Levantine intermediate water hydrodynamic and bottom water ventilation in the northern Tyrrhenian Sea over the past 56,000 years: New insights from benthic foraminifera and ostracods

Angue Minto'o C.M. ^{1,*}, Bassetti M.A. ¹, Morigi C. ^{2,3}, Ducassou E. ⁴, Toucanne Samuel ⁵, Jouet Gwenael ⁵, Mulder T. ²

¹ Université de Perpignan Via Domitia, CEFREM, UMR 5110, 52 Avenue Paul Alduy, 66860 Perpignan, France

² Geological Survey of Denmark and Greenland, Department of Stratigraphy, Copenhagen, Denmark

³ Università di Pisa, Dipartimento di Scienze della Terra, Italy

⁴ Université de Bordeaux, UMR 5805 EPOC, Avenue des Facultés, 33405 Talence cedex, France

⁵ IFREMER-Centre Bretagne, Laboratoire Environnements Sédimentaires, F-29280 Plouzané, France

* Corresponding author : C.M. Angue Minto'o, email address : charlie.angue-mintoo@univ-perp.fr

Abstract :

Foraminifera and ostracods have been quantitatively studied in core MD01-2472, from the upper continental slope (at water depth of 501 m), to evaluate their relationship with bottom water condition variability and decipher the control of the Levantine Intermediate Water (LIW) current on benthic faunas. The occurrence of reworked ostracod species (originating from the continental shelf) and, the presence of shallow water Elphidium/Ammonia benthic foraminifera are used to estimate the degree of along-slope transport at the core site. This has revealed two intervals of along-slope transport also associated with coarse-grained contourite deposits, deposited during the YD and HS2 episodes. Planktonic-benthic foraminiferal and ostracod assemblages reflect climate oscillations. Peaks of the polar planktonic Neogloboquadrina pachyderma (left-coiling S) may be used to identify Heinrich Events. Interstadials are marked by abundant ostracod species such as Paracypris sp., Argilloecia acuminata, and Cytheropteron alatum and the presence of benthic foraminifera like Bulimina marginata, Bulimina costata and Gyroidina altiformis. The B-A and Holocene are characterized by abundant warm water species of planktonic foraminifera and by the ostracod species Polycopse sp. We hypothesize that there is relationship between LIW intensification during cold rapid climate events and benthic fauna assemblage variations due to changes in: 1) bottom water ventilation; and 2) the export of nutrients and/or sediment particles by bottom currents.

Keywords : Ostracods, Foraminifera, LIW, Corsica margin

1. Introduction

The last glacial period (71,000 - 14,000 y BP) was marked by climate instability (Bond et al., 1992; Bond et al., 1993; Dansgaard et al., 1993), and by the millennial-scale alternations of cold (stadial) and warm (interstadial) periods, especially during Marine Isotope Stage (MIS) 3 (57,000 - 29,000 y BP) and MIS 2 (29,000 - 14,000 y BP) when the Dansgaard-Oeschger (DO) cycles occurred (Dansgaard et al., 1993; Meese et al., 1997). This sub-orbital climatic variability suggests the rapid coupling of atmospheric-oceanic systems. Previous studies have demonstrated that these rapid climatic oscillations are recorded in continental and marine records in the northern hemisphere, from Asia (Wang and Sarnthein, 1999) to Europe (Sánchez Goñi et al., 2000; Fletcher and Sánchez Goñi, 2008). In the Mediterranean Sea, these millennial-scale cycles induced rapid changes in oceanographic conditions since the sea surface temperature oscillations acted on thermohaline circulation. The link between atmospheric and marine processes has been described by several authors (Sierro et al., 1999; Cacho et al., 2002; Moreno et al., 2005; Cacho et al., 2006; Frigola et al., 2008; Sierro et al., 2009), illustrating how deep-water circulation (i.e. Western Mediterranean Deep Water, WMDW) in the western Mediterranean Sea was very active during DO stadials and Heinrich stadials (HS), and slowed down during interstadials. Similarly, in the Tyrrhenian Sea, Toucanne et al. (2012) have shown, based on sedimentological evidence (sortable silt particle-size data), that during the last glacial period the Levantine Intermediate Water (LIW) variability was strongly forced by climate variability at both Milankovitch and millennial timescales. In the North Atlantic ocean, the strengthening of the Mediterranean Outflow Water (MOW) in the Gulf of Cadiz during northern hemisphere coolings (e.g. during DO stadials and the Younger Dryas, YD, ca 12,000 y BP) is clearly recorded in the contourite deposits (Voelker et al., 2006; Toucanne et al., 2007). These studies confirm the important control of climate forcing on Atlantic-Mediterranean water exchanges on the geological timescale, in addition to North Atlantic hydrology (Rogerson et al., 2012), and LIW, which constitutes up to 80% of the Mediterranean outflow volume (Bryden and Stommel, 1984; Kinder and Parrilla, 1987; Baringer and Price, 1999).

Planktonic foraminifera are the most common source of paleoceanographic proxies, based on fossil assemblages and/or geochemical data (O and C stable isotopes ratio in this work) and are widely used in the Mediterranean (Pérez-Folgado et al., 2003, 2004; Sierro et al., 2009). Benthic microfossils such as foraminifera and ostracods are also good paleoceanographic tools allowing reconstruction of the physical-chemical parameters such as bottom water, oxygen content and organic matter flux (Jorissen, 1999b; Jorissen and Wittling,

1999; Morigi et al., 2001; Gooday, 2003; Schmiedl et al., 2004; Morigi et al., 2005; Fontanier et al., 2008; Alvarez Zarikian et al., 2009; Bassetti et al., 2010; Schmiedl et al., 2010).

The Western Mediterranean is presently characterized by well-oxygenated and oligotrophic conditions, with an organic carbon flux exported to the sea floor that decreases eastwards (Béthoux et al., 1998). The benthic microfaunal distribution is controlled by the carbon flux reaching the sea floor, which depends not only by the surface productivity but also on the intensity of the hydrosedimentary processes that allow the integration of consumable organic matter into the sediment (De Rijk et al., 2000).

At a regional Mediterranean scale, modern benthic foraminiferal distribution is characterized by low diversity deep-water assemblages dominated by species such as *Glomospira charoides*, *Gyroidina orbicularis*, *Gyroidina altiformis*, *Robertinoides translucens*, *Biloculinella* spp., *Anomalinoides minimus*, *Trochammina inflata* and *Rotamorphina involuta* (De Stigter et al., 1998; De Rijk et al., 1999). Nevertheless, species characterizing a low food environment like *G. charoides* and *G. orbicularis* are more abundant in eastern part than the western. The shelf assemblage is more diverse and consists mainly of *Ammonia beccarii*, *Elphidium lidoense*, *Elphidium granosum*, *Textularia pseudogramen*, *Textularia sagittula*, *Bolivina spathulata*, *Bolivina dilatata*, *Cassidulina crassa*, *Cassidulina levigata/carinata*, *Haplophragmoides membranaceum*, *Gavelinopsis praegeri*, *Bigenerina nodosaria*, *Trifarina angulosa* and *Bulimina marginata* (De Rijk et al., 1999; Mojtabid et al., 2009; Milker and Schmiedl, 2012).

The taxonomy of Mediterranean Sea ostracods is well known from previous studies (Bonaduce et al., 1975; Peypouquet and Nachite, 1984; El Hmaidi et al., 1998, 1999, 2010) and their sensitivity to physical and chemical parameters (i.e. salinity, dissolved oxygen, and temperature) allows climate reconstruction on glacial-interglacial timescales, and short-term periods of environmental change (Ciampo, 2004; Bassetti et al., 2010). In modern ostracod assemblages from the Western Mediterranean, the genera *Argilloecia*, *Krithe*, *Bythocypris*, *Henryowella* and *Cytheropteron* dominate settings deeper than 200 m (Peypouquet and Nachite, 1984; El Hmaidi et al., 1999, 2010). Deep-water assemblages often contain reworked fauna from the continental shelf. In fact, allochthonous ostracods are common in deep-water assemblages (Peypouquet, 1979; Peypouquet and Nachite, 1984; Passlow, 1994; Zhou and Zhao, 1999; El Hmaidi et al., 2010) and can be used as an indicator of the intensity of downslope sediment transport (Passlow, 1994).

In this work we use foraminifera and ostracods to interpret the relationship between bottom hydrodynamic conditions, water mass ventilation and benthic microfossil assemblages

in the Corsica Trough (northern Tyrrhenian Sea) over the last 56,000 years. We use benthic microfossils as “bio-indicators” of changing environmental conditions (bottom water oxygenation and organic matter flux and downslope sediment transport), which can be related to variability of the intensity of circulation (Harloff and Mackensen 1997; Schmiedl and Mackensen, 1997; Schmiedl et al., 1997), complementing sedimentological analyses. We use allochthonous ostracods and foraminifera to estimate alongslope sediment transfer from the continental shelf and slope, and its relationship to contour current speed intensity. This method is considered to enhance facies analyses of fine-grained contourites where primarily sedimentary structures are difficult to distinguish and/or to interpret because they might be either highly modified by bioturbation or even absent. It has previously been used to recognize ice rafted debris (HS) and tsunamites (Smedile et al., 2011). Using these analyses, we establish the link between the intensification of LIW and cold climate events.

2. Geologic and oceanographic setting

The Corsica Trough is in the eastern part of the Western Mediterranean Sea (northern Tyrrhenian sea) and is a narrow (10-30 km at the 200 m isobath) and shallow (430 to ca 900 m from the Corsica Channel to the Golo Basin) north-south trending basin, separating the Corsica Shelf from the Tuscany-Elba Shelf and Pianosa Ridge. The east Corsican margin, where core MD01-2472 was retrieved, is a continental shelf region varying from 5 to 10 km in width in the northern part to 25 km in the south, with a steep continental slope incised by numerous canyons at its margin (Fig. 1). The latter drains several small, steep mountain rivers (the Golo River being the longest with a length of 90 km) that transport mainly coarse-grained material toward the deep part of the basin (Calvès et al., 2012).

Hydrographically, the Western Mediterranean is characterized by three main water masses: the surficial Atlantic Water (AW, down to 200 m water depth), entering through the Strait of Gibraltar and flowing eastwards; the LIW (from 200 to 600 - 1000 m water depth) formed in the Levantine Basin (Eastern Mediterranean); and the WMDW (below 600 - 1000 m water depth) generated in the Gulf of Lions. The LIW enters into the Tyrrhenian Sea through the Strait of Sicily where the Coriolis Force deflects it to the east towards the Western Italian margin and then into the Corsica Trough with a northwards component. The LIW shows strong seasonal oscillations and its flow is maximal during winter and early spring. Measurements of modern LIW velocities in the Corsica Trough show that the LIW reaches 0-10 cm/s in summer and autumn, and 10-40 cm/s in winter and spring (Astraldi and Gasparini, 1992; Vignudelli et al., 2000). This seasonal flow velocity is driven by enhanced LIW

production in the Levantine Basin, and export to the Western Mediterranean (from the Ligurian-Provençal Basin to the Strait of Gibraltar) during wintertime (La Violette, 1994; Wu and Haines, 1996; Millot, 1999; Pinardi and Masetti, 2000). The lowering of the Ligurian-Provençal Basin steric level induced by winter heat losses and evaporation during the periodic intrusions of cold and dry northerly winds in the Gulf of Lions (i.e. Mistral, Tramontana) also play a major role in the seasonal change in LIW flow velocity in the Corsica Trough (Astraldi and Gasparini, 1992, 1994; Vignudelli et al., 2000).

3. Materials and methods

The sediments analysed are from core MD01-2472 (42°36.42 N, 009°43.97 E; 29.1 metres long), which was collected at 501 m water depth on the continental slope of the east Corsica margin during the MD124-GEOSCIENCES 2 cruise (2001) on board the R/V Marion Dufresne II (Fig. 1). Only the uppermost 12 m of core MD01-2472 have been studied here.

3.1. Chronostratigraphy

The chronostratigraphic framework of core MD01-2472 is based on $\delta^{18}\text{O}$ isotopes, AMS ^{14}C dates and Ca intensities derived from high-resolution XRF scanning (Toucanne et al., 2012). Five additional AMS ^{14}C dates were included in the present study (see Table 1 for details). The age dates were corrected for a marine reservoir effect of 400 y, except for those from the period 15,000 - 17,000 y BP for which a correction of 800 y was applied (cf. Siani et al., 2001). Radiocarbon ages were calibrated to calendar years using CALIB 6.0.1 and the IntCal09 calibration curve (Reimer et al., 2009).

3.2. Lithological analyses

Magnetic susceptibility data of core MD01-2472 were measured on non-opened core sections at 2 cm intervals using a Geotek Multi-Sensor Core Logger (MSCL). These data were used for identifying lithologic changes at the centimetre scale.

Grain-size analyses were performed at 5 cm intervals (up to 0.5 cm intervals in coarser sequences) on a Malvern laser microgranulometer for a high resolution facies study with no chemical pre-treatment of the bulk sediment. We used both the medium grain size (D50), which is directly represented in the lithologic log, as well as the sortable silt mean size (SS), i.e. the mean of the 10 - 63 μm grain-size range of McCave et al. (1995), as an index of bottom flow speed (McCave and Hall, 2006). The high-resolution grain-size analyses (0.5 cm interval) presented in this paper were carried out on two coarse-grained intervals (2.45-2.55 m

and 5.3-5.4 m) to constrain sedimentary facies. The SS curve is obtained by measuring 10-63 μm percentages with a 5 cm step, which represents a higher resolution than published in Toucanne et al. (2012).

X-ray analyses were obtained with a SCOPIX image-processing tool. This tool is very useful to identify internal sedimentary structures within single beds and to select samples for sedimentological and paleoceanographical studies (Migeon et al., 1999). Five thin-sections (10 cm long) of impregnated sediments selected from well-preserved and representative sedimentary facies (see Zaragosi et al. (2006), for details) were also analysed in order to interpret sedimentary processes at site MD01-2472. Microscopic observations were made using a fully automated LeicaTM DM6000B Digital Microscope.

3.3. Micropaleontological and geochemical analyses

The sediment core was sampled at 10 cm intervals. The bulk sediment was washed through a 63 μm sieve and dried in an oven at 40°C. The analyses of benthic and planktonic foraminifera and ostracods were carried out under a binocular microscope on the >150 μm fraction. Microfossil counting was performed on 102 samples, and relative abundances calculated for each species. All ostracod specimens were handpicked. At least 300 specimens of benthic and planktonic foraminiferal were counted.

Among planktonic foraminifera, we use *Turborotalia quinqueloba*, *Neogloboquadrina pachyderma* left-coiling (S) as cold water indicators and an assemblage with *Globigerinoides ruber alba* and *rosea*, *Globigerinoides sacculifer* (including *Globigerinoides trilobus*), *Globigerinoides tenellus*, *Globigerinella aequilateralis*, *Orbulina universa* to indicate warm water (Bé and Tolderlund, 1971; Blanc et al., 1975; Bé and Hutson, 1977; Hayes et al., 1999).

All benthic foraminiferal taxa were identified and counted in each sample. We interpret the abundance of *Elphidium* spp. and *Ammonia* sp. (benthic foraminifera), typical of shallow-water, as indicators of reworked sediment from the inner shelf. In order to estimate in oxygen content variation, we used the benthic foraminifera assemblage following the method proposed by Schmiedl et al. (2003) using the following formula: $(\text{OH}/(\text{OH}+\text{LO})+\text{Div})\times 0.5$, with OH = relative abundance of high oxygen indicators (*Pyrgo murrhina*, *Pyrgo* sp., *Triloculina* sp., *Sigmoilopsis schlumbergeri*, *Massilina secans*, *Cibicidoides pachyderma*, *Cibicidoides wuellerstorfi*, *Cibicidoides* sp., *Planulina ariminensis*, *Quiqueloculina* sp., *Cycloforina contorta*, *Biloculinella globula*, *Miliolinella* sp.), LO = relative abundance of low oxygen indicators (*Cassidulinoides bradyi*, *Fursenkoina tenuis*, *Bulimina costata*, *Globobulimina affinis*, *Chilostomella* sp.) and Div = normalized benthic foraminifera

diversity. Diversities were normalized relative to the maximum $H(S)$ value. Finally, the term was multiplied by 0.5 in order to distinguish between anoxic (minimum value = 0) and oxic (maximum value = 1) conditions.

Two groups were identified among ostracod assemblages: the autochthonous and allochthonous. Allochthonous elements were characterized by adding the abundance of species living on the continental shelf (*Pontocythere elongata*, *Heterocythereis albomaculata*, *Xestoleberis* sp., *Paradoxostoma* sp., *Semicytherura* sp., *Loxoconcha levis*, *Carinocythereis* sp., *Hemicytherura videns*, *Hiltermanicythere turbida*, *Pseudocytherura calcarata*, *Costa* sp., *Aurila* sp., *Callistocythere* sp.) (Bonaduce et al., 1975; Carbonel, 1980; Ruiz et al., 1997; Hajjaji et al., 1998; Abad et al., 2005; El Hmaidi et al., 2010; Nachite et al., 2010). The autochthonous group is represented by the upper neritic and bathyal species, considered as *in situ* and not affected by transport.

R-mode Hierarchical Cluster Analysis was performed on the data set, using the PAST (PALEontology STatistic) Program of Hammer et al. (2001). We used Ward's distance matrix for ostracod and benthic foraminifera species. Of the 77 species of benthic foraminiferal and 51 ostracods species (see appendices A and B) identified, only 17 benthic foraminiferal species and 19 ostracod species (which accounted for more than 5% of the assemblage in at least one sample) were retained in this cluster analysis. The Shannon diversity index $H(S)$ was also determined by PAST software.

Stable isotope (O and C) measurements were carried out on core MD01-2472 with an average time resolution of ca. 500 y over the records (Toucanne et al., 2012). Analyses were performed using 3 to 10 specimens of planktonic foraminifera *Globigerina bulloides* and shallow infauna benthic foraminifera *Uvigerina peregrina* from the >150 μm size fraction. The low abundance of *Uvigerina peregrina* in the uppermost 2 m of the core (i.e. interglacial deposits) prevented measurements of stable isotopes for this species. As a result, *Uvigerina mediterranea* was used to replace *Uvigerina peregrina* for the upper part of core MD01-2472. Isotope analyses were conducted at the University of Bordeaux (UMR CNRS 5805 EPOC) using an Optima Micromass. The external reproducibility for standards on this mass spectrometer is $\pm 0.03\text{‰}$ (1 sigma) per mil for $\delta^{13}\text{C}$ measurements, and $\pm 0.03\text{‰}$ (1 sigma) per mil for $\delta^{18}\text{O}$ measurements. A correction factor of -0.25‰ for $\delta^{18}\text{O}$ and of -1.00‰ for $\delta^{13}\text{C}$ was applied to the isotope results from *Uvigerina mediterranea* to account for the relatively constant offset (i.e. vital and habitat preferences) which is generally recorded between both taxa (e.g. Schmiedl et al., 2004; Fontanier et al., 2006).

4. Results

4.1. Chronostratigraphy

The 12 uppermost metres of core MD01-2472 covers an interval of ca 56,000 y BP, i.e. MIS 3, MIS 2 and MIS 1, and includes the last glacial period and the HS (MIS 3 and 2), the glacial-interglacial transition (Termination I) and the present-day interglacial period (MIS 1, Holocene) (Toucanne et al., 2012) as shown in Table 2. Sedimentation rates of the uppermost 12 m range between 17 and 32 cm kyr⁻¹, with an average value of ca 22 cm kyr⁻¹.

4.2. Sedimentological features

Sedimentological analyses of core MD01-2472 reveals coarse-grained units, which are associated with a distinct change in the nature and distribution of sediments and sedimentary structures. These coarse-grained units are more pronounced during H2 and YD intervals (Figs. 2 and 3). The typical vertical succession includes (1) irregular negative grading, then positive grading in the sortable silt curve with a sandy silt bed at maximum grain size, (2) several sharp, gradational bioturbated sedimentary contacts, and (3) changes in bioturbation types (pyritized filaments in ‘normal beds’ and *Planolites*, *Zoophycos* and *Thalassinoides* in coarser-graded units, named ‘mottled’ units). The succession of grain-size modal curves shows poor to moderate sorting with a low negative skew (i.e. both coarse and fine tails; cf. Rivière, 1977). This relatively large fine tail is found even in the middle of the thicker units, which suggests that it is not only due to bioturbation but has a dynamic origin. The series of negative and positive grading is also evident on the modal curves. Alternations of moderately good and poor sorting are typically related to bioturbation and burrowing. Bioturbated facies are visible in X-ray images and thin sections, and appear as irregularly mottled silt, sand and mud (lithologies arranged in pockets, lenses and streaks, Fig. 3). All these features typify fine-grained contourites as defined by Gonthier et al. (1984) and Stow et al. (1996). Coarsening-upward profiles are characteristic of gradually increasing bottom current speed (along-slope transfer). Such fluctuations are progressive (due to long-term variations in currents) but may have occasionally been sudden as shown by sharp contacts, related to current instability and velocity pulsation (McCave and Hall, 2006). This sequence coincides with the gradual increase and gradual decrease of reworked microfossils found in the studied core section (plots in Figs. 2 and 3).

4.3. Microfaunal assemblages evolution since 56,000 years BP

Cluster analyses of the microfossil assemblages reveals three benthic foraminiferal and two ostracod clusters. These clusters can be subdivided into subclusters (Figs. 4 and 5). The cumulative plots of each sub-cluster are shown in Figs. 6 and 7. We describe these sub-clusters as well as planktonic foraminifera distributions (Fig. 8) in stratigraphic order from MIS3 to MIS1.

The MIS 3 and MIS 2 (between 12 m and 3.2 m in core MD01-2472) are characterized by rapid alternation in relative abundances of all clusters (benthic foraminifera and ostracods). In these two intervals, the most common benthic foraminifera are species belong to clusters 3a (*Hyalinea balthica* and *Bolivina spathulata*), 3b (*Bulimina marginata*, *Bolivina costata* and *G. altiformis*) and 3c (*C. wuellerstorfi*, *C. carinata*, *T. angulosa*, *Cibicidoides pachyderma*, *Hoeglundina elegans*, and *Quinqueloculina* sp.) (Fig. 6). Ostracod assemblages equally allowed a good characterization of periods associated to MIS 3-MIS 2 and MIS 1. Elements belonging to clusters A2 (*Bathocythere vanstraateni*, *Macrocypris* sp.), A3 (*Aurila* sp., *Callistocythere* sp., and *Hemicytherura videns*), B3 (*Semicytherura* sp., *Xestoleberis* sp, *Paradoxostoma* sp. and *Loxoconcha levis*) and B4 (*Echinocythereis echinata* and *Krithe* spp.) are abundant (up to 13, 25, 50 and 60%, respectively) during MIS 2 and MIS 3 whereas *Polycope* sp. is rare (<5%) and inversely.

MIS 3 and MIS 2 are punctuated by H1-H5 events and short stadials and interstadials (Is in the figures). This climatic pattern is reflected in the highly variable abundances of all foraminifera and ostracods groups. Highest abundance of the polar species *N. pachyderma* S (Fig. 8) is observed in the HS. Allochthonous species (ostracods and benthic foraminifera) and ostracod species of clusters A3, B3 and B4 show maxima corresponding to HS and stadials. Peaks of ostracod species belonging to clusters B2, B1 and benthic foraminifera of cluster 3b correspond to the Is, as calibrated by the ^{14}C dates. Warm water planktonic taxa do not exhibit consistent maxima during DO interstadials and *T. quinqueloba* species decrease in abundance in each Is phases. $\delta^{18}\text{O}_{G. bulloides}$ values are >3‰ all along the MIS 3-MIS 2 interval.

The MIS 2 interval includes Last Glacial Maximum (LGM) period when *C. wuellerstorfi* gradually decreases in abundance associated with and an increase of species belonging to cluster 3a and cluster 3b, (Figs. 6 and 9). Among the ostracods, species of cluster A2 and B4 are typically abundant during this period of LGM, between 23,000 and 18,000 y BP. (Fig. 7). The planktonic foraminifera *T. quinqueloba* is at its maximum abundance peaks (up to 60%), during the LGM period.

Termination I (between 3.2 m and 2 m in core MD01-2472) is marked by high assemblage variability. Marked increases in the ostracod of *Polycope* sp. (38%) and warm planktonic foraminifera occur during the B-A, whereas they markedly decrease in abundance during the YD (Figs. 7 and 8). The B-A interval is typified by ostracods of Cluster A1 and of cluster B2 (*Henryhowella* sp., *Pseudocythere caudata* and *Paracypris* sp.), representing a marked increase in abundance (12% and 50%, respectively) during this period (Fig. 7). Allochthonous ostracods and *Elphidium-Ammonia*, magnetic susceptibility and sortable silt maximum values show maxima during the YD (Fig. 10). *Krithe* spp. and *C. wuellerstorfi* abundance also decreases in B-A event and increases during YD (Fig. 9).

MIS 1 (between 2 m and 0 m in core MD01-2472) corresponds to $\delta^{18}\text{O}$ values of 1 - 2‰ $\delta^{18}\text{O}_{G. bulloides}$. In this interval, the well-represented species are benthic foraminifera belonging to cluster 1 (*Uvigerina mediterranea* and *Melonis barleeanus*, ca 50%), ostracod species part of cluster A1 (*Monoceratina mediterranea*, *Bythocypris* sp., up to 12%) and benthic foraminifera of cluster 2 (*Pseudoclavulina crustata*, *Chilostomella* sp., *B. nodosaria*; ranging from 5 to 15%) (Figs. 6 and 7). During MIS 1, planktonic foraminifera *T. quinqueloba* and *N. pachyderma* are rare (Fig. 8), allochthonous elements (ostracods and foraminifera, Fig. 10) and ostracods of cluster B4, decrease markedly in abundance. Warm water planktonic foraminifera and *Polycope* sp. increase to 60 and 70% respectively in this interval (Figs. 7 and 8).

On Shannon index (H) plots (ostracods and benthic foraminifera) the boundary between MIS 2 and MIS 1 is marked by a decrease in the microfaunal diversity (in benthic foraminifera and ostracod assemblages; Fig. 9).

The ecological significance of planktonic-benthic foraminifera and ostracods is listed in appendix C.

5. Discussion: Hydrodynamic conditions and water mass ventilation over the last 56,000 years

5.1. Greenland stadials/interstadials and LGM during MIS 3 and MIS 2

The climate in the Western Mediterranean during stadials and HS, was characterized by relatively arid conditions as suggested by pollen reconstructions from marine and continental cores (Nebout et al., 2002; Sánchez Goñi et al., 2002, 2008). High aridity was mainly linked to the vigorous north-westerly winds that formed over the north-western

Mediterranean due to a strong atmospheric pressure gradient in the North Atlantic (Ganopolski and Rahmstorf, 2001). Previous studies (Moreno et al., 2005; Sierro et al., 2005; Cacho et al., 2006; Frigola et al., 2008) have proposed a model of millennial scale variability for WMDW formation in the westernmost Mediterranean area (*i.e.* Alboran Sea) consisting in a stadial stimulation of deep ventilation produced by the reinforcement of north-westerly winds. Cold surface temperature and high salinities are thought to have affected intermediate and deep ocean convection by accelerating the vertical mixing that resulted in the intensification of bottom currents and weak water mass stratification (Rohling et al., 1998).

In the studied core, HS can readily be identified by maxima of polar planktonic foraminifera *N. pachyderma* S (except H3, Fig. 8). There is a good correlation between the *C. wuellerstorfi*, *Krithe* spp. abundance (two benthic species indicator of oxygenated conditions; see appendix C) and the O₂ index occurs during stadial intervals and HS (Fig. 9) suggesting enhanced bottom water oxygenation in the Corsica Trough during this time. *Krithe* spp. are more abundant during cold periods in the Atlantic Ocean (Cronin et al., 1996) and in the Mediterranean Sea (Bassetti et al., 2010). The genus *Krithe* is a common component of global deep-sea ostracod assemblages (Dingle and Lord, 1990). We suggest that increases in *Krithe* spp. abundance in core MD01-2472 during stadials and HS reflects enhanced bottom oxygenation, associated with a lowering of bottom water temperature, also suggested by benthic oxygen isotope ratios (Toucanne et al., 2012).

The results from grain-size analyses in this work have greatly increased the resolution of the data obtained by Toucanne et al. (2012). The sortable silt record of core MD01-2472 reveals 2-4 μm positive shifts during stadials and HS (Fig. 10). In detail, in terms of lithofacies, the sedimentary sequences during H2 (Fig. 2), are composed of muddy and silty mottled facies forming coarsening-up and fining-up units, interpreted to be contourite deposits (Gonthier et al., 1984; Stow et al., 1986). Increases in bottom current intensity in the Corsica Trough during cold intervals (Toucanne et al., 2012) caused increased oxygenation. Enhanced bottom ventilation is corroborated by the increase of benthic $\delta^{13}\text{C}$ observed in the studied core (Fig. 9). Bioturbation by *Planolites* and *Thalassinoides* typically occurred during the cold phases (Fig. 2) associated with coarse sediment with low total organic carbon (TOC) and high energy hydrodynamic conditions (Löwemark et al., 2004). These intervals contain *Trifarina angulosa*, a taxon that may be a good indicator of strong bottom current (Mackensen et al., 1993; Harloff and Mackensen, 1997) and common reworked shallow water benthic foraminifera. Allochthonous ostracods (species of cluster A3 and of clusters B3, Fig. 7) from the continental shelf and the upper slope are also present associated with evidence for

winnowing of fine particles and contourite deposition in the studied area (Toucanne et al., 2012) suggesting transport by vigorous LIW at site MD01-2472 during stadials and HS.

In contrast, allochthonous specimens at site MD01-2472 during Is is relatively rare (<1% for *Elphidium/Ammonia* group, <20% for allochthonous ostracods, Fig. 10) suggesting minor sediment transfer from the shelf and along the slope at this time. The benthic $\delta^{13}\text{C}_{\text{U. peregrina}}$ records show the lowest values during Is (Fig. 9), which may be linked to higher bottom-water residence times associated with decreased LIW ventilation. Moreover, *T. quinqueloba* is relatively rare during Is suggesting a weak surface productivity (Parker, 1971; Hemleben et al., 1989; Kroon, 1991; Johannessen et al., 1994; Rasmussen et al., 2003).

The highly variable benthic $\delta^{13}\text{C}$ values during warm phases of the last glacial period are difficult to interpret. The values may be related to longer bottom-water residence times in the Corsica Trough during interstadials (i.e. high $\delta^{13}\text{C}$ values, >0.5‰) since they correlate to intervals with low O_2 indices (<0.8, Fig. 9) and weak surface productivity (Fig. 8). In addition, this hypothesis is supported by maxima of ostracod clusters B1 and B2 (Fig. 7), including *Paracypris* sp. and *Argilloecia acuminata*, species adapted to poorly oxygenated environments (Cronin, 1983; Andreu, 1992; Alvarez Zarikian et al., 2009). Benthic foraminifera of cluster 3b (*B. marginata*, *B. costata* and *G. altiformis*) also increase in abundance during Is (Fig. 6) suggesting reduced oxygenation. Pyritized filaments are the most common bioturbation types in fine grained sediment during interstadials (Fig. 2), associated with high TOC (Löwemark et al., 2004) suggesting a slight decrease in LIW ventilation and lower bottom water oxygenation in the Corsica Trough during Is.

The highest abundance of *T. quinqueloba*, a taxon related to high surface primary productivity and cold sea surface temperatures, is observed in the LGM associated with an increase of benthic species of clusters 3a-3b (benthic foraminifera, Fig. 6) and clusters A2-B4 (ostracods, Fig. 7). This indicates a rapid response of benthic fauna to nutrient enhancement linked to the surface productivity. It may also explain the reduction in O_2 index values, due to organic matter degradation. However, Schmiedl et al. (2003) interpret O_2 index values between 0.9 and 0.7 to indicate well-oxygenated waters. Thus, the sea floor was well ventilated during the LGM period in Corsica Trough. Similarly, Abu-Zied et al. (2008) used on benthic foraminifera in the Eastern Mediterranean to interpret well ventilated bottom waters during LGM times, Di Donato et al. (2009) also interpret oxic sea floor conditions in the Gulf of Salerno (southern Tyrrhenian Sea).

Allochthonous species (foraminifera and ostracods) were rare during the LGM period and any evident grain-size increase is observed in the sediment interval corresponding to the LGM (Fig. 10). It is possible that bottom flow intensity may not have been strong enough to carry heavier sediment particles in suspension or that the LIW axis was deeper, thus controlling sediment transport mainly in the deep Golo Basin, as shown by Toucanne et al. (2012) in core MD01-2434. Moreover, the LGM period is marked by sea level drop (-120 /- 130 m under the actual level in Tyrrhenian Sea, Lambeck et al., 2011). The Mediterranean ocean climate modeling made by Mikolajewicz (2011) during this period, shows a strongest cooling in summer in the northwestern Mediterranean and weak cooling in the Levantine basin with a weak LIW formation. Thus, this decrease of LIW formation associated to the sea level fall could have conduct to the diminution of LIW velocity and can explain the absence of allochthonous species and negligible grain-size increase in Golo Basin during this period.

5. 2. Termination I

Termination I includes the B-A and the YD events. Similar to other paleoclimatic studies in the Tyrrhenian Sea (e.g. Paterne et al., 1999 among others), a marked increase of warm water planktonic assemblages at the end of the last glacial period coincides with the B-A period (Fig. 8), while cold water planktonic assemblages characterise the YD period. Peaks in abundance of *Paracypris* sp. and *Polycope* sp. (Fig. 7) suggest reduced dissolved oxygen during the B-A at the water-sediment interface, coinciding with reduced of *Krithe* spp. and *C. wuellerstorfi* abundance (Fig. 9) in the B-A, and a lower O₂ index (Fig. 9) that suggests slightly under-oxygenated conditions. In contrast *Krithe* spp. and *C. wuellerstorfi* become common during the YD interval, associated abundant allochthonous ostracods (Fig. 10) and reworked benthic foraminifera (*Elphidium/Ammonia* group, Fig. 10).

Marked changes in facies occurred during the YD period, with the deposition of a 0.75-metre-thick silty unit at site MD01-2472 (Fig. 3). The sediment facies characterized by a coarseaning followed by fining upward with no evidence of basal erosion (Fig. 3) suggest that these features are not turbidites. These sediments are interpreted as contourites and related to episodes of bottom current reinforcement. We suggest enhanced LIW ventilation during the YD event was forced by rapid climatic changes in the Mediterranean, during cold and dry conditions (Kotthoff et al., 2008; Combourieu-Nebout et al., 2009).

Any significant sea-level fall has been described for the YD along the Italian coast (Lambeck et al., 2011), but evidence of a global sea-level rise deceleration has been observed before the Holocene (Bard et al, 2010). On the other hand and at the local scale, Caruso et al.

(2011) present evidence of a possible sea-level variation in the northern part of the Sicilian coast between 12 and 14 ka that culminates during the YD. The latter hypothesis must be verified and supported by regional evidence, but either a relative sea-level fall of small amplitude or a deceleration of the sea level rise, together with a significant reinforcement of the LIW velocity could have played a major role in the reworking of benthic species from the inner shelf and contribute in the formation of the YD contourite in the East Corsica continental slope.

5. 3. Holocene (MIS 1)

The relationship between Holocene climate variability in the Western Mediterranean and Atlantic climate is not well established, since marine sediment records with high sedimentation rates are rare (Rohling and Gieskes, 1989; Rohling and De Rijk, 1999; Rohling et al., 2002; Mayewski et al., 2004; Combourieu-Nebout et al., 2013; Magny et al., 2013; Sadori et al., 2013; Sicre et al., 2013). Recent works analyses of deep-water contourite drifts in the western Mediterranean (Frigola et al., 2007; Melki et al., 2009) highlight the effects of Holocene climate variability on Mediterranean thermohaline circulation. In particular, geochemical and sedimentological proxies suggest global deep-water circulation slowed during the early Holocene (11,700 y - 10,500 y BP) due to the combined effect of rising sea-level and relatively humid climate conditions on land (Peyron et al., 2012). Between 10,500 y and 7,000 y BP the deep-water circulation strengthened until the end of the rapid sea-level rise, followed by a gradual weakening of circulation (to modern times) related to the stability of atmospheric conditions (Frigola et al., 2007).

In core MD01-2472, we do not have sufficient resolution to identify rapid climatic events. Nevertheless, we focus on the long-term patterns can be interpreted from the microfauna assemblages. The high abundance of warm water planktonic species in the Holocene interval (up to 60%, Fig. 8) is related to the increase of atmospheric and sea surface temperature during the last interglacial onset as shown by the planktonic $\delta^{18}\text{O}$ values in the Corsica Trough. *Polycope* ostracod species reach a maximum abundance during the Holocene (varying from 20 to 70%, Fig. 7) suggesting low current velocities and lower bottom water oxygenation (Cronin et al., 1995). The decrease of allochthonous species (ostracods of cluster A3, benthic foraminifera of clusters 3c) and low SS and magnetic susceptibility (Fig. 10) may be due to a reduction in bedload transport in low-energy bottom water conditions. *Krithe* spp. are rare in this interval, suggesting either a lowering in dissolved oxygen content or a decrease in the nutrient flux reaching the upper slope. The rarity of *T. quinqueloba* in the Holocene

period (Fig. 8) weak surface primary productivity (Rasmussen et al., 2003) and the increase of *U. mediterranea* and *M. barleeanus* (Cluster 1, 50%, Fig. 6) indicates overall bottom oligo-mesotrophic sea floor conditions (Fontanier et al., 2003).

6. Conclusions

We have used microfossils in a deep sea core (MD01-2472) to reconstruct a 56,000 year record of bottom water trophic variability and LIW circulation change in the Corsica Trough, northwestern Tyrrhenian Sea. Analyses of planktonic and benthic foraminiferal and as well as ostracods assemblages reveal strong bottom water environmental variability over the last 56,000 years. Intervals with *Krithe* spp. (ostracod), *C. wuellerstorfi* (benthic foraminifera) indicate bottom water oxygenation during stadials (MIS 3 and MIS 2), whereas interstadials are typified by *A. acuminata* and *Paracypris* sp (ostracods) indicating poorly oxygenated environments. The LGM is dominated by *T. quinqueloba* that suggesting high surface primary productivity associated with the establishment of meso-eutrophic bottom conditions. During the Holocene, microfaunal assemblages indicate oligo-mesotrophic bottom conditions and low-energy bottom conditions. Considering the present-day hydrological structure in the Corsica Trough, our data reveal that intensified LIW inflow and ventilation during the last glacial interval (particularly during by Greenland stadials) followed by weaker LIW ventilation during the Holocene.

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Fig. 1 - Angue Minto'o et al.

Figure 1:

A. Bathymetry of the Golo margin and location of core MD01-2472. Black arrows indicate the main path of the LIW (Levantine Intermediate Water) in East Corsica basin. The grey arrows show the general distribution of sedimentary supplies in the basin. **B.** General circulation of the LIW in Mediterranean Sea from Levantine basin to Strait of Gibraltar.

Fig. 2 - Angue Minto'o et al.

Figure 2:

Detail of sedimentary sequence corresponding to the H2. From left to right: X-ray image, interpretative drawing with bioturbation and sedimentary contacts, lithological log with D50 as indicated grain size, radiocarbon dates (y cal. BP) indicated with black arrows, sortable silt, allochthonous ostracod species and *Neogloboquadrina pachyderma* S percentage curves, indurated thin sections between 515 and 540 cm with its interpretative drawing and grain-size histograms related to thin sections.

Fig. 3 - Angue Minto'o et al.

Figure 3: Detail of the YD sequence. From left to right : X-ray image, interpretative drawing with bioturbation and sedimentary contacts, lithological log with D50 as indicated grain size, radiocarbon dates (y cal. BP) indicated with black arrows, sortable silt, allochthonous ostracod species and *Neogloboquadrina pachyderma* S percentage curves, indurated thin sections between 231 and 267 cm with its interpretative drawing and grain-size histograms related to thin sections.

Fig. 4 - Angue Minto'o et al.

Figure 4:

Dendrogram of benthic foraminifera resulting from R-mode cluster analysis, using Ward's distance. Three main clusters are recognized. Cluster 3 is subdivided into three sub-clusters (3a, 3b and 3c).

Fig. 5- Angue Minto'o et al.

Figure 5:

Dendrogram of ostracods resulting from R-mode cluster analysis, using Ward's distance. Two main clusters are recognized and are subdivided into seven sub-clusters (A1, A2, A3, B1, B2, B3 and B4). *Polycope* sp. shows very low correlation with all the other species and it cannot be associated to any of clusters.

Fig. 6 - Angue Minto'o et al.

Figure 6:

The cumulative plots of benthic foraminifera from cluster analysis. Curves show microfauna distribution along the core according to age. MIS 3 and MIS 2 periods are characterized by benthic foraminifera of cluster 3a (*Bolivina spathulata*, *Hyalinea balthica*), 3b (*Bulimina marginata*, *Gyroidina altiformis* and *Bulimina costata*) and 3c (*Quinqueloculina* sp., *Cibicidoides wuellerstorfi*, *Cibicidoides pachyderma*, *Cassidulina carinata*, *Trifarina angulosa* and *Hoeglundina elegans*). MIS 1 is characterized by *Melonis barleeanus*, *Uvigerina mediterranea* (cluster 1) and *Chilostomella* sp., *Textularia* sp., *Bigenerina nodosaria*, *Pseudoclavulina crustata* (cluster 2).

Fig. 7- Angue Minto'o et al.

Figure 7:

The cumulative plots of ostracods from cluster analysis. Curves show microfauna distribution along the core according to age. MIS 3 and MIS 2 periods are characterized by ostracods of cluster A2 (*Macrocypris* sp., *Bathocythere vanstraateni*), Cluster A3 (*Callistocythere* sp., *Aurila* sp., *Hemicytherura videns*), cluster B3 (*Paradoxostoma* sp., *Semicytherura* sp. *Xestoleberis* sp. and *Loxoconcha levis*) and cluster B4 (*Krithe* spp. and *Echinocythereis echinata*). MIS 1 is characterised by species such as *Monoceratina mediterranea*, *Bythocypris* sp. (Cluster A1) and by *Polycope* sp.. The B-A interval is well characterised by species of cluster B2: *Henryhowella* sp., *Paracypris* sp., and *Pseudocythere caudata*.

Fig. 8 - Angue Minto'o et al.

Figure 8:

Stratigraphy of core MD01-2472, from left to right: lithological log with D50 as indicated grain size, benthic and planktonic $\delta^{18}\text{O}$ curves, radiocarbon dates (yr cal. BP) indicated by black arrows and distributions curves of warm planktonic foraminifera, *Turborotalia quinqueloba* and *Neogloboquadrina pachyderma* S. Rapid climate oscillations identified in core MD01-2472 are: YD (Younger Dryas), BA (Bolling-Allerød), H1 to H5 (Heinrich event 1 to 5), Is (Greenland interstadial).

Fig. 9 - Angue Minto'o et al.

Figure 9:

Alongcore variation according to age of: $\delta^{13}\text{C}$ ratios measured on benthic foraminifera *U. mediterranea* and *U. peregrina*; *Krithë* spp. (ostracods) and *C. wuellerstorfi* (benthic foraminifera) relative abundance; O_2 index (calculated using the formula proposed by Schmiedl et al., 2003); Shannon index (H) of benthic foraminifera and ostracods.

Fig. 10 - Angue Minto'o et al.

Figure 10:

D50, magnetic susceptibility and sortable silt (SS) values correlated with allochthonous ostracods species (*Pontocythere elongata*, *Heterocythereis albomaculata*, *Xestoleberis* sp., *Paradoxostoma* sp., *Semicytherura* sp., *Loxoconcha levis*, *Carinocythereis* sp., *Hemicytherura videns*, *Hiltermanicythere turbida*, *Pseudocytherura calcarata*, *Costa* sp., *Aurila* sp., *Callistocythere* sp.) and *Elphidium/Ammonia* spp. To be notice the good correlation between the magnetic susceptibility, allochthonous ostracods and *Elphidium/Ammonia* spp. (reworked foraminifera) curves. Abundance peaks of allochthonous ostracods and *Elphidium/Ammonia* spp. curve correspond to HS (cold phases).

Depth (cm)	Material	Lab code	Corrected ^{14}C age (yr BP)	Cal BP age ranges (2σ)	Cal BP age median probability	Data origin
5	bulk planktic	SacA19752	910 ± 30	760-916	842	Toucanne et al., 2012
70	bulk planktic	SacA19754	3645 ± 30	3,875-4,009	3,960	Toucanne et al., 2012
180	bulk planktic	SacA19756	9100 ± 35	10,196-10,298	10,244	Toucanne et al., 2012
200	bulk planktic	SacA19756	10170 ± 35	11,712-12,026	11,875	this study
220	bulk planktic	SacA19757	$10,240 \pm 40$	11,812-12,121	11,990	Toucanne et al., 2012
290	bulk planktic	SacA19753	$11,790 \pm 50$	13,453-13,786	13,641	Toucanne et al., 2012
320	bulk planktic	SacA19753	$12,510 \pm 40$	14,224-15,070	14,684	this study
380*	bulk planktic	SacA19758	$13,720 \pm 45^*$	16,692-17,018	16,850*	Toucanne et al., 2012
410	bulk planktic	SacA19753	$15,870 \pm 50$	18,828-19,345	19,091	this study
500	bulk planktic	SacA19753	$19,090 \pm 70$	22,396-23,034	22,751	this study
580	bulk planktic	SacA19755	21230 ± 140	24,962-25,867	25,367	Toucanne et al., 2012
600	bulk planktic	SacA19760	22380 ± 100	26,558-27,716	27,063	Toucanne et al., 2012
700	bulk planktic	SacA19753	$27,860 \pm 150$	31,493-32,610	31,948	this study

Table 1:

Radiocarbon ages of core MD01-2472. The dates were corrected for a marine reservoir effect of 400 y, except for the period 15,000-17,000 y BP (marked by an asterisk) to which a correction of 800 y was applied (cf. Siani et al., 2001). Radiocarbon ages were calibrated to calendar years using CALIB 6.0.1 and the IntCal09 calibration curve (Reimer et al., 2009).

Depth(cm)	Events	Proxy
265- 320	Is1	^{14}C
320 – 375	H1	$\delta^{18}\text{O}^*$
520 - 540	Is2	^{14}C
540- 580	H2	$\delta^{18}\text{O}^*$
580 – 605	Is3	^{14}C
645 – 665	Is4	^{14}C
665 – 700	H3	$\delta^{18}\text{O}^*$
700 – 725	Is5	^{14}C
735 – 745	Is6	^{14}C
760 – 785	Is7	^{14}C
820 – 855	Is8	^{14}C
855- 890	H4	$\delta^{18}\text{O}^*$
890 – 910	Is9	^{14}C
915 – 935	Is10	^{14}C
950 – 980	Is11	^{14}C
1010 – 1055	Is12	^{14}C
1055 – 1100	H5	$\delta^{18}\text{O}^*$
1100 – 1140	Is13	^{14}C
1155 – 1200	Is14	^{14}C

616

617 **Table 2:**

618 Rapid climatic oscillations identified on core MD01-2472 and corresponding depth. A
619 correlation between isotopic curves (NGRIP-IceCore event, MD-72core-*Globigerina*
620 *bulloides*, MD-72core-*Uvigerina peregrina*) and ^{14}C data have permitted the characterization
621 of these events on core MD01-2472.

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Appendix A: Taxonomy list of benthic foraminifers identified in core MD01-2472

<i>Ammonia</i> sp.	
<i>Ammonia ammoniformis</i>	
<i>Ammonia beccarii</i>	<i>Melonis barleeanus</i>
Cushman, 1926; Brönnich, 1772; d'Orbigny, 1846	Williamson 1858
<i>Amphicoryna scalaris</i>	<i>Miliolinella</i> sp.
Batsch, 1791	Wiesner, 1931
<i>Asterigerinata mamilla</i>	<i>Nonion asterizans</i>
Williamson, 1848	Fichtel & Moll, 1798
<i>Bigenenerina nodosaria</i>	<i>Nonionella turgida</i>
d'Orbigny, 1826	Williamson, 1858
<i>Biloculinella globula</i>	<i>Planulina ariminensis</i>
Bornemann, 1855	d'Orbigny, 1826
<i>Bolivina alata</i>	<i>Polymorphinella</i> sp.
Seguenza, 1862	Cushman & Hanzawa, 1936
<i>Bolivina</i> sp.	
<i>Bolivina spathulata</i>	
<i>Bolivina striatula</i>	
<i>Bolivina subaenariensis</i>	<i>Pseudoclavulina crustata</i>
d'Orbigny, 1843; Williamson, 1858; Cushman, 1922	Cushman, 1936
<i>Bulimina acuealta</i>	
<i>Bulimina costata</i>	
<i>Bulimina elegans</i>	
<i>Bulimina elongata</i>	
<i>Bulimina marginata</i>	<i>Pullenia quinqueloba</i>
d'Orbigny, 1826, 1852, 1884	Reuss, 1851
	<i>Pyrgo</i> sp.
<i>Cancris auriculus</i>	<i>Pyrgo murrhina</i>
Fichtel and Moll 1798	Defrance, 1824 ; Schwager 1866
<i>Cassidulina carinata</i>	
<i>Cassidulina minuta</i>	<i>Quinqueloculina</i> sp.
Silvestri, 1896; Cushman, 1933	d'Orbigny, 1826
<i>Cassidulinoides bradyi</i>	<i>Rectobolivina</i> sp.
Norman, 1881	Cushman, 1927
<i>Chilostomella</i> sp.	<i>Rectuvigerina phlegeri</i>
Reuss, 1849	Le Calvez, 1958
<i>Cibicidoides bradyi</i>	
<i>Cibicidoides</i> sp.	
<i>Cibicidoides lobatulus</i>	
<i>Cibicidoides pachyderma</i>	
<i>Cibicidoides wuellerstorfi</i>	<i>Robertina translucens</i>
Walker and Jacob 1798; de Montfort, 1808 ; Schwager	Cushman & Parker, 1936
1866 ; d'Orbigny, 1896; Trauth, 1918 ;	<i>Robulus</i> sp.
<i>Cyclogyra</i> sp.	de Montfort, 1808
Schultze, 1854	
<i>Dentalina</i> sp.	
<i>Dentalina guttifera</i>	<i>Rosalina globularis</i>
d'Orbigny, 1826 ; 1846	d'Orbigny, 1826
<i>Elphidium</i> sp.	
<i>Elphidium aculeatum</i>	
<i>Elphidium complanatum</i>	
<i>Elphidium macellum</i>	<i>Sigmoilina tenuis</i>
Fichtel & Moll, 1798; de Montfort, 1808 ; d'Orbigny,	Czjek, 1848
1846, 1839	
<i>Fissurina</i> sp.	
<i>Fissurina apiculata</i>	
<i>Fissurina cucullata</i>	<i>Sigmoilopsis schlumbergeri</i>
Reuss, 1850 ; Silvestri, 1902 ; Sidebottom, 1912	Silvestri 1904
<i>Fursenkoina complanata</i>	<i>Siphonina reticulata</i>

Egger, 1893
Globulimina affinis
D'Orbigny 1839
Gyroidina altiformis
R.E. & K.C. Stewart, 1930
Hoeglundina elegans
d'Orbigny 1826
Hyalinea balthica
Schröter, 1783
Islandiella islandica
Norvang, 1945
Lagena sp.
Lagena hexagona
Lagena striata
Lagena sulcata

Walker & Boys, 1784; Walker & Jacob, 1798;
d'Orbigny, 1839 ; Williamson, 1848

Lagenosolenia sigmoidella
Cushman & Gray, 1946
Lenticulina sp.
Lamarck, 1804
Massilina secans
d'Orbigny, 1826

Czjzek, 1884
Spiroloculina sp.
d'Orbigny, 1826
Spirophthalmidium sp.
Cushman, 1927
Suggrunda eckisi
Natland, 1950
Textularia sp.
Defrance, 1824
Trifarina angulosa
Williamson, 1858

Triloculina sp.
d'Orbigny, 1826
Uvigerina auberiana
Uvigerina bifurcata
Uvigerina mediterranea
Uvigerina peregrina
Cushman, 1923; Hofker, 1932 ; d'Orbigny, 1839
Valvulineria bradyana
Fornasini, 1900

Appendix B: taxonomy list of ostracods identified in core MD01-2472

<i>Argilloecia acuminata</i> Müller, 1894	<i>Krithe keyi</i> Breman, 1978
<i>Aurila</i> sp. Pokorny, 1955	<i>Krithe pernoidea</i> Bornemann, 1855
<i>Bairdia</i> sp. Mccoy, 1844	<i>Leptocythere</i> sp. Müller, 1927
	<i>Loxoconcha levis</i> <i>Loxoconcha minima</i> <i>Loxoconcha</i> sp. Müller, 1894
<i>Bathocythere vanstraateni</i> Sissingh, 1971	<i>Macropypris</i> sp. Brady, 1868
<i>Bosquetina dentata</i> Müller, 1894	<i>Monoceratina mediterranea</i> Sissingh, 1971
<i>Buntonia</i> sp. Howe & Chambers, 1935	<i>Muellerina</i> sp. Bassiouni, 1965
<i>Bythocypris</i> sp. Brady, 1880	<i>Paracypris</i> sp. Sars, 1866
<i>Bythocythere constricta</i> Sars, 1866	<i>Paradoxostoma</i> sp. Fischer, 1855
<i>Callistocythere</i> sp. Ruggieri, 1953	<i>Parakrithe</i> sp. Bold, 1958
<i>Carinocythereis carinata</i> Roemer, 1838	<i>Pedicythere polita</i> Colalongo & Pasini, 1980
<i>Costa</i> sp. Neviani, 1928	<i>Pedicythere tessellata</i> Bonaduce, Ciampo & Masoli, 1976
<i>Cyprideis</i> sp. Jones, 1856	<i>Phlyctocythere</i> sp. Key, 1958
<i>Cytherella lata</i> Brady, 1880	<i>Polycope</i> sp. Sars, 1866
<i>Cytheropteron alatum</i> Sars, 1866	
<i>Cytheropteron monoceros</i> <i>Cytheropteron zinzulusae</i> Bonaduce, Ciampo & Masoli, 1976	<i>Pontocythere</i> sp. Dubovsky, 1939
<i>Cytheropteron nodosum</i> Brady, 1868	<i>Propontocypris</i> sp. Sylvester-Bradley, 1947
<i>Cytheropteron testudo</i> Sars, 1869	<i>Pseudocythere caudata</i> Sars, 1866
<i>Echinocythereis echinata</i> Sars, 1866	<i>Pseudocytherura calcarata</i> Seguenza, 1880
<i>Eucythere</i> sp. Brady, 1868	<i>Pterygocythereis jonesii</i> Baird, 1850
<i>Hemicytherura videns</i> Müller, 1894	<i>Sagmatocythere</i> sp. Athersuch, 1976
<i>Henryhowella</i> sp. Puri, 1957	<i>Semicytherura</i> sp. Wagner, 1957
<i>Heterocythereis albomaculata</i> Baird, 1838	<i>Thaerocythere</i> sp. Hazel, 1967
<i>Hiltermannicythere turbida</i> Müller, 1894	<i>Urocythereis favosa</i> Roemer, 1838
<i>Krithe</i> sp. Brady in Crosskey & Robertson, 1874	
<i>Krithe compressa</i> Seguenza, 1980	<i>Xestoleberis</i> sp. Sars, 1866

Appendix C: Ecological significance of planktonic/benthic foraminifers and ostracods species

1. Ecological significance of planktonic foraminifers: Neogloboquadrina pachyderma and Turborotalita quinqueloba

- *Neogloboquadrina pachyderma* S: Cold sea surface temperature indicator:

N. pachyderma S indicates the coolest sea surface conditions. It strongly dominates planktonic foraminiferal assemblages in polar areas (Bé and Tolderlund, 1971; Bandy, 1972; Cifelli, 1973) at temperatures below 7 - 9°C (Bé and Tolderlund, 1971; Bé and Hutson, 1977; Reynolds and Thunell, 1986). It has also been found living in seasonal sea ice (Spindler, 1990; Serrano and Guerra-Merchán, 2012). The presence of *N. pachyderma* S in the Mediterranean Sea during the middle Quaternary is thought to be related to the entry of cold waters carrying these forms from the North Atlantic (Sierro et al., 2005; Serrano and Guerra-Merchán, 2012).

- *Turborotalia quinqueloba*: high surface primary productivity indicator:

Turborotalia quinqueloba is a subpolar species that rapidly responds to changes in nutrient supply (Reynolds and Thunell, 1985). It is often related to upwelling or oceanic fronts (Parker, 1971; Hemleben et al., 1989; Kroon, 1991; Johannessen et al., 1994) and thus considered as an indicator of high surface productivity (Rasmussen et al., 2003)

2. Ecological significance of benthic foraminifers

- Cluster 1: *Uvigerina mediterranea* and *Melonis barleeanus*; oligo-mesotrophic bottom conditions

U. mediterranea and *M. barleeanus* appear more abundant during Holocene period (with a percentage up to 50%) than during MIS 2 and MIS3.

U. mediterranea is a shallow infaunal species (Corliss, 1985; Corliss and Emerson, 1990; Gooday, 1994; Jorissen et al., 1998) and is regarded as feeding on labile organic matter in well-oxygenated microhabitats with a low tolerance to dysoxic conditions (Lutze and Coulbourn, 1984; Corliss, 1985; Schmiedl et al., 2000).

M. barleeanus is an intermediate infaunal species that seems to be adapted to the presence of refractory organic matter (Fontanier et al., 2002) and occurs slightly deeper in the sediment in a zone of nitrate reduction (Jorissen et al., 1998).

- Cluster 2: *Bigenerina nodosaria*, *Textularia* sp., *Chilostomella* sp. and *Pseudoclavulina crustata*; oxygenation drop conditions

Cluster 2 shows abundance maxima in MIS 1 and it is composed of the following species:

Chilostomella species are deep infaunal taxon and are commonly found in oxygen-depleted and organically-enriched environments (Bernhard and Sen Gupta, 1999; Jorissen 1999b, Schmiedl et al., 2003). *Bigenerina nodosaria* is found under the same environmental conditions and is typical of intermediate platforms but its extension in bathyal environments can be associated with fine-grained sediment (Alves Martins and Dragao Gomes, 2004).

Textularia sp. is also part of the infauna taxa and is associated with fine-grained sediment (Haunold et al., 1997).

Very little is known concerning the ecological requirements of *Pseudoclavulina crustata*, thus we are not able to relate its occurrence to particular environmental conditions. However, we observe its presence only in MIS 1.

- Cluster 3a: *Hyalinea balthica* and *Bolivina spathulata*; meso-eutrophic bottom conditions

In cluster 3a, *H. balthica* and *B. spathulata* are very abundant (10% to 50%) in MIS 2 and MIS 3 (from 56,000 y to 11,800 y BP) and show a significant decrease in MIS 1 (from 11,800 y to present), as illustrated in Fig 7.

Hyalinea balthica is essentially a neritic and epibathyal species (Parker, 1958) found in several environments. It is recorded in the Atlantic, Pacific, and Indian Oceans, the Gulf of Mexico, and the Caribbean, Barents, North, and Mediterranean Seas. In the modern ocean, *H. balthica* is most abundant in cooler waters of the North Atlantic (van Morkhoven et al., 1986). It has a preference for shallow infaunal microhabitats in the topmost sediment levels, where high densities are found (Fontanier et al., 2002; Hess and Jorissen, 2009). Ross (1984) put in evidence the presence of *H. balthica* in the Sicily Strait both during glacial and interglacial phases, with a considerable decrease in abundance during the Holocene. Morigi et al. (2001) and Abu-Zied et al. (2008) describe *H. balthica* as a component of eutrophic and relatively well-oxygenated water assemblage.

Bolivina spathulata prefers a shallow to intermediate infaunal microhabitat (Corliss, 1991; Barmawidjaja et al., 1992; De Stigter et al., 1998). In the modern Mediterranean Sea, *B. spathulata* is part of a species group that commonly occurs in a wide range of mesotrophic to eutrophic settings (Barmawidjaja et al., 1992; Jorissen et al., 1995; De Stigter et al., 1998; De Rijk et al., 2000; Schmiedl et al., 2000; Mojtahid et al., 2009).

- Cluster 3b: *Bulimina marginata*, *Bulimina costata* and *Gyroidina altiformis*; meso-eutrophic bottom conditions

Bulimina marginata, *B. costata* and *G. altiformis* are abundant from 56,000 to 11,800 y BP: in MIS 2, MIS 3 and Termination I with a percentage reaching 30%. From 11,800 y to recent (MIS 1), they show a diminution of abundance (Fig. 7).

Bulimina marginata is an opportunistic species inhabiting shallow infauna microhabitats with high organic input associated with nutrient-rich waters (Abu-Zied et al., 2008; Frezza and Carboni, 2009).

Jorissen (1999b), considers *B. costata* as one of the most tolerant species to low oxygen content in sediments, but bottom water oxygenation seems not to be the only parameter controlling the abundance of this species. The intensity of organic carbon flux (food) is thought to be responsible for *B. costata* distribution (Schmiedl et al., 1997; Schmiedl et al., 2000; Rogerson et al., 2006).

Gyroidina altiformis is considered as a mesotrophic–oligotrophic benthic foraminifer (De Rijk et al., 2000; Fontanier et al., 2002).

- Cluster 3c: *Cibicidoides wuellerstorfi*, *Cassidulina carinata*, *Quinqueloculina* sp., *Trifarina angulosa*, *Hoeglundina elegans*, *Cibicidoides Pachyderma*; well oxygenated bottom conditions

Cibicidoides wuellerstorfi, *C. carinata*, *T. angulosa*, *C. pachyderma*, *H. elegans*, and *Quinqueloculina* are more abundant in MIS 2 and 3, with a global percentage comprised between 10% and 40%, compared to MIS 1 where they strongly decrease (5-11%; Fig. 7)

Cibicidoides wuellerstorfi is an epifaunal species (Lutze and Thiel, 1989), typical of highly oxygenated environments and a fluctuating input of organic matter. This epifaunal taxon is also able to develop in environment where bottom water oxygenation values indicate hypoxic conditions (Rathburn and Corliss, 1994; Jorissen et al., 2007)

Cassidulina carinata can be considered as opportunistic and is observed in ecosystems with an intermittent supply of organic matter to the sea floor (Abu-Zied et al., 2008; Frezza and Carboni, 2009). Hayward et al. (2002) have shown that *C. carinata* and *T. angulosa* are part of a shallow water association, occurring within coarse substrates under well-oxygenated, high energy regimes and sustained food input.

Trifarina angulosa is a shallow infaunal species (Cacho et al., 2001; Schönfeld, 2001; De Stigter et al., 1998) and occurs in low to moderate abundances from subtidal to middle bathyal depths (Lutze, 1980; Jorissen, 1988). *T. angulosa* is adapted to strong water turbulence of varying intensity and might indicate strong bottom currents (Mackensen et al., 1993; Harloff and Mackensen, 1997).

In the Mediterranean Sea, the distribution of *C. pachyderma* is associated with oligotrophic to mesotrophic and well-ventilated conditions (Schmiedl et al., 2000). It is a bathyal species which often shows a decrease in the Mediterranean during deglacial periods (Alves Martins and Dragao Gomes, 2004).

Hoeglundina elegans has mainly shallow infaunal microhabitat. It is found in well-oxygenated environments (Corliss and Emerson, 1990; Cacho et al., 2001; Schönfeld, 2001; Geslin et al., 2004). In the literature, this species is often described as typical of low organic carbon areas (Lutze and Coulbourn, 1984; Corliss, 1985, 1991; Corliss and Emerson, 1990; Fontanier et al., 2002).

Quinqueloculina sp. is part of the species found in infralittoral zones (Jorissen, 1987; Redois and Debenay, 1999).

3. Ecological significance of ostracods

- Cluster A1: *Monoceratina mediterranea* and *Bythocypris* sp.; bathymetry evolution

Monoceratina mediterranea has been found in recent sediments from the Adriatic Sea at water depths >160 m, (Bonaduce et al., 1975) and its occurrence in core MD01-2472 follows the evolution of the bathymetry in the Holocene. *Bythocypris* sp. has been described in the Mediterranean Sea as inhabiting deep water settings (Bonaduce et al., 1975; Ertekin and Tunoglu, 2008) at depths greater than 200 m. These two species constituting the cluster A1 are more abundant in B-A interval (12%) and MIS 1 (Holocene period, 9%) compared to MIS 2 (2%) and MIS 3 (3%).

- Cluster A2: *Macrocypris* sp. and *Bathocythere vanstraateni*; surface productivity signal

Macrocypris sp. seems to respond to nutrient-rich waters, whereas it preferably inhabits Mg-enriched waters (Cadot et al., 1972; Durazzi, 1977; Wansard, 1999). Its presence might be related to the increasing surface productivity or/and river detrital input (Bassetti et al., 2010). *B. vanstraateni* is a bathyal species requiring cold, nutrient-rich waters and, possibly, a low sedimentation rate (Alvarez Zarikian et al., 2009)

B. vanstraateni, *Macrocypris* sp. are very well represented in MIS 2 and MIS 3. They completely disappear in MIS 1 (Fig. 8).

- Cluster A3: *Callistocythere* sp., *Hemicytherura videns* and *Aurila* sp.; downslope transport signal

Aurila sp. belongs to the infralittoral species and is widely distributed in the Mediterranean and along the coast of north-western Europe (Bonaduce et al., 1975). Abundance of *Aurila* sp. is often related to increased rates of detrital sedimentation (Babinot and Boukli-Hacene, 1998). *Callistocythere* sp. and *H. videns* also indicate the infralittoral zone (Carbonel, 1980; Ruiz et al., 1997; Abad et al., 2005; El Hmaidi et al., 2010; Nachite et al., 2010). In the Mediterranean Sea, *Callistocythere* sp. is often observed in sandy-silt bottoms. Based on the depth (501 m) where the core was taken, this cluster can be use as an indicator of displacement or transport. *Aurila* sp., *Callistocythere* sp. and *H. videns* are well represented in MIS 2 and MIS 3, particularly in Greenland stadials.

- Cluster B1: *Cytheropteron alatum* and *Argilloecia acuminata*; poorly oxygenated conditions

Argilloecia acuminata is a deep-water species found in the eastern and western Mediterranean Sea (Bonaduce et al., 1975; Colalongo and Pasini, 1980; Müller, 1894). The genus *Argilloecia* is known to predominate in organic-rich sediment, and was reported as the most common ostracod living in the oxygen minimum zone of the upper continental slope off southeastern North America (Cronin, 1983). *Argilloecia* is also an important component of the Pliocene (Cronin et al., 1996) and late Pleistocene (Cronin et al., 1999; Didié and Bauch,

2000) assemblages from the Mid-Atlantic Ridge and eastern North Atlantic that represent climatic transitions, especially deglacial periods and stadial-interstadial transitions (Yasuhara et al., 2008). Peaks of *Argilloecia* may indicate low oxygen bottom waters (Alvarez Zarikian et al., 2009). In the Mediterranean Sea, *C. alatum* and *A. acuminata* are found in ostracod assemblages corresponding to the early and late Holocene in the Alboran sea (El Hmaidi et al., 2010). In core MD01-2472, *A. acuminata* and *C. alatum* are found more abundantly during MIS 3, particularly in Greenland interstadials (up to 60%), and decrease during MIS 2. In MIS 1, abundance generally ranges between 20% and 35%, (Fig. 8).

- Cluster B2: *Henryhowella* sp., *Pseudocythere caudata* and *Paracypris* sp.; low energy and low oxygenated environments

Pseudocythere caudata and *Henryhowella* sp. are bathyal species. *Paracypris* sp. and *Henryhowella* sp. are typical of low energy environments (Guernet, 2005). *Paracypris* sp. can tolerate low oxygen content (Andreu, 1992). During the MIS 3, *Paracypris* sp., *P. caudata* and *Henryhowella* sp. present abundance peaks in correspondence with Greenland interstadials (with percentages between 1% and 30%). They greatly increase during Termination I with peak of 50% at 14,300 y BP (B-A period, Fig. 8).

- Cluster B3: *Semicytherura* sp., *Paradoxostoma* sp., *Xestoleberis* sp. and *Loxoconcha levis*; downslope transport signal

Semicytherura sp., *Xestoleberis* sp., *Paradoxostoma* sp. and *L. levis* are species found in infralittoral environments, in the Mediterranean Sea (Bonaduce et al., 1975; Hajjaji et al., 1998). These species are more abundant during MIS 2 and MIS 3 with abundance peaks related to cold phases. However, they decrease during the LGM period and their highest percentage is found during the YD period (53%, Fig 8).

- Cluster B4: *Echinocythereis echinata* and *Krithe* spp.; well-oxygenated conditions

Echinocythereis echinata is well known for characterizing nutrient-rich waters (Didié et al., 2002; Bassetti et al., 2010). *Krithe* spp. are here considered as markers of generally well-oxygenated, cold water environments. Species of *Krithe* have different depth distributions ranging from < 500 to > 5000 m (Rodriguez-Lazaro and Cronin, 1999), but

previous studies have shown that the genus is mainly associated with cold water masses (Cronin et al., 1999; Ayress et al., 2004; Alvarez Zarikian et al., 2009; Bassetti et al., 2010;).

E. echinata and *Krithe* spp. are abundant in MIS 2 and in MIS 3 (Fig. 8). During MIS 1, *Krithe* spp. decrease to <10% (Fig. 9).

Polycope sp.; low current velocities and lower bottom water oxygenation indicator

Polycope sp. is a swimming ostracod, preferring fine-grained, organic-rich sediments and low current velocities, implying low bottom water oxygenation (Benson et al., 1983; Cronin et al., 1995; Alvarez Zarikian et al., 2009). It is the most abundant ostracod species with percentages up to 70% in MIS 1 (Fig. 8). *Polycope* sp. shows a very low correlation with all the other ostracod species and can not be grouped to any of clusters.

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