PALAEO 3

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Benthic foraminifera-based reconstruction of the first Mediterranean-Atlantic exchange in the early Pliocene Gulf of Cadiz

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ABSTRACT

Upper Miocene to lower Pliocene sediment cores from Integrated Ocean Drilling Program (IODP) Hole U1387C (IODP Expedition 339) have been studied. The main goal of this study is to reconstruct initial Mediterranean-Atlantic water exchange after the opening of the Gibraltar Strait in the early Pliocene. Benthic foraminiferal assemblages are the focus of the palaeoceanographic analyses of this work. A distinct faunal turnover indicates a considerable change of the depositional environment at the Miocene/Pliocene boundary. Foraminiferal composition suggests high rates of organic carbon flux and poorly oxygenated sea-floor environment for the basal, late Messinian interval. In contrast, earliest Pliocene assemblages point to periodic advection of warm, better ventilated and likely Mediterranean-sourced waters to the studied site. Parallel periodic changes in *Siphonina tubulosa*, *Globocassidulina subglobosa*, and *Planulina ariminensis* and previously established sedimentological and geochemical records (Zr/Al, $\delta^{18}O$) suggest a rather sluggish Mediterranean Outflow between ~5.3 and 5.2 Ma. Benthic foraminifera, along with sedimentological and geochemical data thus provide the earliest indications of Mediterranean-Atlantic water exchange following the opening of the Gibraltar Strait. Sandy layers become frequent towards the top of the interval. These sediments are rich in shelf foraminifera, reflecting episodes of turbidite deposition possibly caused by tectonic adjustments related to the opening of the Gibraltar Strait. The allochthonous assemblages frequently contain *Cibicides lobatulus* and *C. refulgens*, species that have been considered indicators of Mediterranean Outflow Water (MOW) in previous studies. Our results warrant for caution when applying these species as MOW proxy in the fossil record if there is evidence for downslope transport.

1. Introduction

Marking the end of the Messinian Salinity Crisis (MSC), the opening of the Gibraltar Strait took place ~5.33 Ma ago, leading to the refilling of the Mediterranean basin, the re-establishment of Mediterranean/Atlantic exchange and the onset of outflow of Mediterranean Water into the Gulf of Cadiz (Duggen et al., 2003; Flecker et al., 2015; García-Castellanos et al., 2009; Hernández-Molina et al., 2014; Roveri et al., 2014). Mediterranean Outflow is a key component of a climatic system that links the North Atlantic, via moonsonal rainfall in North Africa and runoff, to the Mediterranean (Bahr et al., 2015; Marzocchi et al., 2015). A number of studies have attempted to reconstruct the history of

MOW and to evaluate the contribution of this warm and saline water mass to North Atlantic circulation in different climatic states since the late Pliocene (e.g., Bigg et al., 2003; Hernández-Molina et al., 2006, 2014, 2016; Iorga and Lozier, 1999; Kaboth et al., 2016; Khélifi et al., 2009, 2014; Ochoa and Bray, 1991; Rahmstorf, 1998; Rogerson et al., 2012; Schönfeld and Zahn, 2000). The study of early MOW composition is critical in order to constrain proposed models in the Mediterranean during the MSC (Caruso et al., 2015; Kuroda et al., 2016; Manzi et al., 2009; Roveri et al., 2014). In addition, early MOW could represent an extreme high density water mass in a more warm and humid climate, with possible implications for the global oceanography through the enhancement of the Atlantic Meridional Overturning Circulation (AMOC; Fauquette et al., 1999; Rogerson et al., 2010, 2012). However, initial stages of MOW remain poorly explored.

To address this question, the present study takes advantage of upper Miocene to lower Pliocene sediment cores that have been recovered at IODP Site U1387 in the northern Gulf of Cadiz during IODP Expedition 339 (Fig. 1; Hernández-Molina et al., 2013; Stow et al., 2013). Despite

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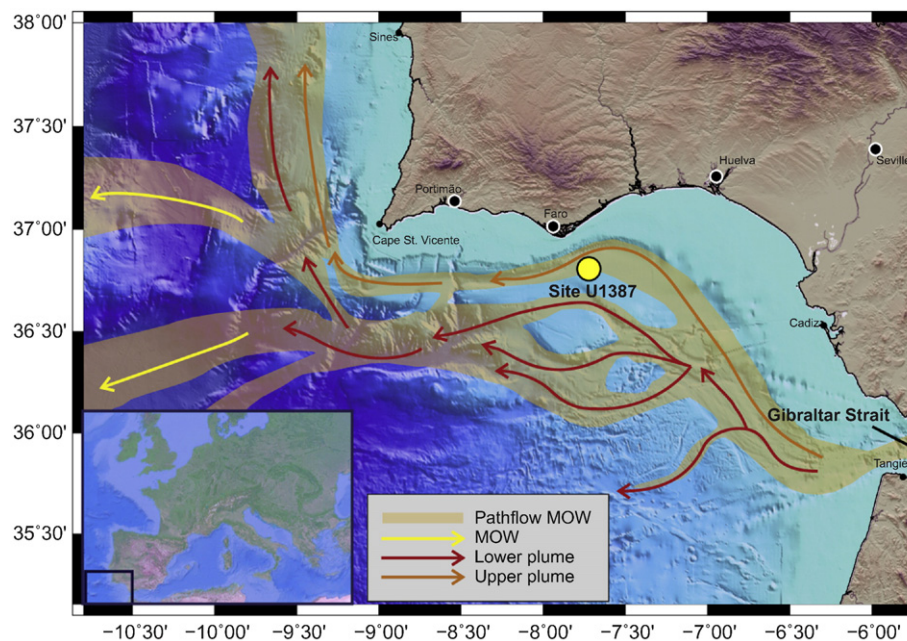
Fig. 1. Location of the IODP Site U1387 and present day pathway of the upper/lower plumes of the Mediterranean Outflow Water (MOW; based on Hernández-Molina et al., 2014).

the increasing number of Late Miocene records in the Gulf of Cadiz and Guadalquivir Basin regions (e.g., Pérez-Asensio et al., 2012a, 2013, 2014; Van den Berg et al., 2015) clear evidence of Mediterranean influence only appears to be recognized at IODP Site 1387 in Van der Schee et al. (2016) from a geochemical approach. The present study complements the latter study and aims to complete an assessment of palaeoceanographic changes at the site across the Miocene/Pliocene boundary (MPB) primarily based on benthic foraminifera. This method has been successfully applied previously to reconstruct Mediterranean circulation patterns and Mediterranean-Atlantic exchange since the Miocene (Kouwenhoven and Van der Zwaan, 2006; Schönfeld and Zahn, 2000; Seidenkrantz et al., 2000; Singh et al., 2015). Due to their high diversity, benthic foraminiferal species occupy a wide range of epi- and infaunal microhabitats and seafloor environments. The assemblage composition at a given site is mainly determined by oxygen concentration in the ambient bottom and pore waters, and the quantity and quality of food; other parameters such as water depth, temperature and salinity are generally considered of minor importance in the deep ocean (Jorissen et al., 1995, 2007; Murray, 2006). Strong bottom current regimes such as in the Gulf of Cadiz favor abundances of active suspension feeders (Rogerson et al., 2011; Schönfeld, 1997, 2002a). This group of foraminifera is called the "elevated epifauna" as its members occupy elevated substrates to feed directly from intensified bottom currents (Schönfeld, 1997, 2002a, 2002b). As percentages of elevated epifauna are thought to be strongly correlated with the intensity of MOW today, it has been suggested as an indicator of MOW in the past (Schönfeld, 2002a; Schönfeld and Zahn, 2000; Singh et al., 2015).

Obtained ecological parameters data inferred from microfossil assemblages have been compared with the proposed geochemical bottom current proxy Zr/Al ratio (Bahr et al., 2014) and stable isotopes used in Van der Schee et al. (2016) to identify bottom current activity and Mediterranean-sourced water. The multi-proxy record provides new and refined insights into initial Mediterranean-Atlantic exchange at the Miocene/Pliocene transition. Our findings further allow an assessment of benthic foraminifera as indicators of Mediterranean-sourced waters in the early Pliocene Gulf of Cadiz under palaeogeographic, palaeoceanographic and palaeoclimatic conditions significantly different to today.

2. Regional setting

The northern slope of the Gulf of Cadiz is today bathed by MOW. This water mass is composed of Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW) and shows an average temperature of 13 °C and salinity of 36.5‰ (Bryden et al., 1994; Hernández-Molina et al., 2006). After exiting the Gibraltar Strait, it follows the Iberian Margin as intermediate water mass first westward and then mostly northward, until it mixes with ambient North Atlantic Central Water (NACW) at Rockall Plateau (~58°N, 17°W). MOW thus injects heat and salt at intermediate water depths into the eastern North Atlantic and, in turn, is thought to enhance AMOC (Iorga and Lozier, 1999; Johnson et al., 2002). Once it enters the Gulf of Cadiz, MOW splits into two plumes due to Coriolis forcing and sea-floor topography: the upper plume (Mediterranean Upper Water) flowing between 400 and 600 m, and the lower plume (Mediterranean Lower Water) between 600 and 1200 m (Fig. 1; Price et al., 1993). A number of studies suggests that the strength of MOW in general as well as of the individual plumes vary in different climate states in the Pleistocene and Pliocene (e.g., Bahr et al., 2014; Hernández-Molina et al., 2014; Khélifi et al., 2014; Llave et al., 2006; Schönfeld and Zahn, 2000). However, little is known about its impact in the earliest Pliocene.

The strong and persistent bottom currents of MOW resulted in the deposition of thick contourite drift bodies which provide excellent sedimentary archives for palaeoceanographic studies (Bahr et al., 2014; Llave et al., 2006; Stow et al., 2013). The beginning of contourite drift deposition has been estimated to 4.5–4.2 Ma, providing the earliest record of MOW current so far (Hernández-Molina et al., 2014; Stow et al., 2013). Individual contourite beds have been identified at IODP Hole U1387C in sediments with an age between ~5.2 and 5.3 Ma, probably the result of weak Mediterranean current in the Gulf of Cadiz shortly after the opening of the Gibraltar Strait at ~5.33 Ma ago (Van der Schee et al., 2016). These upper Miocene to lower Pliocene sediments are the focus of the present study.

IODP Site U1387 is located on the Faro Drift (36°48.3210′N, 7°43.1321′W; 558.4 m water depth), and is bathed by Mediterranean Upper Water (Fig. 1; Stow et al., 2013). Today, bottom current speeds in the order of 20 cm/s prevail at the site (Nelson et al., 1999; Zenk, 1975). The main objective to drill IODP Site U1387 was the recovery of
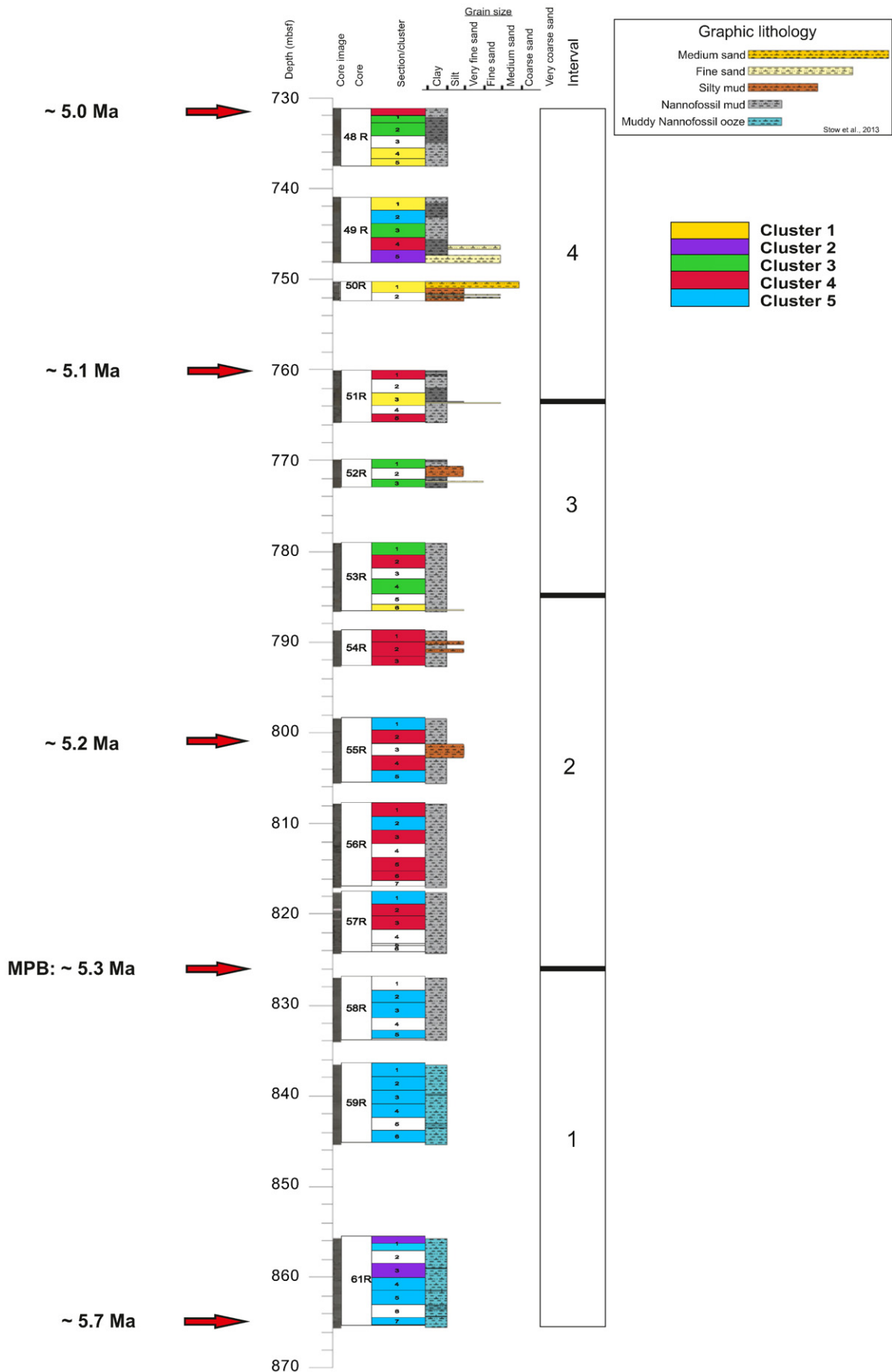
Fig. 2. Lithological logs from IODP Hole U1387C (Stow et al., 2013). Colored sections indicate the corresponding clusters in Fig. 3. Intervals in which the section has been subdivided are indicated. Age constraints are inferred from Van der Schee et al. (2016).

a complete upper Miocene to Holocene sedimentary sequence to reconstruct the onset of MOW activity after the opening of the Gibraltar Strait (Stow et al., 2013). Three holes were drilled at this site: Holes U1387A and U1387B to 352.4 and 338.3 m below sea floor (mbsf), respectively, extending to the Pleistocene; and Hole U1387C to 870 mbsf with its base in the upper Miocene. The preliminary shipboard stratigraphic framework assigned a late Miocene (<6.35 Ma) to earliest Pliocene age to the studied interval, and the MPB was tentatively placed at the top of the lithostratigraphic Unit IV at ~751 mbsf in Hole U1387C (Stow et al., 2013). Recently, the Miocene/Pliocene boundary was identified at ~826 mbsf in Hole U1387C based on a combination of seismic correlation, re-evaluated bio and magnetostratigraphic constraints and geochemical proxy records (Fig. 2; Hernández-Molina et al., 2016; Van der Schee et al., 2016). The revised age model constrains the base of the section to ~5.7–5.75 Ma and the top to ~5.0 Ma, and allows for a tentative correlation of the benthic δ¹⁸O record to North Atlantic reference sections (Van der Schee et al., 2016).

3. Material and methods

3.1. Sample material

This study focuses on cores 61R to 48R (870–731 mbsf) of Hole U1387C, representing the upper Miocene and lower Pliocene (Stow et al., 2013). The suffix 'R' after the core number denotes that these cores were taken with the rotary coring system of the drillship JOIDES Resolution (Stow et al., 2013). The hemipelagic sediments of the studied interval are composed of muddy nannofossil ooze in the lowermost part (cores 61R-59R), and predominantly nannofossil mud in cores 58R-48R (Fig. 2; Stow et al., 2013). Regular alternations of light and dark colored sediments occur in cores U1387C-61R to 58R, 52R-51R, and 49-48R (Van der Schee et al., 2016). Intercalated silty beds start to appear with core 55R and increase in number towards the top of the section (Fig. 2; Stow et al., 2013). Some beds of fine and medium sands, interpreted as turbidites, occur in the uppermost part of the studied interval, most prominently in cores 50R and 49R (Stow et al., 2013; Van der Schee et al., 2016). Individual contourite beds have been identified in cores 55R and 54R (Van der Schee et al., 2016).

Bulk sediment samples of approximately 25 cm³ were collected from cores 61R-48R of IODP Hole U1387C at the Bremen Core Repository for micropalaeontological, stable isotope and grain size analysis. They were freeze-dried overnight, weighed, disaggregated in tap water overnight, sieved through 63 and 150 μm sieves, dried, and weighed once more at the University of Salamanca. Herein, we present the micropalaeontological data. For isotopic and grain-size analyses see the companion paper by Van der Schee et al. (2016).

3.2. Micropalaeontological analyses

Foraminiferal analyses (size-fraction >150 μm) were conducted on 50 samples. A minimum of 300 specimens was picked from each sample (when such number was available in the sample; 6 out of 50 contained <300). Residues were split in equal halves in large samples to facilitate counting. The number of splits was carefully recorded, and the total number of foraminifera in each sample was calculated accordingly (Schönfeld, 2012; Appendix 1). Specimens of *Cibicidoides pachyderma*, *Cibicides lobatulus*, *C. refulgens*, *Planulina ariminensis*, *Uvigerina pigmea*, *Globobulimina* spp., *Ammonia* spp., *Asterigerinata* spp. and *Elphidium* spp. used for isotopic analyses before splitting were added to the total number (Appendix 1). All benthic foraminifera were identified to the lowest possible taxonomic level and counted. Due to drilling depth and frequent downslope transport in the upper part of the studied interval, preservation of the fossilized tests was sometimes poor, with many specimens showing signs of abrasion. This fact complicated species identification, particularly in the upper part of the studied interval, forcing us to group some taxa at the genus or even higher taxonomic level. A

stereomicroscope ZEISS STEREO Discovery V8 and a Zeiss Digital Scanning Electron Microscope (DSM 982 Gemini) at the Institute of Earth Sciences, University of Graz have been used for identification and documentation. For taxonomic references, see Appendix at the end of the paper.

Abundances of epifaunal and infaunal taxa have been contrasted in Fig. 5 to infer changes in export productivity/bottom water oxygenation throughout the studied interval (Jorissen et al., 2007). Only taxa with clear microhabitat preferences have been considered (Appendix 2).

3.3. Statistical analysis

Multivariate statistical analyses have been performed by using the PAST software package (version 3.0) to define foraminiferal assemblages and to evaluate palaeoenvironmental changes over time. The PAST software package has been chosen as it is specifically designed for palaeontological analysis. Q-mode cluster analysis (Unweighted Pair-group method with arithmetic mean (UPGMA) algorithm, Bray-curtis similarity index for abundance data) has been applied in order to group the samples according to their similarity in foraminiferal content (Fig. 3; Hammer et al., 2001). Forty-four species, occurring with abundances >5% in at least one sample and representing on average 77% of the total fauna, have been included in this analysis (Appendix 2). A cut-off level of 5% has been chosen to reduce noise by rare species and to reveal the dominant statistical patterns more clearly. Analyses at cut-off levels of 1% for the same data-set have shown that the number and composition of the clusters remain generally the same, but they are separated less clearly. Consequently, each cluster represents a group of samples with similar foraminiferal assemblages indicative of certain ecological conditions. A Similarity Percentage analysis (SIMPER, Bray-Curtis similarity index, all samples pooled, Table 1) has been performed on the same data-set to assess which taxa are responsible for the observed differences between the groups of samples (Clarke, 1993).

4. Results

A total of 32,375 foraminiferal shells (average: 647.5 shells/sample) from 132 taxa have been picked and identified from the sample material. Calculated total numbers of benthic foraminifera are presented in Appendix 1. Abundance patterns of the most common species (up to a contribution of 3% in each cluster by the SIMPER analysis; Table 1) are plotted in Fig. 4. Foraminiferal assemblages reveal several major faunal turnovers which are well expressed in the distribution of clusters (Figs. 2–4).

4.1. Multivariate statistics

Five groups of samples can be distinguished as a result of the Q-mode cluster analysis (correlation coefficient: 0.71) (Fig. 3). Each cluster represents groups of samples according to similarities in foraminiferal composition. SIMPER analysis on the foraminiferal dataset shows the principal foraminiferal species contributing to differences between clusters (Table 1). Only 10 taxa (*Uvigerina pigmea*, *Siphonina tubulosa*, *Globocassidulina subglobosa*, *Elphidium* spp., *Osangularia culter*, *Uvigerina auberiana*, *Bulimina mexicana*, *Cibicidoides bradyi*, *Uvigerina* cf. *pigmea*, *Cibicidoides* spp., *Sphaeroidina bulloides*) are responsible for ~51% of the differences between groups (Table 1). Major contributors to cluster 1 are *Elphidium* spp. (16.6%), *Cibicides lobatulus* (7.7%), *Asterigerinata* spp. (7.5%), *Cibicidoides* spp. (6.1%), *Ammonia* spp. (5.6%), *U. pigmea* (4.6%), *Cibicides* spp. (4.4%) and *Cibicides refulgens* (3.7%). Cluster 2 is dominated by *U. auberiana* (22.1%), *U. pigmea* (21.8%) and *B. mexicana* (13.2%) with minor contributions of *S. bulloides* (3.3%) and *Cibicidoides* spp. (3.1%). Cluster 3 is characterized by *U. pigmea* (15.5%), *O. culter* (12.0%), *Cibicidoides* spp. (5.7%), *Cibicidoides* cf. *mundulus* (4.6%) and *G. subglobosa* (4.0%). Cluster 4 is mainly composed of *S. tubulosa* (9.6%), *G. subglobosa* (8.0%), *U. pigmea* (6.5%), and lower contributions of
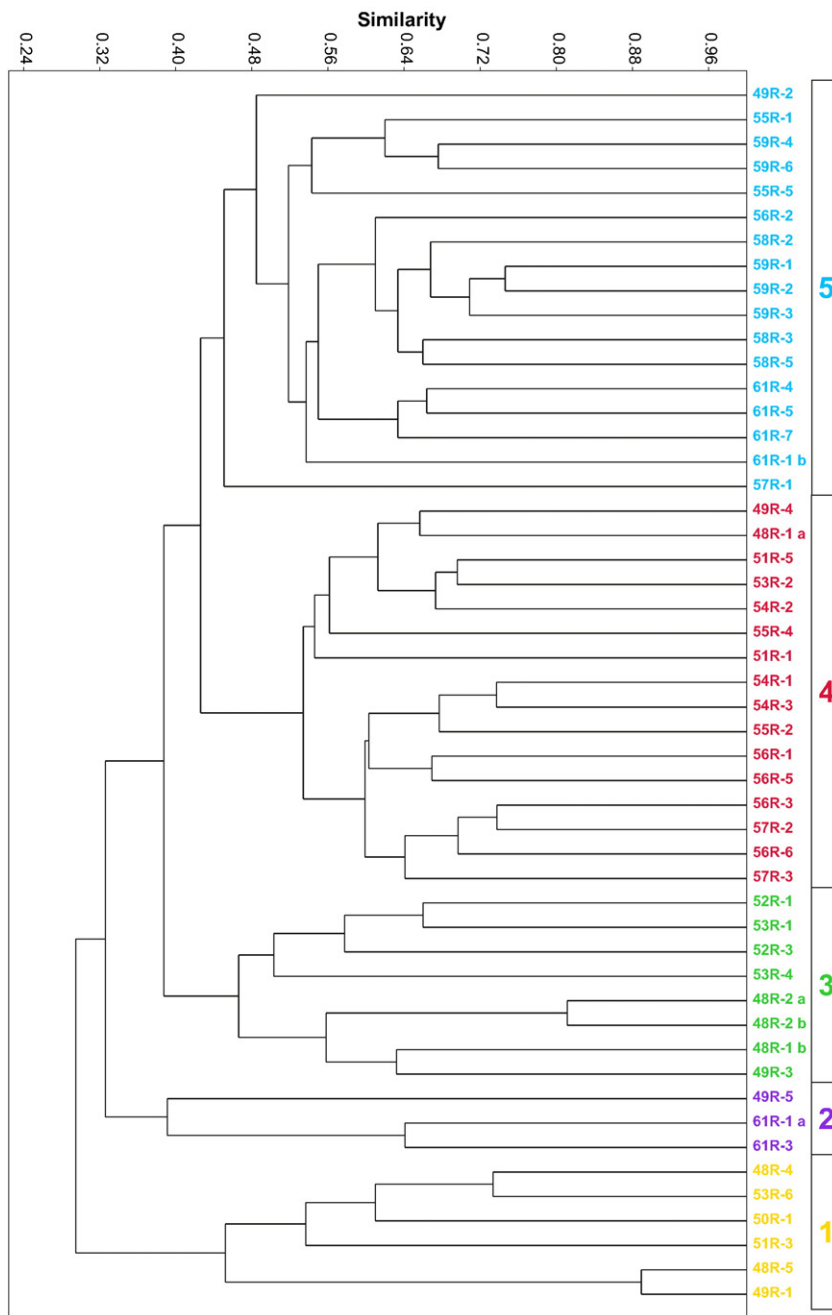
Fig. 3. Q-mode cluster analysis (UPGMA, Bray Curtis; correlation: 0.71) for autochthonous benthic foraminifera >150 μm from IODP Hole U1387C. Numbers indicate groups of samples with a similar foraminiferal composition, representing fossil assemblages. Autochthonous taxa occurring >5% abundance in at least one sample have been considered for the analysis.

Lenticulina spp. (3.6%), *Cibicidoides* spp. (3.5%) and *S. bulloides* (3.1%). In cluster 5, the contribution of taxa is more equally distributed: U. pigmea (6.2%), *B. mexicana* (5.6%), *C. bradyi* (4.6%), *Cibicidoides* spp. (4.4%), *Cibicidoides crebbsi* (4.4%), *Gyroidinoides soldanii* (3.8%), *Stilostomella* spp. (3.8%), *Eggerella bradyi* (3.4%), *S. bulloides* (3.2%) and *G. subglobosa* (3.1%).

4.2. Stratigraphic distribution of foraminiferal assemblages

Fig. 2 shows the distribution of sample clusters containing different foraminiferal composition. Core sections have been colored accordingly. Foraminiferal assemblages have been assigned according to the cluster in which they become more dominant (up to a contribution of 3% in each cluster according to the SIMPER analysis), adopting the same color as the correspondent cluster (Fig. 4). Three marked changes in

assemblage distribution allow the distinction of four intervals. Interval 1 extends from 865.55 to 829.5 mbsf and is composed of fine-grained muddy sediments. Samples from cluster 5 are predominant in this interval with the exception of sections 61R-3 and 61R-1 in which cluster 2 is dominant. A major shift in foraminiferal composition occurs after the Miocene/Pliocene boundary when assemblage 5 is largely replaced by assemblage 4. The dominant lithology in Interval 2 (822.05 mbsf to 786.62 mbsf) is nannofossil mud; silty beds occur at ~802, 791.96, 790.48 and 788.82 mbsf (Fig. 2). Interval 3 extends from 784.38 to 764.92 mbsf and is distinguished by the predominance of cluster 3. The interval is mainly composed by nannofossil mud with a coarser layer at 770.22 mbsf. Finally, Interval 4 extends from 763.06 to 731.5 mbsf and is characterized by a heterogeneous distribution of foraminiferal assemblages. In contrast to previous intervals, assemblage 1 occurs frequently, alternating with assemblages 3 and 4 and, to a

Table 1
Similarity percentage (SIMPER) analysis for benthic foraminiferal assemblages >150 μm (combined fractions). Overall average dissimilarity: 63.57. Taxa occurring at least once at >5% abundance were included in the data matrix.

Taxon	Average dissimilarity	Contribution (%)	Cumulative (%)	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Uvigerina pigmea	6.2	9.8	9.8	4.6	21.8	15.5	6.5	6.2
Siphonina tubulosa	3.9	6.1	15.8	2.1	0.0	0.2	9.6	0.2
Globocassidulina subglobosa	3.4	5.3	21.2	2.8	1.6	4.0	8.0	3.1
Elphidium spp.	3.2	5.1	26.2	16.6	0.0	1.5	0.3	0.0
Osangularia culter	3.1	4.8	31.0	1.2	0.8	12.0	0.9	0.7
Uvigerina auberiana	2.8	4.5	35.5	0.2	22.1	2.1	1.1	0.1
Bulimina mexicana	2.8	4.3	39.8	1.4	13.2	1.6	2.7	5.6
Cibicidoides bradyi	2.0	3.1	43.0	0.8	0.6	2.3	0.3	4.6
Uvigerina cf. *pigmaea*	1.8	2.9	45.9	0.3	0.0	3.2	2.0	2.4
Cibicidoides spp.	1.8	2.8	48.7	6.1	3.1	5.7	3.5	4.4
Sphaeroidina bulloides	1.6	2.5	51.2	2.2	3.3	2.8	3.1	3.2
Cibicidoides crebbsi	1.6	2.5	53.7	1.0	2.1	2.4	1.7	4.4
Gyroidinoides soldanii	1.5	2.3	56.0	0.5	1.1	1.1	0.7	3.8
Asterigerinata spp.	1.4	2.3	58.3	7.5	0.0	0.4	0.2	0.0
Cibicides lobatulus	1.4	2.2	60.5	7.7	0.0	0.4	0.2	0.0
Cibicidoides cf. *mundulus*	1.4	2.1	62.7	0.9	0.0	4.6	0.2	0.6
Stilostomella spp.	1.3	2.1	64.8	1.7	2.1	2.5	2.9	3.8
Eggerella bradyi	1.3	2.1	66.9	0.3	0.9	0.4	0.6	3.4
Cibicidoides pachyderma	1.3	2.0	68.9	0.8	2.8	1.1	1.7	2.8
Dentalina spp.	1.2	1.9	70.8	1.5	0.7	1.1	2.8	2.5
Lenticulina spp.	1.2	1.8	72.6	1.0	0.3	1.3	3.6	1.2
Sigmoilopsis schlumbergeri	1.1	1.7	74.3	0.7	1.1	1.4	2.0	2.6
Ammonia spp.	1.1	1.7	76.0	5.6	0.0	0.4	0.1	0.0
Brizalina spp.	1.0	1.6	77.6	0.5	0.5	0.6	1.5	2.0
Cibicides spp.	1.0	1.6	79.2	4.4	0.4	0.5	0.4	0.8
Globobulimina spp.	1.0	1.5	80.7	0.6	0.2	0.3	0.7	1.9
Uvigerina sp.1	0.9	1.5	82.2	0.7	0.7	0.6	2.1	0.4
Siphonodosaria spp.	0.9	1.4	83.6	0.2	0.7	1.1	1.6	1.2
Uvigerina holllicki?	0.9	1.4	85.0	0.6	0.6	1.9	1.5	0.9
Plectofrondicularia spp.	0.9	1.3	86.3	0.3	0.0	1.3	1.7	0.4
Amphicoryna hirsuta	0.9	1.3	87.7	0.3	0.1	0.4	2.1	0.4
Gyroidinoides spp.	0.8	1.3	89.0	1.2	0.0	1.5	0.4	0.6
Ehrenbergina hystrix	0.8	1.3	90.3	0.1	1.2	0.1	0.1	1.8
Textularia spp.	0.8	1.2	91.5	0.7	1.4	0.5	1.4	1.4
Lagena spp.	0.8	1.2	92.7	0.8	0.5	0.7	1.4	1.5
Uvigerina basicordata	0.7	1.2	93.8	0.0	1.7	1.1	0.6	0.6
Oridorsalis umbonatus	0.7	1.2	95.0	0.5	0.7	1.1	0.6	1.9
Uvigerina hispida	0.7	1.1	96.1	0.1	0.0	1.0	0.1	1.5
Cibicides refulgens	0.7	1.1	97.2	3.7	0.0	0.0	0.0	0.0
Praeglobobulimina pupoides	0.6	1.0	98.2	0.0	0.3	0.9	0.4	1.0
Trifarina carinata	0.4	0.7	98.9	1.9	0.0	0.3	0.2	0.0
Cibicidoides mundulus	0.4	0.6	99.5	0.3	1.0	0.4	0.2	0.5
Vaginulina spp.	0.2	0.3	99.8	0.1	0.0	0.0	0.4	0.0
Lenticulina iota	0.1	0.2	100.0	0.0	0.0	0.0	0.0	0.3

minor extent, assemblages 2 and 5. The lithological composition is more heterogenic as well with nannofossil mud and intercalated sandy layers at 751.23, 746.8 and 745.42 mbsf (Fig. 2; Stow et al., 2013).

Abundances of epi and infaunal taxa vary antagonistically and show a general predominance of epifauna throughout the studied interval (Fig. 5). Interval 1 is characterized by the predominance of infaunal taxa. Interval 2 shows a general increase of epifaunal taxa with minor short-term oscillations that continue in interval 3, in which larger peaks occur at 784.38 and 770.22 mbsf. Interval 4 is characterized by two abrupt increases of infaunal taxa at 746.8 and 733.12 mbsf.

5. Discussion

Foraminiferal abundances and statistical analyses reveal three distinct faunal turnovers in the studied interval of IODP Hole U1387C indicating major changes of the palaeoenvironment (Fig. 4). The first turnover occurs between 829.5 and 822.05 mbsf and coincides with the Miocene-Pliocene boundary (Hernández-Molina et al., 2016; Van der Schee et al., 2016). The change in foraminiferal assemblages may thus reflect palaeoceanographic changes related to the opening of the Gibraltar Strait and the beginning inflow of Mediterranean-sourced waters into the Gulf of Cadiz. The second prominent shift of foraminiferal assemblages between 786.62 and 784.38 mbsf is not associated with an apparent change in lithology except for an increase of coarse grained

sediments at ~770.22 mbsf. Consequently, the herein distinguished Intervals 2 and 3 have not been distinguished in the sedimentological and geochemical study of Van der Schee et al. (2016). In contrast, the last turnover of foraminiferal assemblages between 764.92 and 763.06 mbsf is clearly associated with a change towards a heterogeneous lithology with increased grain size/occurrence of sandy layers probably indicating a more unstable period with frequent downslope transport. In the following, we discuss the palaeoenvironmental conditions inferred for each interval in detail. All ages refer to Van der Schee et al. (2016).

5.1. Foraminiferal assemblages and palaeoenvironmental changes

5.1.1. Interval 1 (865.55–829.5 mbsf; ~5.7–5.33 Ma)

Foraminiferal assemblages 5 and 2 of Interval 1 are generally characterized by the predominance of infaunal species adapted to mesotrophic and eutrophic environments with lowered levels of bottom and pore water oxygenation (Figs. 4, 5; Jorissen et al., 2007). The high content of nannofossils in the fine-grained sediments of Interval 1 and the absence of indications for substantial bottom currents suggest that the benthic environment was controlled by export productivity from the surface waters (Stow et al., 2013). Regular alternations of dark and light colored sediments and parallel minima and maxima in benthic $\delta^{13}C$, respectively, suggest cyclical changes in organic carbon supply to
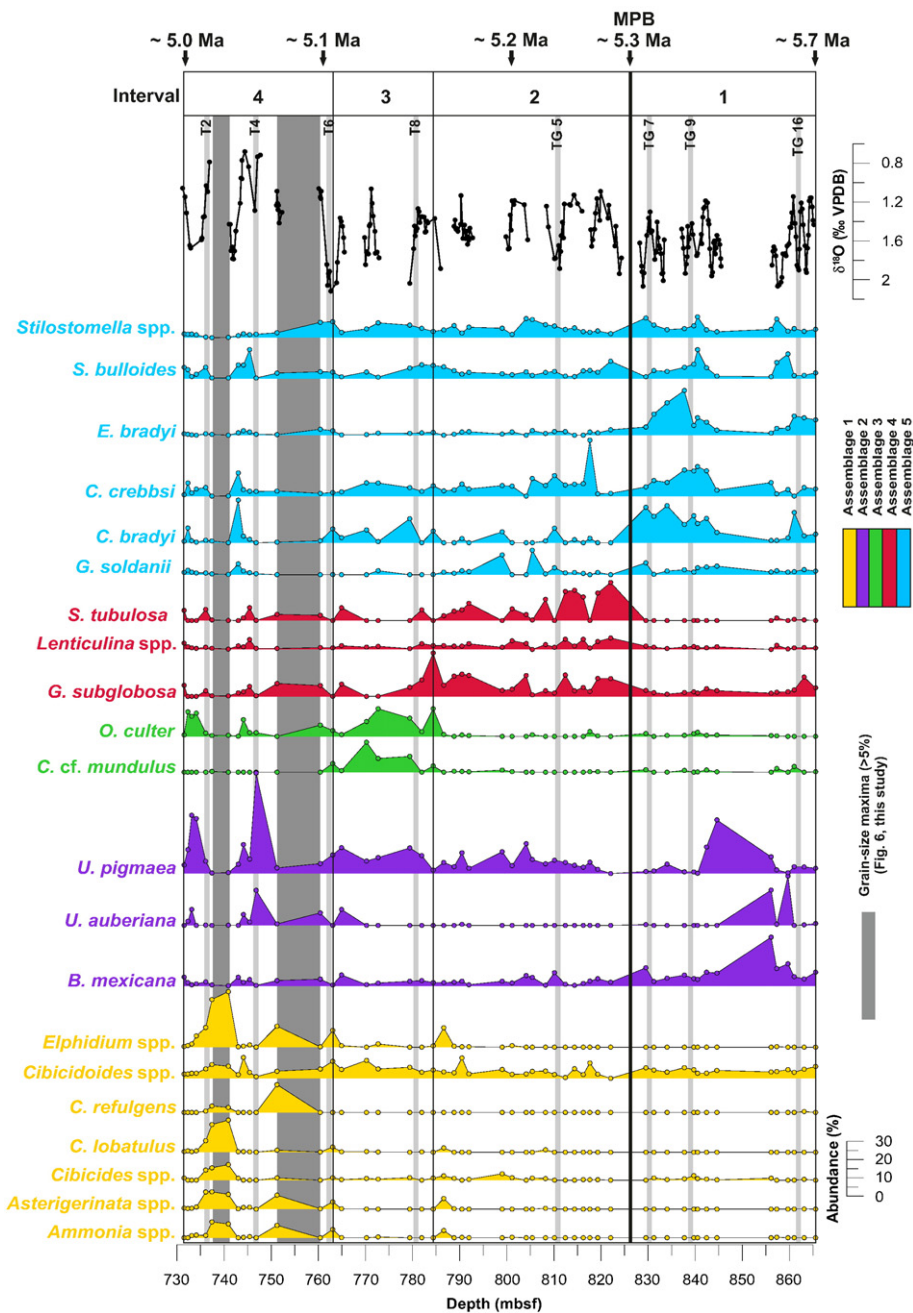
Fig. 4. Variations in relative abundances of major benthic foraminiferal taxa. Colors correspond to foraminiferal assemblages characterizing the sample clustering in Fig. 3. Dark grey bars indicate main periods of grain-size maxima (>5%) according to Fig. 6. Black curve: benthic δ¹⁸O (‰ VPDB). Light grey bars indicate TG and T Marine Isotopic Stages according to Van der Schee et al. (2016). Pictures of the main taxa are displayed in Fig. 7.

the seafloor, probably forced by precession (Van der Schee et al., 2016). This signal is not apparent in benthic foraminifera (in contrast to Interval 2; see below). Continuous abundances of *Gyroidinoides* spp., *Cibicidoides bradyi*, *C. crebbsi*, *Eggerella bradyi*, *Sphaeroidina bulloides* and *Stilostomella* (assemblage 5) are punctuated by strong peaks of *Uvigerina pigmea* and *U. auberiana* and *Bulimina mexicana* (assemblage 2) in the interval between 860 and 840 mbsf (Figs. 2, 4). The varying abundances can be best explained by changes of oxygenation and, more importantly, the quantity, quality and seasonality of food supply (Fig. 5). The life mode of the cosmopolitan *C. bradyi* differs from other species of the genus by occupying epifaunal as well as infaunal micro-habitats down to 4 cm in low oxygen environments (Rathburn and Corliss, 1994; Rathburn et al., 1996). *E. bradyi* is an intermediate to deep infaunal species common in oligotrophic environments as well

as in areas of high, often seasonal export productivity (Enge et al., 2012; Kuhnt et al., 2000). Little is known about the extinct *C. crebbsi*; however, its tolerance for low levels of oxygen is suggested by similar increases of this species with *C. bradyi* and *E. bradyi* in this interval. *S. bulloides* is most common in eutrophic sea-floor environments and oc-curs in the upper bathyal of the Gulf of Cadiz (Loubere and Fariduddin, 2003; Schönfeld, 2002b). The extinct *Stilostomella* spp. most likely occupied an infaunal habitat and preferred high food flux (Hayward et al., 2012). *Bulimina mexicana* (and the closely related *B. inflata*) is commonly described from oxygen-depleted, mesotrophic and eutrophic environments (Altenbach et al., 1999; Loubere and Fariduddin, 2003; Phipps et al., 2012). Along the Iberian Margin, this species occurs most commonly at mesotrophic sites under the influence of North Atlantic Deep Water (NADW; Grunert et al., 2015; Phipps et al.,
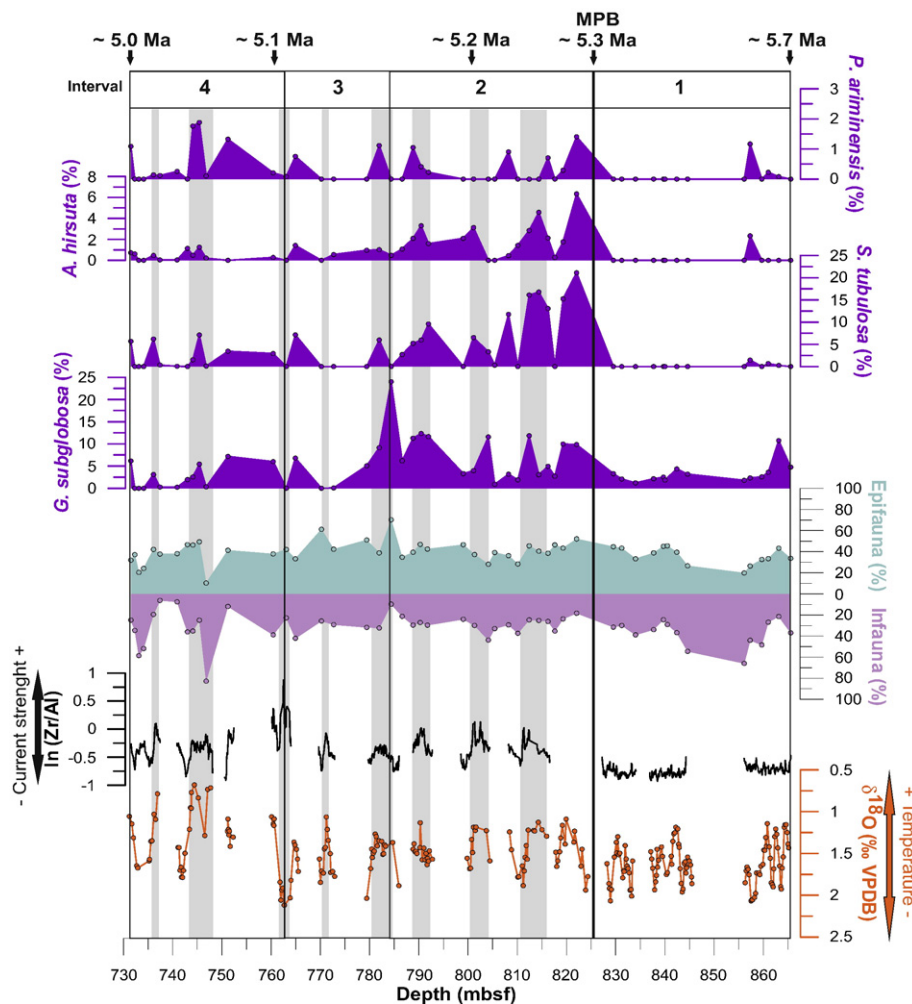
Fig. 5. Benthic δ¹⁸O (orange, inverted axis), ln (Zr/Al) (black, 3-point running mean), relative abundances of epifauna/shallow infauna (blue, % *Cibicides* spp., *Cibicidoides* spp., *Globocassidulina subglobosa*, *Gyroidinoides* spp., *Lagena* spp., *Lenticulina* spp., *Oridorsalis umbonatus*, *Osangularia culter*, *Sigmoilopsis schlumbergeri*, *Siphonina tubulosa*, *Sphaeroidina bulloides*, *Textularia* spp., *Vaginulina* spp.) vs. infauna/intermediate/deep infauna (pink, % *Amphicoryna hirsuta*, *Brizalina* spp., *Bulimina striata*, *Dentalina* spp., *Eggerella bradyi*, *Globobulimina* spp., *Siphonodosaria* spp., *Stilostomella* spp., *Trifarina carinata*, *Uvigerina* spp.) from Appendix 2, based on Corliss (1991), Jorissen (2003), Murray (2006), Pérez-Asensio et al. (2012b), Rathburn and Corliss (1994), Schmiedl et al. (2000) and Szarek et al. (2007); relative abundances of *Siphonina tubulosa*, *Globocassidulina subglobosa*, *Planulina ariminensis* and *Amphicoryna hirsuta* (purple). Grey bars indicate periods of Zr/Al maxima.

2012; Schönfeld, 2002b). Assemblages mainly composed of these taxa characterize the lowermost part of the hole >860 mbsf and samples <840 mbsf. Overall, the foraminiferal assemblages indicate a mesotrophic to slightly eutrophic environment that could be related to either lowered oxygenation or higher carbon flux, as suggested by the larger amount of infaunal taxa (Fig. 5). The trend towards higher abundances of *C. bradyi*, *C. crebbsi* and *E. bradyi* in the upper part of this interval coincides with a lithological change from nannofossil ooze to nannofossil mud which has been interpreted as an increase of terrestrial organic matter (Stow et al., 2013). Thus, there is the possibility that these species might be able to process the refractory organic matter more effectively.

Abrupt peaks of *B. mexicana*, *U. auberiana*, and *U. pigmea* are noticeable between 860 and 842 mbsf (~5.67–5.47 Ma; Fig. 4). Parallel maxima in *U. auberiana* and *B. mexicana* such as in the studied interval (assemblage 2) are commonly observed today in oxygen depleted, eutrophic environments, in particular under intense, perennial upwelling conditions (Caulle et al., 2014; Licari, 2006; Schmiedl et al., 1997). Abundances of both species are opposed to maximum abundances of *U. pigmea*. The latter species is today restricted to poorly oxygenated eutrophic environments along the equatorial western African margin, but has been recorded along the Iberian Margin during the Pleistocene

(Grunert et al., 2015; Schönfeld, 2006; Schönfeld and Altenbach, 2005). This species seems to be adapted to high, spring bloom dominated organic carbon flux, and highly sensitive to a distinct phytoplankton composition in its diet (Schönfeld, 2006; Schönfeld and Altenbach, 2005). The occurrences of the three species thus indicate maximum fluxes of fresh, labile organic carbon to the seafloor in Interval 1, and the abundance patterns of the individual species may perhaps reflect changes in seasonality and the type of organic carbon.

Within the bounds of available age constraints for Interval 1, benthic foraminiferal abundance patterns might be best explained by long-term, astronomically-forced climatic trends that determined organic carbon fluxes at IODP Site U1387. Assemblages <860 mbsf (~5.7–5.67 Ma) and >842 mbsf (~5.47–5.33 Ma) occur under warm climate conditions (Roveri et al., 2014; Van der Laan et al., 2005, 2006). Increased river runoff from the Iberian Peninsula delivered terrestrial organic matter, stimulating primary productivity, and led to an increased stratification of the water column (Pérez-Asensio et al., 2014). Ultimately, the stagnant conditions favored benthic species such as represented by assemblage 5 which are adapted to a poorly oxygenated, mesotrophic to eutrophic seafloor environments. The increase in *C. bradyi*, *C. crebbsi* and *E. bradyi* and the coeval decreasing nannofossil abundance <842 mbsf occur during an increasingly warmer

climate <5.45 Ma, probably enhancing river runoff and the delivery of terrestrial, i.e. refractory organic carbon to the seafloor (see below; Stow et al., 2013; Van der Laan et al., 2005, 2006). The parallel maxima of *B. mexicana* and *U. auberiana*, the latter virtually absent from Interval 1 otherwise, occur during a minimum in the 400 kyr-eccentricity-cycle and a predominance of obliquity over precession (Van der Schee et al., 2016). The combined effects of this orbital configuration lowered seasonal contrast and initiated a prolonged period of climate deterioration following marine isotope stage (MIS) TG16 (~5.65 Ma, Fig. 4) that is well documented in the area (Roveri et al., 2014; Van den Berg et al., 2015; Van der Laan et al., 2006). The cooling culminates during glacial periods MIS TG14 and TG12, and warm climate conditions are re-established only with MIS TG9 (~5.45 Ma; Fig. 4; Van der Laan et al., 2005, 2006). Climate cooling likely resulted in more arid conditions in the region and reduced river runoff, probably favoring upwelling conditions in the northern Gulf of Cadiz, thereby providing the high amount of fresh, labile organic carbon preferred by uvigerinids (Altenbach et al., 1999; Pérez-Asensio et al., 2012b, 2014; Van den Berg et al., 2015). As pointed out previously, the opposed abundance patterns of *U. auberiana* and *U. pigmea* may be explained by changes in the seasonal timing of upwelling conditions and/or primary producers, probably as a result of climate recovery during MIS TG11-TG10 (Schönfeld and Altenbach, 2005). A more detailed evaluation of this period is unfortunately hampered by the poor recovery of core 60R (Fig. 2).

5.1.2. Interval 2 (822.05–786.62 mbsf; ~5.33–5.18 Ma)

Interval 2 is characterized by regular alternations in the predominance of species of assemblages 4 and 5 (Fig. 4). Taxa characteristic for assemblage 4 such as *Siphonina tubulosa* and *Globocassidulina subglobosa* are dominant in this interval (Fig. 4). The cosmopolitan *S. tubulosa* occurs in warm, oligotrophic, comparably well-oxygenated intermediate waters and occupies an epifaunal to shallow infaunal habitat (Jones, 1994; Szarek et al., 2007). *G. subglobosa* is commonly described as a species from oligotrophic environments with episodic input of phytodetritus, often under the influence of intensified bottom currents (D'haenens et al., 2012; Mackensen et al., 1995; Morigi, 2009; Schmiedl et al., 1997). Abundance maxima of these taxa are matched by occurrences of *Planulina ariminensis*, a species considered an indicator of MOW in the Gulf of Cadiz (Rogerson et al., 2011; Schönfeld, 2002a; see also Section 5.2). All mentioned taxa are abundant during minima in benthic δ18O, and maxima in Zr/Al (Figs. 4, 5). These abundance patterns are contrasted by species of assemblage 5 which also occurred regularly in Interval 1, most prominently *Uvigerina pigmea*, *Bulimina mexicana*, *Cibicidoides crebbsi* and *C. bradyi*. In this case, maxima of these species occur during benthic δ18O maxima and minima in Zr/Al (Figs. 4, 5). As discussed previously, these species of assemblage 5 are indicative of oxygen depleted, mesotrophic and eutrophic seafloor environments. Sustained and higher abundances of *U. pigmea* compared to Interval 1 suggest substantial increase of trophic conditions during these phases (Fig. 4).

The distinct alternations thus indicate regular changes between a warm, oligotrophic, well-oxygenated and a colder, eutrophic, oxygen depleted seafloor environment shortly after the Miocene-Pliocene boundary at 826 mbsf (Fig. 4). Van der Schee et al. (2016) have presented several lines of evidence that this change of the depositional environment is related to the opening of the Gibraltar Strait, the onset of Mediterranean/Atlantic exchange, and weak bottom-current flow of Mediterranean-sourced water at IODP Site U1387 shortly thereafter: an average decrease of benthic δ18O, i.e. warming of bottom waters, after the Miocene/Pliocene boundary; cyclical increases in Zr/Al and grain-size; the occurrence of individual contourite beds in cores 54R and 55R. Our data agree this interpretation and allow more detailed evaluation from an ecological perspective. The foraminiferal assemblages suggest that the presence of warm, likely Mediterranean-sourced waters alternating with colder waters of likely Atlantic origin at IODP Site U1387 between ~5.3 and 5.18 Ma (Fig. 4). A long-term increase of epifaunal taxa indicates better oxygenation during this interval that can be related to the initial

Atlantic/Mediterranean exchange (Fig. 5). The similarity between the foraminiferal assemblages to the geochemical record suggests that the periodic advection of warm, Mediterranean-sourced waters is controlled by precessional forcing, which in turn controls freshwater discharge and deep-water production in the Mediterranean (Lourens et al., 1996; Rogerson et al., 2012; Rohling et al., 2015). Furthermore, the microfossil data suggest that the likely Mediterranean-sourced waters arriving at IODP Site U1387 are better ventilated and depleted in nutrients, whereas the colder Atlantic-sourced waters are comparably poorly ventilated, and nutrient-rich. By contrast, present-day MOW carries more suspended food particles than NADW, and is comparably oxygen depleted (Caralp, 1988; Freitas and Abrantes, 2002; Reid, 1979). The opposite hydrographic properties may be explained by the rather sluggish Mediterranean/Atlantic exchange and weak bottom currents resulting in the deposition of the suspension load of Mediterranean-sourced waters closer to the Gibraltar Strait in the early Pliocene. Different patterns of primary productivity and circulation in the Mediterranean may also contribute. When Mediterranean-sourced waters are absent from IODP Site U1387 as indicated by abundances of species of assemblage 5 (Fig. 4), mesotrophic to eutrophic conditions under persistent warm climate conditions similar to the late Miocene seem to be established.

5.1.3. Interval 3 (784.38–764.92 mbsf; ~5.18–5.1 Ma)

Interval 3 is marked by a faunal turnover with detectable high abundances of *Osangularia culter* and *Cibicidoides* cf. *mundulus* (assemblage 3), and the near disappearance of taxa characteristic for assemblage 4 such as *Siphonina tubulosa* (Fig. 4). *O. culter* is most commonly described from epi and shallow infaunal habitats in mesotrophic environments in well-oxygenated, often warm intermediate and deep waters (Licari et al., 2003; Schmiedl et al., 1997; Szarek et al., 2007). Due to its preference on high levels of oxygen, *O. culter* has been used as an indicator of well-oxygenated water masses such as NADW in the fossil record (Schmiedl and Leuschner, 2005; Schmiedl et al., 1997). Similarly, *Cibicidoides* cf. *mundulus* is most abundant in epi and shallow infaunal habitats in oligotrophic and mesotrophic environments along the Iberian Margin under strong NADW influence and outside MOW (Grunert et al., 2015; Schönfeld, 1997, 2002b). The occurrence of these species is perhaps related to the influence of a NADW-like water mass at IODP Site U1387, which is also suggested by the scarcity of bottom current indicators (assemblage 4 in Fig. 4). Based on the available age constraints, this incursion occurs during MIS T8, the first severe glacial period of the early Pliocene (Fig. 4; Lisiecki and Raymo, 2005; Van der Schee et al., 2016). Due to the lack of coeval records from deeper parts of the Gulf of Cadiz, it can only be speculated at this point if Mediterranean/Atlantic exchange was severely reduced by restriction of the Gibraltar Strait due to lowered sea-level; or if Mediterranean waters were forced to water depths below IODP Site U1387 due to an interplay of increased salinity (arid conditions in the Mediterranean) and lowered sea-level (Rogerson et al., 2012).

The beginning of Interval 3 marks the onset of a long-term increase in average grain-size that starts with occasional silty beds and culminates in the frequent deposition of sandy turbidite layers in Interval 4 (Fig. 2; Stow et al., 2013; Van der Schee et al., 2016). It is noteworthy that maximum abundances of *O. culter* in both intervals occur in samples with an increased silt portion whereas it is scarce or absent in the muddy deposits of Intervals 1 and 2, and sandy beds of Interval 4 (Fig. 4). Abundances of *O. culter* might thus also reflect the coarsening of the substrate and potentially, the increased input of refractory, shelf-derived organic carbon. However, such a preference for silty sediments has not been demonstrated so far. Given its well-documented dependency on more oxic levels, the absence of allochthonous shelf taxa in samples of Interval 3, and its co-occurrence with *C.* cf. *mundulus*, another species typical for well-oxygenated Atlantic waters, we consider a change of water properties that could be related to less Mediterranean influence.

This change in water mass properties, clearly evident in the foraminiferal assemblages, has not been recognized in the sedimentological
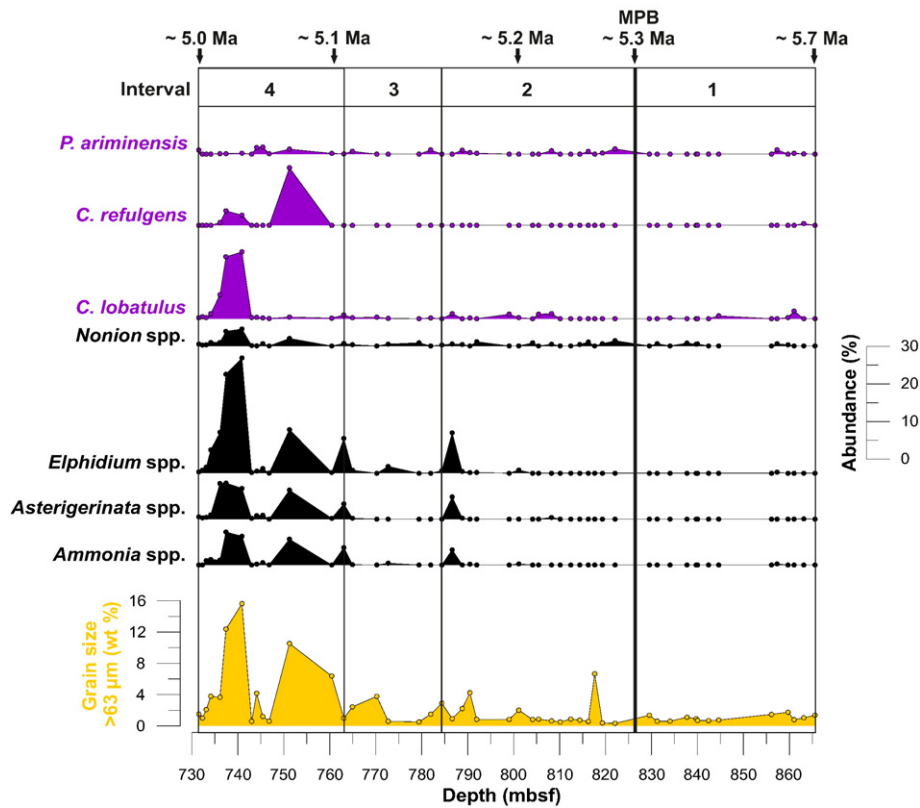
Fig. 6. Grain-size records (yellow), relative abundance of shelf taxa (black) and elevated epifauna (purple).

and isotopic proxy records of Van der Schee et al. (2016). A closer inspection of the proxy records in Interval 3 shows that the amplitudes of δ^{18}O maxima increase considerably compared to Interval 2. Furthermore, Zr/Al maxima are less well expressed and no contourite beds have been identified (Fig. 5). Reduced advection of organic carbon through bottom currents might result in an increased control of surface water productivity on organic carbon flux, reflected in continuous abundances of *Uvigerina pigmea* and, less well expressed, *Bulimina mexicana* throughout Interval 3 with maxima in darker colored sediments.

5.1.4. Interval 4 (763.06–731.5 mbsf; ~5.1–5.0 Ma)

Interval 4 shows a highly heterogenic sequence of assemblages of different diversity, indicating a complex and dynamic depositional environment. As highlighted earlier, Interval 4 is characterized by frequent occurrences of sandy layers attributed to turbidites (Stow et al., 2013; Van der Schee et al., 2016). Foraminiferal shells from samples in those layers are often poorly preserved, abraded and of dark color, documenting post-depositional transport processes. The most abundant species in sandy layers are taxa that are restricted to the shelf (e.g., *Ammonia*, *Elphidium*, *Asterigerinata*, *Nonion*; Leckie and Olson, 2003; Mendes et al., 2012), or are known for their wide bathymetric range (e.g., *Cibicides lobatulus*; Bolliet et al., 2014; Jones, 1994; Mendes et al., 2012). Based on the abundances of shelf dwellers in our dataset, downslope transport is minimal in Intervals 1 and 2. Two episodes occur at the end of Intervals 2 and 3, and they become particularly pronounced in Interval 4 (Fig. 6). Shelf instability and turbiditic downslope

transport through canyons is a common phenomenon in the Gulf of Cadiz since the early Pliocene (Brackenridge et al., 2013; Hernández-Molina et al. 2003, 2006, 2014; Maldonado et al., 1999; Stow et al., 2013; Van der Schee et al., 2016). These episodes have been related to tectonic adjustments after the opening of the Gibraltar Strait, and our new data indicate that they occur preferentially during glacial periods with pronounced obliquity minima, probably promoting shelf instability (Hernández-Molina et al., 2014; Van der Schee et al., 2016).

Between episodes of downslope transport, an overall decrease of epifaunal taxa and periodic increases of infaunal and deep infaunal taxa point to episodic increases of organic matter influx and/or decreases in oxygenation (Fig. 5). Autochthonous assemblages resemble in some aspects assemblages of Intervals 1 and 3. *Uvigerina pigmea* and *U. auberiana*, the latter being absent from interval 2 and the lower part of interval 3, dominate these autochthonous assemblages, particularly <745 mbsf, accompanied by variable abundances of *Sphaeroidina bulloides*, *Cibicidoides bradyi*, *C. crebbsi*, *Stilostomella* spp., and *Osangularia culter* (Fig. 4). The parallel abundance patterns of *U. pigmea* and *U. auberiana* contrast Interval 1. As discussed previously, both species thrive in oxygen-depleted environments with high levels of organic carbon flux (Caulle et al., 2014; Schönfeld and Altenbach, 2005). The co-occurrence of these two species as well as with oligotrophic species such as *O. culter* may thus be explained by different timing and composition of phytoplankton blooms reflected in the composition of the time-averaged assemblages. Besides export productivity, the high

abundances could also reflect the temporary injection of high amounts of organic carbon through downslope transport as is well documented for the closely related *U. peregrina* (Schönfeld and Altenbach, 2005). However, *U. pigmea* seems to be highly sensitive to the origin of organic carbon and has not been reported from such unstable environments (Schönfeld and Altenbach, 2005).

The complex depositional environment and intervals of poor recovery make it hard to distinguish a water mass signal. A negative shift of average benthic $\delta^{18}O$ values in Interval 4 has been previously interpreted as indicative of stronger presence of Mediterranean water (Van der Schee et al., 2016). This interpretation is not supported by autochthonous assemblages. Although *Siphonina tubulosa* and *Globocassidulina subglobosa* and other species of assemblage 4 occur more continuously in Intervals 1 and 3, they are markedly less abundant than in Interval 2, indicating only a reduced presence of a warm and more energetic bottom current (Figs. 4, 5). Similar to Interval 3, *O. culter* contrasts abundances of these taxa, suggesting episodes of strong admixture of cold waters, possibly related to Atlantic influence.

5.2. Benthic foraminifera as indicators of early MOW reconstruction

Previous evidence for early Pliocene Mediterranean/Atlantic exchange and the presence of Mediterranean, probably MOW-like waters at IODP Site U1387 has been based on seismic (onset of contourite drift deposition), sedimentological (occurrence of contourite beds, grain-size) and geochemical (Zr/Al, $\delta^{18}O$) data (Hernández-Molina et al., 2014, 2016; Van der Schee et al., 2016). While the onset of drift deposition and the presence of a proper contour current can be arguably well dated to 4.5–4.2 Ma, the reconstruction of Mediterranean/Atlantic exchange directly after the opening of the Gibraltar Strait is more challenging (Hernández-Molina et al., 2014). As discussed in the previous section, the new microfossil data provide additional means to address this issue, but also call into question the suitability of a specific group of benthic foraminifera as water mass indicators in the early Pliocene Gulf of Cadiz.

The term "elevated epifauna" describes a group of benthic foraminiferal species inhabiting elevated substrates above the sediment surface to optimize food acquisition under the influence of strong bottom currents (Schönfeld 1997, 2002a, 2002b). Abundances of these taxa have been directly related to the presence of MOW in the Gulf of Cadiz, and have been used as a proxy for bottom current strength and MOW reconstruction in the Pleistocene (Rogerson et al., 2011; Schönfeld, 2002a; Singh et al., 2015). Following this approach, occurrences of these species should provide evidence of Mediterranean/Atlantic exchange and MOW presence at IODP Hole U1387C after the opening of the Gibraltar Strait. In our samples, the elevated epifauna is represented by *Planulina ariminensis*, *Cibicides lobatulus* and *Cibicides refulgens*. Mediterranean/Atlantic exchange after the opening of the Gibraltar Strait and before the onset of drift deposition is generally considered weak (Hernández-Molina et al., 2014; Rogerson et al., 2011; Van der Schee et al., 2016), which may explain the scarcity of all three species throughout the section, except for Interval 4 in which *C. lobatulus* and *C. refulgens* show exceptionally high abundances in samples that also contain large amounts of allochthonous shelf dwellers (assemblage 1; Fig. 6). Both species are known to have a broad bathymetric distribution from coastal shelf environments to the deep sea (Dorst and Schönfeld, 2013; Jones, 1994; Linke and Lutze, 1993; Mendes et al., 2012). The evident correspondence of high abundances of shelf dwellers, *C. lobatulus* and *C. refulgens*, clearly expressed in assemblage 1, strongly indicate their allochthonous origin (Figs. 2, 3, 6). This observation calls the suitability of *C. lobatulus* and *C. refulgens* as MOW indicators into question in the present case, and in general calls for careful consideration of this method when there is evidence for downslope transport in the studied sediments. As a consequence, the rare *P. ariminensis* which has an upper depth limit on the upper slope, remains the sole species of the elevated epifauna considered autochthonous in our samples and, thus, a reliable

indicator for the presence of a strong bottom current related to Mediterranean-sourced waters (Jones, 1994; Linke and Lutze, 1993; Lutze and Thiel, 1989; Rogerson et al., 2011; Schönfeld, 1997, 2002a, 2002b; Van Morkhoven et al., 1986). *P. ariminensis* is absent in Interval 1 except for two samples, and occurs more frequently after the Miocene/Pliocene boundary (Fig. 5). Peaks coincide with Zr/Al maxima and $\delta^{18}O$ minima but abundances are <2%, indicating only a minor influence of bottom current strength (Rogerson et al., 2011).

The potentially very different properties of a Mediterranean-sourced water mass in the early Pliocene (see Section 5.1.2) may further put severe limitations on the application of this proxy (elevated epifauna) method. Consequently, several other taxa present in the assemblages are considered to reveal information about Mediterranean-sourced waters reaching IODP Site U1387 during the early Pliocene, even if they have not been considered indicators of MOW before. As mentioned in Section 5.1.2., abundance patterns of *Siphonina tubulosa* and *Globocassidulina subglobosa*, as well as *Amphicoryna hirsuta* resemble those of the elevated epifaunal *P. ariminiensis* (Fig. 5). Rarely present in Interval 1, these species show a marked increase after the Miocene/Pliocene boundary, and are particularly abundant in Interval 2 (Fig. 5). As pointed out previously, *S. tubulosa* thrives in warm, oligotrophic, comparably well-oxygenated intermediate waters in an epifaunal to shallow infaunal habitat, and is present along the Iberian Peninsula from the Gulf of Cadiz to the Bay of Biscay in distal MOW settings (Balestra et al., in press; Dorst and Schönfeld, 2013; Jones, 1994; Szarek et al., 2007). Shipboard data show that *S. tubulosa* occurs in the fossil record of IODP Site U1387 until ~2.6 Ma, and might thus be related to the first Mediterranean-sourced waters in the Gulf of Cadiz throughout the Pliocene (Stow et al., 2013). As indicated previously, the cosmopolitan species *G. subglobosa* has been suggested as an indicator of increased bottom current velocities in oligotrophic environments (Mackensen et al., 1995; Rasmussen et al., 2002, 2003; Schmiedl et al., 1997). *A. hirsuta* is limited to IODP Site U1387 in surface samples of IODP Expedition 339 (Balestra et al., in press); the genus is suggested to be shallow infaunal (Pérez-Asensio et al., 2012b), but still little is researched about its ecological preferences. The presence of Mediterranean-sourced waters at IODP Site U1387 between 5.3 and 5.0 has been discussed in Section 5.1.2. Shipboard data show that *S. tubulosa* occurs in the fossil record of IODP Site U1387 until ~2.6 Ma, and might thus provide a valuable indicator of Mediterranean-sourced waters in the Gulf of Cadiz throughout the Pliocene (Stow et al., 2013). Noteworthy, occurrences of *P. ariminensis*, *S. tubulosa*, *G. subglobosa*, and *A. hirsuta* in the lowermost part of Interval 1 (863–857 mbsf) might indicate a short-term re-connection of the Mediterranean and Atlantic around 5.65 Ma during a period of relatively warm climate and high sea-level. Evidence for such brief episodes of exchange during the early MSC phase is scarce, but indicated by occurrences of marine microfossils in clays intercalated with evaporitic deposits (Wade and Bown, 2006).

Additional support for a relation to Mediterranean-sourced waters comes from the good correspondence of all of the four species with isotopic and Zr/Al records, particularly well-expressed in Interval 2 (Fig. 5). Zr/Al ratio appear as a robust bottom water speed proxy when contourite system is well developed or minor turbidite influence the same site during Late Pleistocene, when the presence of a moat prevent this site from direct turbidite input (Bahr et al., 2014). Conversely, the sensibility of Zr/Al ratio to bottom current speed is not fully tested yet. For this reason, the combination between microfossil and geochemical records appear to be highly complementary in this study for the reconstruction of early MOW.

6. Conclusions

Detailed analyses of benthic foraminifera, grain-size and geochemical data (Zr/Al, $\delta^{18}O$) from IODP Site U1387 allowed the reconstruction of Mediterranean/Atlantic exchange after the opening of the Gibraltar Strait. Foraminiferal composition indicates a eutrophic sea-floor

environment in the late Messinian. Episodic events of high export productivity are common throughout the whole interval being most pronounced in the lower and upper parts. The Miocene/Pliocene boundary has been placed at 826 mbsf depth. An abrupt increase in abundances of benthic foraminifera preferring warm waters and increased bottom current strength occurs just after the MPB, providing the earliest evidence for the influence of Mediterranean waters at the site after the opening of the Gibraltar Strait before the onset of contourite drift deposition. In turn, periods of enhanced bottom current activity inferred from grain size analysis and geochemical proxies suggest the beginning influence of Mediterranean waters at the site. Consequently, the presented multi-proxy records delineate the possible earliest indications of initial Mediterranean/Atlantic exchange after the opening of the Gibraltar Strait and before the onset of contourite drift deposition. The periodic advection of Mediterranean water between ~5.3 and ~5.2 Ma, probably forced by precession, is suggested by parallel cyclical changes in microfossil abundances and geochemical records. A stronger influence of Atlantic-sourced bottom waters is indicated between ~5.2 and 5.0 Ma. Due to the lack of cores of similar age in the Gulf of Cadiz, possible explanations for this change, such as a sinking of Mediterranean-sourced waters to a greater water depth, cannot be verified by the present data set. Grain size data reveal an increase in the frequency of sandy and silty beds at the top of the studied interval. High abundances of shelf dwelling microfossil taxa in the sandy layers relate them to episodic downslope transport of material indicating periods of high instability occurring after the opening of the Gibraltar Strait. *Cibicides lobatulus* and *C. refulgens*, considered indicators of MOW in the Gulf of Cadiz, occur frequently within these sandy layers, warning us about their applicability as bottom current indicators when there is evidence for downslope transport. The identification of more detailed periods of ecological changes in the studied interval not revealed by the geochemical proxies (Zr/Al, stable isotopes) corroborates that benthic foraminifera are excellent proxies for accurate palaeoceanographic reconstructions.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.palaeo.2017.02.009.

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