappears after a short-lived bloom, and *B. aculeata* displays a dramatic decrease in abundance, and the abundance of ? *mexicana* is still in a low level comparable to that during MIS 13a (Fig. 4).

*U. peregrina parva* and *M. barleeanum* have a similar trend of abundance variation which shows predominance during MIS 13a, a remarkable decrease during the glacial MIS 12 and sporadic occurrence during TV (Fig. 4). Their abundance maxima are 48.1% and 27.0%, respectively, and they account for a substantial proportion of the benthic foraminiferal population during MIS 13a. *C. neoteretis* mainly occurs during the glacial MIS 12 and its relative abundance ranges between 1.6% and 20.8% with an average of 9.5% much higher compared to MIS 13a and TV (Fig. 4). *N. turgida* appears at the end of MIS 12a, and rapidly dominates the population during the late TV (Fig. 4). The *Cibicidoides* species mainly distribute

during MIS 13a and the glacial MIS 12, and the average abundance of the former time interval (6.4%) is more than twice as higher as that of the latter time interval (2.8%) (Fig. 4). *Brizalina* sp. shows a high relative abundance at the beginning of TV (Fig. 4). *Q. agglutinans* is the dominant species of genus *Quinqueloculina* and mainly occurs during the late TV with the maximum abundance of 24.4% (Fig. 4).

#### 4.3 Multivariate statistics

#### 4.3.1 Q-mode cluster analysis

The result of cluster analysis reveals five  $\sum oups$  of samples based on their similarities in foraminiferal composition ( $\nabla_{12}$  4), and hence divides the studied interval into five sections, which coincides with the subdivision of planktonic foraminiferal oxygen isotope stratign phy. The nMDS analysis reveals the same result as the cluster analysis (Fig. 3). The detailed changes of benthic foraminiferal assemblages in the five groups are presented from bottom to top as follows.

Group 5 (128.3 1-12 5.86 mcd) corresponds to the late MIS 13a (490.8-480.6 ka). *U. peregrina parva* (24.4%) and *M. barleeanum* (20.0%) are dominant species, and *B. mexicana* (9.0%), *Cibicidoides* spp. (6.4%) and *Sphaeroidina bulloides* (4.5%) are important associated taxa.

Group 4 (126.86-125.19 mcd) can be divided into two parts which have a similar benthic foraminiferal faunal composition. Group 4a (126.86-126.03 mcd) corresponding to MIS 12c (480.6-459.0 ka), is characterized by *B. mexicana* (50.1%), *C. neoteretis* (8.1%), *M. barleeanum* (5.1%), *U. peregrina parva* (4.4%) and

*Cibicidoides* spp. (4.0%). Group 4b (126.03-125.19 mcd) corresponds to MIS 12b (459.0-440.1 ka) and is mainly composed of *B. mexicana* (56.6%), *C. neoteretis* (9.4%) and *M. barleeanum* (4.8%).

Group 3 (125.19-124.53 mcd) represents the history of MIS 12a (440.1-427.7 ka). *B. aculeata* (26.2%) and *B. mexicana* (20.0%) are major contributors of this group. Other important associated species are *C. neoteretis* (10.7%), *Trifarina carinata* (3.8%) and *Brizalina* sp. (3.4%).

Both Group 2 (124.53-124.17 mcd; 427.7-425.11 a) and Group 1 (124.17-124.01 mcd; 425.1-424.0 ka) belong to TV. Group 2 is characterized by *B. aculeata* (36.4%), *B. exilis* (15.2%), *N. turgida* (11.7%), *Brizal nc* sp. (6.4%) and *U. proboscidea* (6.3%). Group 1 is dominated by *N. turgida* (14.1%), *Quinqueloculina* spp. (13.5%), *Pullenia quinqueloba* (10.2%) with *B. n. exicana* (5.9%), *Chilostomella oolina* (5.5%), *B. aculeata* (4.0%), Brizalina alata (3.5%) and *Fursenkoina* spp. (3.3%) as important accessary taxa.

SIMPER analycies supports that the grouping is largely determined by *B*. *mexicana*, *B. aculeate*, *U. peregrina parva*, *M. barleeanum* and *N. turgida* which are responsible for 88.5% of the difference between groups (Table 2).

#### 4.3.2 Factor analysis

Four benthic foraminiferal assemblages are recognized based on Q-mode factor analysis which has extracted four factors that together account for 93.1% of total faunal variance (Table 3). They are *B. mexicana* assemblage, *U. peregrina parva- M.* 

barleeanum assemblage, *B. aculeata* assemblage and *N. turgida* assemblage. *B. mexicana* assemblage is represented by *B. mexicana* which has a distinct positive score of Factor 1. *C. neoteretis* is the associated species of this assemblage. *B. mexicana* assemblage shows significant occurrence during MIS 12c-b and low occurrence during the rest of the time interval especially MIS 13a and TV (Fig. 6a). *U. peregrina parva* and *M. barleeanum* are the major species of *U. peregrina parva- M. barleeanum* assemblage and have high positive scores of Tector 2. This assemblage mainly occurs during MIS 13a (Fig. 6b). *B. aculeata* assemblage is dominated by *B. aculeata* which has a high positive score of Fector 3 with *B. exilis, C. neoteretis, Brizalina* sp., *U. proboscidea* as associated species. It is particularly abundant during MIS 12a and the early TV (440.1-425.1 a) (Fig. 6c). Major constituents in *N. turgida* assemblage have distinct negative scores of Factor 4, including *N. turgida, Quinqueloculina* spp. and *P. aui ncueloba*. This assemblage dominates the benthic foraminiferal population du.ing the late TV (425.1-424.0 ka) (Fig. 6d).

# 4.4 Benthic $\delta^{13}$ C record

The stable carbon isotope compositions of *Cibicidoides* spp. vary between 0.756‰ and 1.557‰. The benthic  $\delta^{13}$ C values are high from the late MIS 13a to MIS 12b and a prominent decrease is noticed during MIS 12a (Fig. 6e). No benthic  $\delta^{13}$ C data is presented during the time interval of 430.4-427.4 ka due to a lack of enough tests of *Cibicidoides* spp. for stable isotope measurements.

#### 4.5 Benthic foraminiferal accumulation rates (BFAR)

BFAR varies greatly between 39 and 14109 individuals/cm<sup>2</sup>kyr with the highest value during MIS 13a and the lowest value during MIS 12c (Fig. 6f). The fluctuations in the BFAR values display two obvious spikes, 14109 within MIS 13a and 8405 within MIS 12a. MIS 13a and MIS 12a are characterized by remarkably high BFAR values, which vary between 264 and 14109 with an average value of 1900 during MIS 13a and range from 609 to 8405 with an average value of 27<sup>1</sup>5 during MIS 12a. MIS 12c and MIS 12b are featured by low BFAR values, fluctuating between 39 and 4434 with 802 on average. The early period of TV can 'e divided into two time intervals based on the variations in BFAR values. 1: • .ime interval of 427.7-425.1 ka with higher BFAR is distinguished from the 'ime interval of 425.1-424.0 ka.

# 5. Discussion

Benthic foraminifer.<sup>1</sup> I una convey important information of environmental changes and have b en videly used for paleoceanographic reconstructions, but the prerequisite is the the fauna are autochthonous and not influenced by post-depositional downslope transport of fossil shells from shallower depths. As suggested by Hall and McCave (2000), the glacial section of cores drilled off the Iberian margin may receive downslope supply. Abundant shallow-water dwellers such as *Elphidium* spp., *Ammonia* spp., *Cibicides lobatulus* and *Cibicides refulgens* were observed in upper Miocene sediments from IODP Site U1387 recovered off the southwestern Iberian margin, which documented post-depositional transport processes

(García-Gallardo et al., 2017). Although the allochthonous assemblage was also found at Site U1391, its relative abundance accounted at most for 5.8% of the benthic foraminiferal population much lower than ~60% at Site U1387 (Fig. 6g), suggesting that benthic foraminifera at the studied site can reliably record the paleoceanographic changes off the western Iberian margin during the late MIS 13 and MIS 12.

Dissolved oxygen, food supply and substrate have been considered as the most important environmental parameters that control the in-equiment distribution of deep-sea benthic foraminifera (Mackensen et al., 1985 · Jo issen et al., 1995; Jorissen, 1999; Van der Zwaan et al., 1999; de Rijk et al., 2000; Geslin et al., 2004). These parameters are often interconnected and one of them plays a dominant role only when its value approaches or exceeds the to eral ce limit for a certain species (Murray, 2006). N. turgida and B. aculeata are often associated with fine-grained, organic-rich sediments (Mackensen et al., 1985, 1990; Alvisi et al., 2013) but adapt to different dissolved oxygen levels (C. potondi et al., 2015). The two species frequently occur at Site U1391 during different time intervals (Fig. 4), suggesting that nutrients and dissolved oxygen rate or than substrates are the leading factors that affect the benthic foraminiferl distribution at Site U1391. Eutrophic and dissolved oxygen levels are also important parameters to differentiate water masses (Schnitker, 1980; Boyle and Keigwin, 1987; Oppo and Lehman, 1993; Rodríguez-Tovar et al., 2015). Therefore, changes in benthic foraminiferal faunal composition at Site U1391 may indicate a bottom water hydrological evolution off the Portuguese margin and further reflect the Northeastern Atlantic intermediate water circulation pattern.

Multivariate statistical analyses reveal five distinct faunal turnovers at Site U1391 from the late MIS 13 to TV, which divide this time series into five intervals and the studied section into five groups. Sediment samples of Group 5 and Group 4 are clearly differentiated from those of Group 3-1 by their similarities in foraminiferal composition, as evidenced by the cluster analysis (Fig. 4). In the following, we discuss the detailed paleoceanographic environmental changes of the five time intervals separately, from foraminiferal ecological arai stuble carbon isotopic perspectives, combined with variations in BFAR and the seliment colour.

5.1 Bottom water hydrological conditions off the Portuguese margin during the late MIS 13 (490.8-480.6 k.)

The late MIS 13 is characterized by U. peregrina parva– M. baleeaunum assemblage (Fig. 6b). The important associated taxa include Cibicidoides spp. which mainly consists of C. pactaderma and C. pseudoungeriana. As a subspecies of U. peregrina (Schönfeld, 2006), except that the living specimens of U. peregrina parva often have a shallover water depth distribution than U. peregrina (Schönfeld and Altenbach, 2005), U. peregrina parva has a similar ecological preference to U. peregrina which thrives in areas that receive a strong input of organic matter (Altenbach et al., 1999; Gooday, 2003). M. baleeaunum is abundant in moderately organic matter rich sediments (Jorissen, 1987). C. pachyderma adapts to oligotrophic to mesotrophic environments with high oxygen levels in the western Mediterranean Sea (Schmiedl et al., 2000, 2003), and is found common at intermediate organic

matter flux conditions in the Atlantic Ocean (Altenbach et al., 1999; Gooday, 2003). In the benthic foraminiferal population of the late MIS 13a, *U. peregrina parva* and *M. baleeaunum* at least double the associated taxa in the relative abundance. *U. peregrina parva*–*M. baleeaunum* assemblage indicates mesotrophic to slightly eutrophic seafloor conditions during the late MIS 13a. It is supported by high BFAR values and the presence of dark-colour sediments which are closely associated with the delivery of high organic matter to the sea floor (Fig. 6f, 6h). High is pulsic  $\delta^{13}$ C indicates oxic bottom water environment (Fig. 6e), in accordance with the previous investigation on adaptability of *U. peregrina* species to oxygen which found living specimens at the western Iberian margin with high oxygen levels of 4.1-5.3 ml/l (Schönfeld, 2001).

*U. peregrina parva* frequently c.cu red in cores off southern Portugal since the last Glacial with distinct abundance maxima of 40% under active mid-depth circulation and decreased relative double double under sluggish mid-depth circulation (Zahn et al., 1997; Schönfeld and Altenbach, 2005). Distinct abundance maxima of *U. peregrina parva* off disconserial margin are probably attributed to strong lateral advection of the MOV current that raises the food supply to levels comparable to those under the northwest African upwelling zone (Schönfeld and Altenbach, 2005). *U. peregrina parva* accounts for a proportion of high up to 48.1% with an average of 24.4% at Site U1391 during the late MIS 13a (Fig. 4), which may be related to the strong influence of the MOW current. It agrees well with the study of Caralp (1988) that found abundant *Uvigerina, M. baleeaunum* and *C. pseudoungeriana* at intermediate sites off the Iberian margin are often linked to strong MOW current. In

addition, high benthic  $\delta^{13}$ C values and frequent occurrences of *Planulina ariminensis* which indicates intensified MOW (Fig. 6e, 6i; Caralp, 1988; Schönfeld, 1997; Baas et al., 1998; Rogerson et al., 2011; Guo et al., 2017; García-Gallardo et al., 2017), also suggests that the North Atlantic intermediate water was filled by MOW during the late MIS 13a.

Low relative abundance of *P. ariminensis* at ~488 ka within MIS 13a coincides with the minima of precession and Ti/Al ratio at ODP Size 267/968 (Konijnendijk et al., 2014; Fig. 6i, 6j, 6k), reflecting the impact of the resh vater budget of the eastern Mediterranean Sea on the MOW strength (Bahr  $\epsilon$  t al. 2015). No sapropel layers were deposited in the eastern Mediterranean Sea  $\mu \mu$  ing this time interval, which implies a continuous formation of Mediterrane $\epsilon \mu \mu$  sep vaters feeding the MOW current.

5.2 Paleohydrological evolution and possible changes in intermediate water circulation of the Northeastern Atlantic during MIS 12

## 5.2.1 MIS 12c and 12i (480.6-440.1 ka)

Compared with the late MIS 13a, no distinct changes in benthic  $\delta^{13}$ C were observed during MIS 12c-b (Fig. 6e). Both time intervals show high  $\delta^{13}$ C values that indicate a high oxic and well-ventilated environment, which possibly explains why Group 5 and Group 4 fall into the same cluster. However, a major shift in the benthic foraminiferal composition from *U. peregrina parva – M. barleeanum assemblage* to *B. mexicana* assemblage was found (Fig. 4; Fig. 6a, 6b), accompanied by the presence of lighter-colour sediments and a remarkable decrease in BFAR (Fig. 6f, 6h). *B.* 

mexicana commonly occurs at mesotrophic sites under the influence of NADW along the Iberian margin (Phipps et al., 2002; Schönfeld, 2002), and it is one of the most important constituents of the benthic foraminiferal assemblage at IODP Site U1385 during MIS 1 and MIS 5e when organic matter flux reduced and a better ventilated bottom water environment bathed by NADW prevailed (Grunert et al., 2015). We infer that the Northeastern Atlantic intermediate water was mostly filled by a NADW-like water mass, the nutrient-depleted and high  $\hat{c}^{13}$ C GNAIW during MIS 12c-b. This deduction is supported by the frequent occurrence of C. neoteretis (Fig. 4). Today, C. neoteretis is restricted to polar and co.d boreal regions of the North Atlantic > 46°N and mainly inhabits in  $\sqrt{a} e^{r}$  depth between 1000 and 1500 m (Mackensen et al., 1985, 1990; Seide .iki untz, 1995; Husum et al., 2015) with bottom water temperature of about -1 °C and salinities of about 34.9‰ (Mackensen et al., 1985). GNAIW which formed not b of the polar front in the Northeastern Atlantic and occupied the water depth ranging from 1000 to 2600 m during the last glacial (Duplessy et al., 198°, *Oppo and Lehman, 1993*), is a very cold (~-1 °C) water mass (Adkins et al., 2002; Thiagarajan et al., 2014) hospitable for C. neoteretis. Sporadic occurrence of *P. ariminensis* revealed that the main MOW current of this time interval settled much deeper in the water column than today (Fig. 6f; Schönfeld and Zahn, 2000; Rogerson et al., 2005), probably caused by a low North Atlantic vertical density gradient associated with cold periods (Rogerson et al., 2012), so it was not recorded at the studied site. The present-day MOW carries more suspended particulate matter and is comparatively oxygen-depleted than NADW (Freitas and Abrantes, 2002), which

on some degree illustrates that the hydrological variability revealed by the faunal turnover are linked to reorganization of the Northeastern Atlantic intermediate water circulation.

#### 5.2.2 MIS 12a (440.1-427.7 ka)

The benthic foraminiferal population is dominated by *B. aculeata* and *B.* mexicana with C. neoteretis as the important associated space-during MIS 12a (Fig. 4). In the eastern South Atlantic and the eastern W dde'l Sea, B. aculeata is very abundant in areas of high primary productivity and considered as a representative species of "northern high-productivity faun?" 'recause it lies south of the Polar Front and north of the average winter ice lir.m in Upper Circumpolar Deep Water (UCDW) (Mackensen et al., 1990, 1993; Murray, 2006). At the western Iberian margin, the frequent occurrence of *B. aculeut i* ndicates increased organic matter flux to the sea floor (Grunert et al., 2015). Conversely, B. mexicana prefer less eutrophic and well-oxygenated bottom where environments (Grunert et al., 2015). The dominance of B. mexicana in the bunchic foraminiferal population at Site U1391 during MIS 12c-b was replaced by B. aculeata during MIS 12a (Fig.4; Fig. 6a, 6c), indicating an increase in organic matter flux to the sea floor and a decrease in dissolved oxygen concentration. It agrees well with the records of BFAR and the benthic  $\delta^{13}$ C. The BFAR values were much higher and the benthic  $\delta^{13}$ C was obviously lower during MIS 12a than during MIS 12c-b (Fig. 6e, 6f).

Compared to MIS 12c-b, the occurrence of C. neoteretis remains frequent but B.

*mexicana* shows a dramatic decrease in relative abundance during MIS 12a (Fig. 4), suggesting that Site U1391 was still under the influence of GNAIW but its influence significantly waned. *B. aculeata* rapidly occurs in large numbers at Site U1391 during MIS 12a (Fig. 4), which may be linked to the increased influence of Southern-sourced waters (SSW). A decrease in the benthic  $\delta^{13}$ C supported the SSW influence on bottom water off the Portuguese margin (Fig. 6e).

#### 5.2.3 The early TV (427.7-425.1 ka)

The early part of TV is characterized by *B*, *acu<sup>1</sup>eata* assemblage which consists of *B. exilis*, *N. turgida*, *Brizalina* sp. and *U. proboscidea* as its associated species (Fig.6c; Table 2, Table 3). *B. exilis* is a und highly abundant in the upper part of the oxygen deficient zone of the southeastern Arabian Sea (Kaithwar et al., 2020), and prefers organic matter in an unallered form (Caralp, 1989). *N. turgida* is typical of environments where orgatic natter accumulates and periodical oxygen deficiency occurs (Van der Zwaen and Jorissen, 1991; Van der Zwaan et al., 1999). *Brizalina* sp. and *U. proboscidea* vas considered to be indicators of high productivity and low oxygen (Gupta and Srinivasan, 1992; Murgese and De Deckker, 2005). Mohan et al. (2011) proposed that the dominance of *U. proboscidea* in the Neogene of Blake Ridge, Northwestern Atlantic Ocean suggested an increased influence of SSW. Therefore, *B. aculeata* assemblage indicates a eutrophic and poorly-oxygenated bottom water environment off the western Iberian during the early TV.

The aforementioned species which prefer low-oxygen and eutrophic seafloor environments account for more than 76% of the benthic foraminiferal population during the early TV (Table 2). However, the relative abundance of *B. mexicana* and *C. neoteretis* indicative of less eutrophic and well-oxygenated bottom water conditions remarkably decrease from 61.5% during MIS 12c-b to 30.7% during MIS 12a and to 8.1% during the early TV (Table 2). The distinct faunal turnover suggests a stronger influence of SSW and a negligible influence of GNAIW. A prominent IRD peak was detected during the early TV (Fig. 3f), and severe str. tific ation of surface-subsurface waters caused by meltwater-induced salinity reduction may result in cessation of the GNAIW formation, thus leading to significar.ly decreased ventilation of the North Atlantic intermediate water (Venz et  $r_{in}$ , 995).

## 5.2.4 The late TV (425.1-42<sup>4</sup>.9 kc)

*N. turgida, Quinque ocuina* spp., *Pullenia quinqueloba* and *Chilostomella oolina* are the major constituents of *N. turgida* assemblage during the late TV (Fig. 6; Table 2, Table 3). *N. turgida* and *C. oolina* prefer deep-infaunal microhabitats (Corliss, 1985, 1991) and can tolerate oxygen-stressed environments caused by increasing organic matter load (Van der Zwaan and Jorissen, 1991; Mojtahid et al., 2009). *P. quinqueloba* commonly thrives below an oxygen threshold of ~50µmol/1 (Fontanier et al., 2008). Low oxygen concentration is responsible for low benthic foraminiferal faunal densities during the late TV and is the reason why major species in *B. aculeata* assemblage show a distinct decrease in relative abundance but *N*.

*turgida* does the opposite (Fig. 4). Like *N. turgida, B. exilis* is also an oxygen-tolerant species (Kaithwar et al., 2020). This species is found abundant during the early TV but nearly disappear during the late TV, which may be attributed to the forms of organic matter reaching the seafloor. *N. turgida* reacts quickly to the input of labile organic matter and reproduces (Diz et al., 2006), but *B. exilis* develops only when the organic matter unaltered (Caralp, 1989). Low BFAR values during this time interval did not reflect low organic matter flux to the seafloor here use the BFAR proxy is unreliable under the prevalence of severe dysoxia (den Du1; et al., 2000).

# 6. Conclusions

Intermediate water variability of the subtropical Northeastern Atlantic during the late MIS 13 and MIS 12 was reconstructed based on high-resolution foraminiferal stable isotopes and benthic form initiat faunal records of IODP Site U1391 drilled at 1085 water depth off the western Iberian margin. Distinct benthic foraminiferal turnovers and variation in the benthic stable carbon isotopes revealed high oxic and mesotrophic to slightly eutrophic bottom water environments during the late MIS 13, relatively mesotrophic and well-oxygenated seafloor conditions during MIS 12c-b, a prominent increase in organic matter supply and a slight decrease in dissolved oxygen concentration during TV. During the late MIS 13 and MIS 12c-b, organic matter supply was the dominant factor that controlled the benthic foraminiferal distribution. During MIS 12a and TV, dissolved oxygen concentration became the limiting factor along

with the increasing organic matter reaching the seafloor.

The bottom water hydrological evolution off the Portuguese margin from the late MIS 13 to the early period of TV was probably linked to variations in the Northeastern Atlantic intermediate water circulation. The intermediate-depth water was filled by MOW during the final stage of MIS 13 and mainly by GNAIW during MIS 12c-b. In addition to GNAIW, waters of southern origin accounted for a substantial proportion of the intermediate-depth water during MIS 12a. During TV, the intermediate water was almost filled by waters of southern origin.

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## **Data Availability**

The dataset related to this article includes stable oxygen and carbon isotopes of planktonic foraminifera *Globigerina bulloides* and benthic foraminifera *Cibicidoides* spp. and *Uvigerina peregrina parva*, benthic foraminiferal census data (> 125  $\mu$ m size fraction), factor loadings and the sediment redness a\*. This dataset can be found at https://data.mendeley.com/datasets/jkwg3hjz3k/2, an open-sourced online data

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#### **Captions of Figures and Tables**

**Fig. 1.** (a) Mediterranean Outflow Water (MOW) pathway (pink area; modified from Iorga and Lozier (1999) and Bower et al. (2002)) in the modern eastern North Atlantic Ocean with locations of IODP Site U1391 and Core MD01-2446. (b) Modern hydrography off the western Iberian margin with CTD dep<sup>-1</sup> profiles of temperature, salinity and dissolved oxygen concentration of Stain 2018<sup>7</sup> i<sup>-1</sup> Cruise 35LU19890509 (37° 17.862' N, 9° 39.492'W; blue solid circle in (a), Hydrographical data were from Global Ocean Data Analysis Project, Version 2. Sw = surface water; NACW = North Atlantic Central Water; MOW = Mediterranean Outflow Water; NADW = North Atlantic Deep Water. Figures were draged with ODV software (Schlitzer, 2018).

Fig. 2. Correlation of plankt nic and benthic foraminiferal  $\delta^{18}$ O between Site U1391 and Core MD01-2446 (Voetker et al., 2010). Red circles mark the tie points used to establish the age appart of Site U1391 according to Table 1.

**Fig. 3.** Age model and sedimentation rates of Site U1391 during 490-424 ka. *G. bulloides*  $\delta^{18}$ O record (a) and *U. peregrina parva*  $\delta^{18}$ O record (b) of Site U1391; *G. inflata*  $\delta^{18}$ O record (c), *Uvigerina* spp.  $\delta^{18}$ O record (d) and the number of lithic fragments >315 µm (e) of Core MD01-2446 (Voelker et al., 2010); the number of lithic fragments >300 µm (f), sedimentation rates (g) and mass accumulation rates

(MARs; h) at Site U1391. Substages (12a, 12b, 12c and 13a) are named according to Railsback et al. (2015).

**Fig. 4.** Variations in the relative abundances of major benthic foraminiferal species and five sample groups identified by the cluster analysis of major benthic foraminiferal percentage data at Site U1391. Group 5 corresponds to the late MIS 13a. Group 4 represents the history of MIS 12c and MIS 12b. Group 3 corresponds to MIS 12a. Group 2 and Group 1 occur within Termination V (ΓV). Substages are named according to Railsback et al. (2015).

Fig. 5. Non-metric multidimensiona' sculin<sub> $\mathcal{E}$ </sub> (nMDS) analysis (Euclidean distance; stress = 0.09) for the 26 highes, ranked benthic foraminiferal species/taxa at Site U1391. Sample groups are the sar with those identified in Fig. 5.

**Fig. 6.** Variations in the loadings of the first four factors extracted based on Q-mode factor analysis of ben hic foraminiferal percentage data (a: Factor 1 loading; b: Factor 2 loading; c: Factor 3 loading; d: Factor 4 loading), benthic  $\delta^{13}$ C (e), BFAR (f), the relative abundance of shallow-water foraminifera (g), the sediment rendess a\* (h; Expedition 339 Scientists, 2013), the relative abundance of *P. ariminensis* (i), Ti/Al ratios at ODP Site 967/968 drilled in the eastern Mediterranean Sea (Konijnendijk et al., 2014) (j), precession (Laskar et al., 2004) and *G. bulloides*  $\delta^{18}$ O at Site U1391. Positive Factor 1: *B. mexicana* assemblage; positive Factor 2: *U. peregrina parva* 

assemblage; positive Factor 3: *B. aculeata* assemblage; negative Factor 4: *N. turgida* assemblage. Substages are named according to Railsback et al. (2015).

**Plate I**. Scanning electron microscope pictures of major benthic foraminiferal species identified in this study. 1-2. *Bulimina mexicana* (Cushman); 3-4. *Bulimina aculeata* d'Orbigny; 5-6. *Uvigerina peregrina parva* Lutze; 7-8. *Melonis barleeanum* (Williamson); 9. *Bulimina exilis* Brady; 10-12. *Cassidulina. neoteretis* Seidenkrantz; 13-15. *Nonionella turgida* (Williamson); 16-17. *Puller ia q uinqueloba* (Reuss); 18-19. *Uvigerina proboscidea* Schwager; 20-21. *Quir neu culina agglutinans* d'Orbigny; 22-24. *Cibicidoides pseudoungerianus* (Cur nt in); 25-27. *Cibicidoides pachyderma* (Rzehak). Scale bar next to the number rypresents 100 μm.

**Table 1.** Tie points used to establish the chronology of Site U1391 based on the correlation of planktonic for miniferal  $\delta^{18}$ O between Site U1391 (Guo et al., 2017 and this study) and Core MIP(1-2446 (Voelker et al., 2010).

**Table 2.** Similarity percentage (SIMPER) analysis for the 26 highest ranked benthic foraminiferal species/taxa at Site U1391. Overall average dissimilarity: 2922. The average relative abundance of taxa that exceeds 5% in their respective group is shown in bold.

**Table 3.** Factor score of the first four factors for the 26 highest ranked benthic foraminiferal species/taxa along with faunal variance at Site U1391. Species/taxa with high positive/negative factor score (shown in bold) are important to the assemblage.



Fig. 1



Fig. 2



g. 3



Fig. 4









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| Site U1391 depth (mcd) | Age (ka) | Reference data   |
|------------------------|----------|--|
| 124.01                 | 424      | Guo et al. (2017, 2020)                                  |
| 124.93                 | 430.568  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.03                 | 434.829  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.11                 | 437.308  | MD01-2446 age fromVoelker et al. (2010); present study)  |
| 125.23                 | 441.533  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.27                 | 442.378  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.47                 | 445.758  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.55                 | 446.603  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.71                 | 452.940  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 125.95                 | 456.320  | MD01-2446 age fromVoelker et . (2010); present study     |
| 126.15                 | 463.043  | MD01-2446 age fromVoelker , a. (2010); present study     |
| 126.27                 | 470.327  | MD01-2446 age fromVoelker (* al., 2010); present study   |
| 126.62                 | 475.930  | MD01-2446 age fromVoe ker e al. (2010); present study    |
| 126.86                 | 480.602  | MD01-2446 age from velker et al. (2010); present study   |
| 126.90                 | 481.770  | MD01-2446 age from velker et al. (2010); present study   |
| 127.01                 | 483.405  | MD01-2446 age fro. العاد et al. (2010); present study    |
| 127.82                 | 489.946  | MD01-2446 age fromVoelker et al. (2010); present study   |
| 132.10                 | 497.421  | MD01-244( a', e 1 omVoelker et al. (2010); present study |

| Table | 1 |
|-------|---|
| Iuoio |   |

2.10 497.421 MD01-244C a<sup>2</sup>210

Table 2

| m                         | Average<br>dissimilarity | Contribution (%) | Cumulative<br>contribution<br>(%) | TV         |            | MIS<br>12a | MIS<br>12c-b | MIS<br>13a |
|---------------------------|--------------------------|------------------|-----------------------------------|------------|------------|------------|--------------|------------|
| Taxa                      |                          |                  |                                   | Group<br>1 | Group<br>2 | Group<br>3 | Group<br>4   | Group<br>5 |
| Bulimina                  | 1401.0                   | 47.9             | 47.9                              | 5 9        | 5.0        | 20.0       | 52 5         | 9.0        |
| mexicana                  | 1401.0                   | 47.9             | 77.9                              | 5.7        | 5.0        | 20.0       | 54.5         | 7.0        |
| Bulimina                  | 514.8                    | 17.6             | 65.6                              | 4.0        | 36.4       | 26.2       | 1.0          | 1.6        |
| aculeata                  | 01110                    | 1,10             | 0010                              |            | 0011       | 20.2       | 110          | 110        |
| Uvigerina                 | 309.2                    | 10.6             | 76.1                              | 0.0        | 0.6        | 3.9        | 3.8          | 24.4       |
| peregrina parva           | 007.2                    | 1010             | , 011                             | 0.0        |            | 017        | 210          |            |
| Melonis                   | 189.0                    | 6.5              | 82.6                              | 1.2        | 0.3        | 3.9        | 4.8          | 20.0       |
| barleeanum                | 10,10                    | 010              | 0210                              |            |            | 017        |              | 2010       |
| Nonionella                | 171.8                    | 5.9              | 88.5                              | 24.3       | 11.7       | 0.9        | 0.0          | 0.0        |
| turgida                   | 1,110                    | 017              | 0010                              |            | 1107       | 017        | 010          | 010        |
| Bulimina exilis           | 74.1                     | 2.5              | 91.0                              | ٦.3        | 15.2       | 0.4        | 0.0          | 0.1        |
| Cassidulina               | 55.4                     | 1.9              | 92.9                              | 3          | 3.1        | 10.7       | 9.0          | 1.8        |
| neoteretis                |                          |                  |                                   | 200        | 011        | 1007       | 2.0          | 110        |
| Quinqueloculina           | 50.6                     | 1.7              | 94.6                              | 13.5       | 0.5        | 1.1        | 0.7          | 0.8        |
| spp.                      | 2010                     |                  |                                   | 1010       | 0.0        |            | 017          | 010        |
| Cibicidoides spp.         | 25.2                     | 0.9              | 95.5                              | 0.8        | 0.2        | 2.0        | 3.1          | 6.4        |
| <i>Brizalina</i> sp.      | 22.6                     | 0.               | 96.3                              | 1.9        | 6.4        | 3.4        | 2.7          | 2.1        |
| Pullenia<br>quinqueloba   | 20.5                     | (1.7             | 97.0                              | 10.2       | 1.4        | 0.6        | 0.4          | 1.6        |
| Hyalinea balthica         | 17.9                     | 0.5              | 97.6                              | 0.0        | 0.0        | 0.4        | 2.5          | 2.7        |
| Uvigerina                 |                          |                  |                                   |            |            |            |              |            |
| proboscidea               | 14.3                     | 0.5              | 98.1                              | 1.0        | 6.3        | 0.5        | 0.0          | 0.1        |
| Sphaeroidina<br>bulloides | 11.6                     | 0.4              | 98.5                              | 0.0        | 0.1        | 0.6        | 0.8          | 4.5        |
| Chilostomella             |                          |                  |                                   |            |            |            |              |            |
| oolina                    | 9./                      | 0.3              | 98.8                              | 5.5        | 1.4        | 0.0        | 0.0          | 0.0        |
| Trifarina carinata        | 7.0                      | 0.2              | 99.1                              | 1.6        | 0.9        | 3.8        | 1.0          | 0.9        |
| Brizalina                 |                          |                  |                                   |            |            |            |              |            |
| earlandi                  | 4.8                      | 0.2              | 99.2                              | 0.2        | 0.1        | 0.2        | 2.0          | 0.0        |
| Fursenkoina spp.          | 4.6                      | 0.2              | 99.4                              | 3.3        | 1.0        | 0.5        | 0.1          | 0.1        |
| Cibicides spp.            | 3.4                      | 0.1              | 99.5                              | 2.9        | 0.9        | 2.2        | 0.7          | 0.9        |
| Sigmoilopsis              |                          |                  |                                   |            | . ·        |            |              |            |
| schlumbergeri             | 3.0                      | 0.1              | 99.6                              | 0.0        | 0.4        | 2.2        | 2.0          | 1.0        |
| Brizalina alata           | 2.6                      | 0.1              | 99.7                              | 3.5        | 0.1        | 0.0        | 0.4          | 0.1        |
| Textularia spp.           | 2.2                      | 0.1              | 99.8                              | 0.0        | 0.0        | 2.3        | 0.4          | 0.7        |
| Gyroidinoides             | • -                      | 0.1              | 0.5.5                             |            | 0.5        |            |              |            |
| orbicularis               | 2.2                      | 0.1              | 99.8                              | 1.0        | 0.8        | 1.7        | 1.8          | 1.8        |
| Globobulimina             | 1.8                      | 0.1              | 99.9                              | 0.0        | 0.5        | 0.3        | 0.6          | 1.8        |

| affinis            |     |     |       |     |     |     |     |     |
|--------------------|-----|-----|-------|-----|-----|-----|-----|-----|
| Pullenia bulloides | 1.5 | 0.1 | 100.0 | 0.0 | 0.0 | 0.6 | 0.5 | 1.2 |
| Elphidium spp.     | 1.3 | 0.0 | 100.0 | 1.7 | 0.5 | 0.6 | 0.3 | 0.0 |

| Таха                       | Factor 1 | Factor 2 | Factor 3 | Factor 4 |
|----------------------------|----------|----------|----------|----------|
| Brizalina alata            | 0.0174   | -0.0045  | -0.0555  | -0.5801  |
| Brizalina earlandi         | 0.2186   | -0.0386  | -0.0315  | -0.0238  |
| Brizalina sp.              | 0.1577   | 0.2493   | 0.7161   | -0.06 2  |
| Bulimina aculeata          | -0.3792  | -0.0552  | 4.7316   | 0 :211   |
| Bulimina exilis            | -0.2585  | -0.0870  | 1.2447   | ر 14. ט- |
| Bulimina mexicana          | 4.9400   | 0.0985   | 0.2807   | -0.3036  |
| Cassidulina neoteretis     | 0.9512   | 0.0847   | 0.82, 7  | ).1228   |
| Chilostomella oolina       | -0.0556  | -0.0074  | 0.6386   | -0.9161  |
| Cibicides spp.             | 0.0448   | 0.101    | .1713    | -0.4024  |
| Cibicidoides spp.          | 0.2736   | 0.9040   | J 9100   | -0.0590  |
| Elphidium spp.             | 0.0161   | -0.006.  | 0.0614   | -0.2589  |
| Fursenkoina spp.           | -0.0281  | - ).010  | 0.0922   | -0.5381  |
| Globobulimina affinis      | 0.0010   | 2.837    | 0.0287   | 0.0156   |
| Gyroidinoides orbicularis  | 0.14¢ó   | 9.2364   | 0.1116   | -0.0950  |
| Hyalinea balthica          | 0.1.799  | 0.4019   | -0.0608  | 0.0036   |
| Melonis barleeanum         | -0.736   | 3.1662   | 0.0119   | -0.1135  |
| Nonionella turgida         | -0. `517 | -0.1116  | 0.5296   | -4.0364  |
| Pullenia bulloides         | 0.0223   | 0.1905   | 0.0218   | 0.0269   |
| Pullenia quinqueloba 🛛 🥣   | -0.0936  | 0.2289   | -0.0407  | -1.7376  |
| Quinqueloculina spp.       | 0.0195   | 0.0616   | -0.1520  | -2.1367  |
| Sigmoilopsis schlumbergeri | 0.2218   | 0.1014   | 0.1364   | 0.1004   |
| Sphaeroidina bulloides     | -0.0585  | 0.7200   | -0.0087  | 0.0166   |
| <i>extularia</i> spp.      | 0.0504   | 0.1120   | 0.1582   | 0.1137   |
| Frifarina carinata         | 0.1147   | 0.1272   | 0.3024   | -0.1022  |
| Uvigerina peregrina parva  | -0.2425  | 3.7543   | 0.0125   | 0.1477   |
| Uvigerina proboscidea      | -0.1200  | -0.0345  | 0.5309   | -0.2283  |
| Faunal variance (%)        | 50.9     | 19.5     | 16.7     | 6.0      |

#### **Declaration of interests**

 $\boxtimes$  The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

# Highlights

- Intensified Mediterranean Outflow Water during the late MIS 13.
- Strong influence of Glacial North Atlantic Intermediate Water from MIS 12c to 12b.
- Increase influence of southern-sourced waters (SSW) during MIS 12a.
- The Northeastern Atlantic intermediate water filled mostly by SSW during TV.