Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, 2014, n° 36, 27–37. ***e-ISSN : 2458-7184***

Late Quaternary history of the Mediterranean outflow to the southern part of the Gulf of Cadiz, evidence from benthic foraminiferal carbon isotope

Histoire de l'écoulement méditerranéen vers le Sud du Golfe de Cadix au Quaternaire terminal, argument à partir des isotopes du carbone des foraminifères benthiques

Yassine EL FRIHMAT[1*], Dierk HEBBELN[2], EL Bachir JAAIDI[1] & Nadia MHAMMDI[3]

1. *Faculty of Sciences, University Mohammed V of Rabat, Agdal, Rabat, Morocco *(y.elfrihmat@gmail.com).*
2. *Center for Marine Environmental Sciences (MARUM), University of Bremen, Leobener Str., 28359 Bremen, Germany.*
3. *Scientific Institute, University Mohammed V of Rabat, Agdal, Rabat, Morocco.*

Abstract. Five sediment cores taken from the Larache offshore (~ 35°N, 7°W) were investigated in order to determine the water depth draining and the advection strength of the Mediterranean Outflow Water (MOW) to the Atlantic during the last 40 kyrs. The benthic $\delta^{13}C$ records and the gradients generated allowed to register past shifts in the proportions of the MOW during the late Quaternary. The variation through time of the benthic $\delta^{18}O$ values suggests shifts in the salinity and or temperature, this has a direct influence on the water mass density, and therefore on the depth advection of the MOW. Besides, the mean grain-size revealed a significantly stronger advection during the Younger Dryas (YD) and Dansgaard-Oeschger (D-O) stadials.

Keywords : Late Quaternary, Mediterranean Outflow water, benthic foraminifera, grain-size, carbon and oxygen isotopes.

Résumé. Cinq carottes sédimentaires récoltées au large de Larache (~35°N, 7°W) ont été investiguées afin de reconstruire la profondeur et la force d'écoulement des eaux méditerranéennes (MOW) vers l'Atlantique durant les derniers 40 ka. L'étude de la variation des valeurs de l'isotope carbone ($\delta^{13}C$) et des gradients générés ont permis d'enregistrer en fonction du temps les changements de la proportion des eaux méditerranéennes traversant le détroit de Gibraltar. La variation à travers le temps des valeurs de l'isotope oxygène ($\delta^{18}O$) suggère des changements dans la salinité et/ou la température, ceci a une influence directe sur la densité de la masse d'eau, et donc sur la profondeur d'écoulement de la MOW. Par ailleurs, l'analyse granulométrique indique que la vitesse d'écoulement la plus forte a été enregistrée durant le « Younger Dryas » (YD) et les stades Dansgaard-Oeschger (D-O).

Mots-clés : Quaternaire terminal, écoulement d'eaux méditerranéennes, foraminifères benthiques, granulométrie, isotopes ^{13}C et ^{18}O.

INTRODUCTION

The densities difference between the Mediterranean Sea and the Atlantic Ocean implies the exchange of water through the Strait of Gibraltar. Mediterranean Outflow Water (MOW) provides a pronounced high salinity (>38‰) component to the modern hydrography of the Atlantic Ocean (Wust 1936, Worthington 1976, Reid 1981, Lacombe & Richez 1985, Turner 1986, Washburn & Kaese 1987, Ochoa & Bray 1991, Jaaidi, 1993, Price & Yang 1998, Hallberg 2000, Xu *et al.* 2006, Bozec *et al.* 2011). As a result, a plume of warm and saline water mass takes form and builds a layer in intermediate-depth of the Atlantic ocean (e.g., Iorga & Lozier 1999, Johnson & Stevens 2000). This water mass has long been recognized as an important contributor to the heat and salt content of the North Atlantic (Zenk 1975, Reid 1979).

Climatic changes, sea-level and the changing hydraulic control conditions in the Strait of Gibraltar are the main factors, which induced variations of the Mediterranean−Atlantic water-mass exchanges (Béthoux 1984, Bryden & Stommel 1984, Rohling & Gieskes 1989, Rohling & Bryden 1994, Matthiesen & Haines 1998, Myers *et al.* 1998, Matthiesen & Haines 2003). Zahn *et al.* (1987) results reveal an ongoing advection of MOW to the Atlantic during the last 140,000 years B.P. Nevertheless, at a very similar location (core 15666: 34.96°N, 7.12°W, and 803 m depth) to our study area and for different time slices, Sarnthein *et al.* (1994) results show a progressive decrease of the MOW advection from the glacial to the Holocene. In addition and at smaller time scales, the strength of the MOW has fluctuated between periods of enhanced flow and weaker advection rates (e.g. Elant 1985, Jaaidi 1993).

The oscillations in the MOW's intensity occurred in phase with Greenland temperature variations with a stronger outflow during the stadials and lower advection was observed during interstadials: an acceleration of the MOW were recorded during Dansgaard-Oeschger stadials, Heinrich events and the Younger Dryas (Faugères *et al.* 1986, Vergnaud-Grazzini *et al.* 1989, Cacho *et al.* 2000; Sierro *et al.* 2005, Voelker *et al.* 2006; Toucanne *et al.* 2007). During the warm Dansgaard-Oeschger interstadials, the Bølling-Allerød (11−14 ka BP) and the Early Holocene (5−9 ka BP), the meridional carbon isotope gradient indicates a significantly decreased but still active MOW (Thunell *et al.* 1984, Vergnaud Grazzini *et al.* 1986, Zahn *et al.* 1987, Grousset et al. 1988 Schönfeld 2002, Toucanne *et al.* 2007). An additional reduced, but less pronounced, rate of MOW advection occurred at about 50.000 years, this stage is known for particularly strong freshwater runoff from North Africa (Street & Grove 1979). Previous studies focused on the pathway of the MOW to the northeastern Atlantic have shown that this water mass became denser and settled deeper in the water column during the last glacial (Schönfeld & Zahn 2000) and that its flow strength varied on millennial time scales (e.g., Voelker *et al.* 2006).

In addition, the changes in the Mediterranean Outflow Water through the strait of Gibraltar since the Last Glacial Maximum are well recorded in the sediments deposited on the Gulf of Cadiz (Rogerson *et al.* 2006); accordingly, and in order to reconstruct the buoyancy depth and the advection history of the Mediterranean outflow to the southern part of the Gulf of Cadiz (~ 35°N; 7°W) during the late quaternary (~ 40 kyr), five sediment cores were investigated in this study and were retrieved from the Larache continental slope (Fig. 1).

REGIONAL SETTING

Present-day oceanographic circulation in the Gulf of Cadiz is dominated by the exchange of antagonistic currents of water masses between the Atlantic Ocean and the Mediterranean Sea (Ochoa & Bray 1991). The relatively cold Atlantic Inflow Water flows eastward along the Iberian margin partly entering the Mediterranean Sea. It is composed of North Atlantic Surficial Water and North Atlantic Central Water (NACW). The upper-thermocline NACW deepens from about 300 m water depth close to the Strait of Gibraltar to about 600 m in the outer and southern parts of the gulf of Cadiz? (Ochoa & Bray 1991, Mauritzen *et al.* 2001). Below this level, the MOW flows between ~ 500 and 1400 m water depth above the North Atlantic Deep Water (NADW) (Ambar & Howe 1979, Ambar 1983, Ambar *et al.* 1999, Baringer & Price 1999).

The MOW consists of changeable parts of Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW), which contributes an estimated 0.2Sv (Kinder & Parilla 1987, Tomczak & Godfrey 1994) to the 1Sv outflow volume (Kinder & Parilla 1987, Bryden & Stommel 1984). Upon leaving the Strait of Gibraltar, MOW is characterized by increased density sinks to water depths between 800 and 1500 m (Zenk 1971, Armi & Farmer 1985, Gascard & Richez 1985) and spreads to the west and southwest (Kawase & Sarmiento 1986, Kaese & Zenk 1987). On the flow to the south, the water mass characteristics of MOW mixes with underlying waters and becomes continuously less dense and the influence of formerly deep advection diminishes to the south. As a result, off capes Ghir and Yubi, the lower MOW boundary is rather 200 m deeper than 700 m off Spain (Eberwein & Mackensen 2008).

The hydrographic δ^{13}C record, obtained at 36°N/09°W (Duplessy 1972, reveals that the modern MOW is characterized by heavy δ^{13}C values reaching about 1.3 ‰, and which are more pronounced at 35°N (Ganssen 1983, Ganssen & Sarnthein 1983). To the south, between Cape Ghir and Cape Yubi, the $\delta^{13}C_{DIC}$ values of the MOW range between 0.65 and 0.83 ‰, with a mean of 0.72 ± 0.08 ‰.

METHODOLOGY

In order to reconstruct the Late Quaternary (~ 40 kyr) history of the Mediterranean Outflow to the southern part of the Gulf of Cadiz in Moroccan Atlantic margin (~ 35°N), five sediment cores which cover the last 40 kyrs were investigated. The sediment cores (Tab. 1) were recovered from the Larache continental slope (Fig. 1) at water depths ranging from 507 m to 1380 m with the aid of a gravity corer during RV Sonne Cruise SO-175 in November 2003 and RV Pelagia Cruise 64PE284 in February 2008.

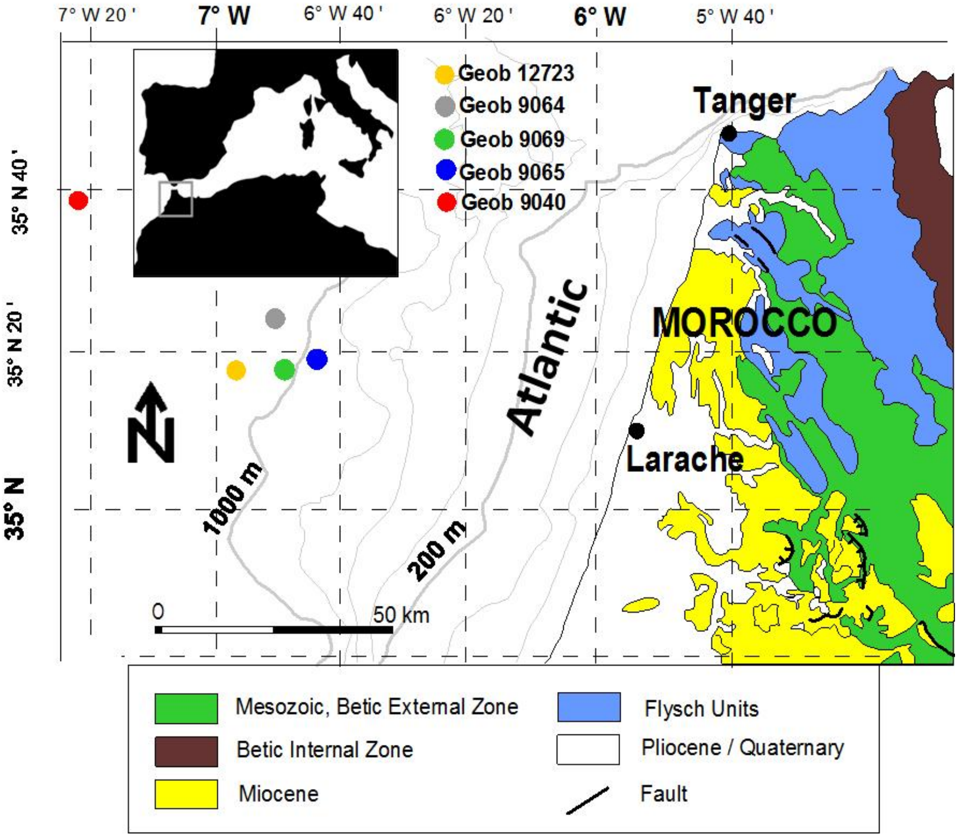

Figure 1. Geological map showing the cores distribution in the study area (from Medialdea *et al.* 2009).

Generally, *Cibicidoides wuellerstorfi* calcifies its test close to a 1:1 relationship with the $\delta^{13}C$ of ambient dissolved inorganic carbon (DIC) (Woodruff *et al.*, 1980, Belanger *et al.* 1981, Graham *et al.* 1981, Zahn *et al.* 1986), and thus faithfully records bottom water $\delta^{13}C_{DIC}$ (Duplessy *et al.* 1988, McCorkle & Keigwin 1994, Mackensen & Licari 2004, Eberwein & Mackensen 2006). Hence, decreasing $\delta^{13}C$ values of this species with increasing water depth of NW Africa are interpreted as reflecting the $\delta^{13}C_{DIC}$ of the different water masses occurring there (Eberwein & Mackensen 2008). Consequently, we used $\delta^{13}C$ of *Cibicidoides wuellerstorfi* to reconstruct the approximate boundaries between water masses in the Moroccan Atlantic Margin (~ 35°N), in addition to the Late Quaternary variations in the advection rate of the Mediterranean Outflow Water into the Atlantic Ocean.

We present records of benthic stable isotopes from sediments retrieved from the sea floor; an initial screening of samples distributed along the cores showed that *Cibicidoides wuellerstorfii* was sometime absent or sparse downcore. Instead, *Uvigerina peregrine,* which calcifies its test close to equilibrium of the bottom water $\delta^{18}O$ (Shackleton 1974, McCorkle *et al.* 1990), appeared present in most of the samples also displaying better preservation and it was chosen to compensate *Cibicidoides wuellerstorfii.* On average, five to seven individuals of benthic foraminifera were handpicked from the > 150 µm size fraction of each sample, sufficient to reach the minimum weight of material (180 µg) detectable by the mass spectrometer. Oxygen and carbon isotopic data obtained are reported in the usual notation, which is referred to the PeeDee belemnite (V-PDB) standard. The benthic isotope were measured in the Department of Geosciences (FB5-Geowissenschaften) at the Bremen University using a Finnigan MAT 252 mass spectrometer with a precision of ± 0.07 ‰ for $\delta^{18}O$ and ± 0.05 ‰ for $\delta^{13}C$. The deep-sea sediments comprise biogenic and terrigenous components, to isolate the terrigenous fraction from biogenic sediments, samples are taken from the sediment cores in a spatial resolution of 5 cm and treated in order to remove organic carbon, calcium carbonate and biogenic opal by using H_2O_2 (35%), HCL (10%) and NaOH respectively. Once prepared, the grain-size can be measured with the Coulter laser particle sizer that gives the relative proportions of various grain size classes.

RESULTS

Age Model

Age Model of the cores Geob 12723, Geob 9065 and Geob 9069 was obtained by correlating the Fe/Ca ration (Fig. 2) with the core Geob 9064, which has been dated by ^{14}C. Furthermore, the chronostratigraphic framework of the core Geob 12723 was improved by correlation of the benthic carbon isotope record with published values of the core MD99-2339 (35.88°N, 7.53°W; 1170 m water depth (Voelker *et al.* 2006)). They show clear similarities and matching sections and provide thus additional age control points. It is therefore possible to conclusively deduce an accurate age model of the core Geob 12723 (Fig. 3). Ages between the tie points were obtained by linear interpolation and the major transition Holocene-Last Glaciation could be easily identified in all cores.

Oxygen isotope

The $\delta^{18}O$ values of benthic foraminifera (*C. wuellerstorfi*) are displayed in (Fig. 4). The graph shows that $\delta^{18}O$ increases down the water column, reflecting decreasing temperature and or increasing salinity depth wise. Interestingly, the Holocene to Glacial benthic $\delta^{18}O$ shift (taken as the difference between the most enriched value of $\delta^{18}O$ in the Last Glacial Maximum (LGM) and the minimum value recorded in the Holocene) decreases down the water column, in the shallower core (Geob 9069) this offset is found to be 2.18 ‰, in the deeper cores (Geob 9065 and Geob 9064) it reaches 1.65 ‰ and 0.96 ‰, respectively. The benthic $\delta^{18}O$ values of the core Geob 12723 vary between 1.8 ‰ and 3.67 ‰ recorded at 7 kyr and 26.65 kyr, respectively.

Carbon isotope

The means of the benthic $\delta^{13}C$ records show that the Last Glacial Maximum exhibits the lowest values varying between – 0.04 ‰ (Geob 9040) and 0.43 ‰ (Geob 9069). The Holocene and the Late Glacial are characterized by relatively higher values, the mean benthic $\delta^{13}C$ varies between 0.36 ‰ (Geob 9064) and 1.23 ‰ (Geob 9069) in the Holocene, and between 0.66 ‰ (Geob 9064) and 1.26 ‰ (Geob 12723) during the late Glacial.

Table 1. Cores information.

Station No.	Latitude °N	Longitude °W	Water depth (m)	Recovery (m)
GeoB 9065-1	35:19.60	6:42.08	507	6.29
GeoB 9069-1	35:18.21	6:49.14	669	5.13
GeoB 9064-1	35:24.91	6:50.71	702	5.44
GeoB 12723-1	35:18.50	6:57.80	883	4.48
GeoB 9040-1	35:39.56	7:23.38	1380	3.43

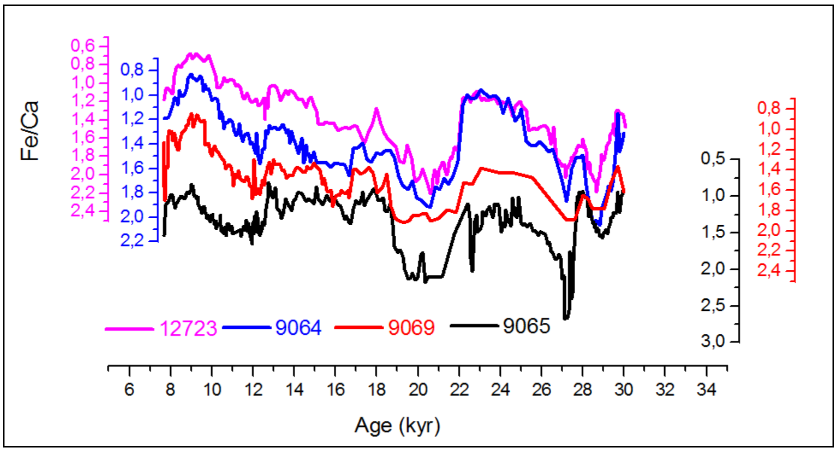

Figure.2 Correlation of the gravity cores using the Fe/Ca ratio.

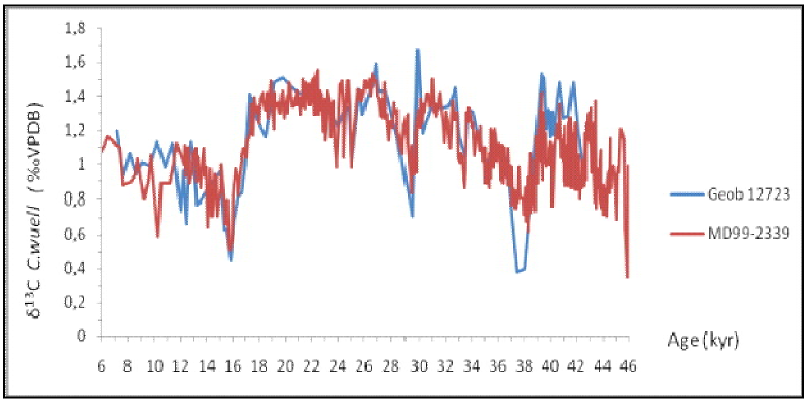

Figure 3. Correlation between the benthic $\delta^{13}C$ records of Geob 12723 and the core MD99-2339.

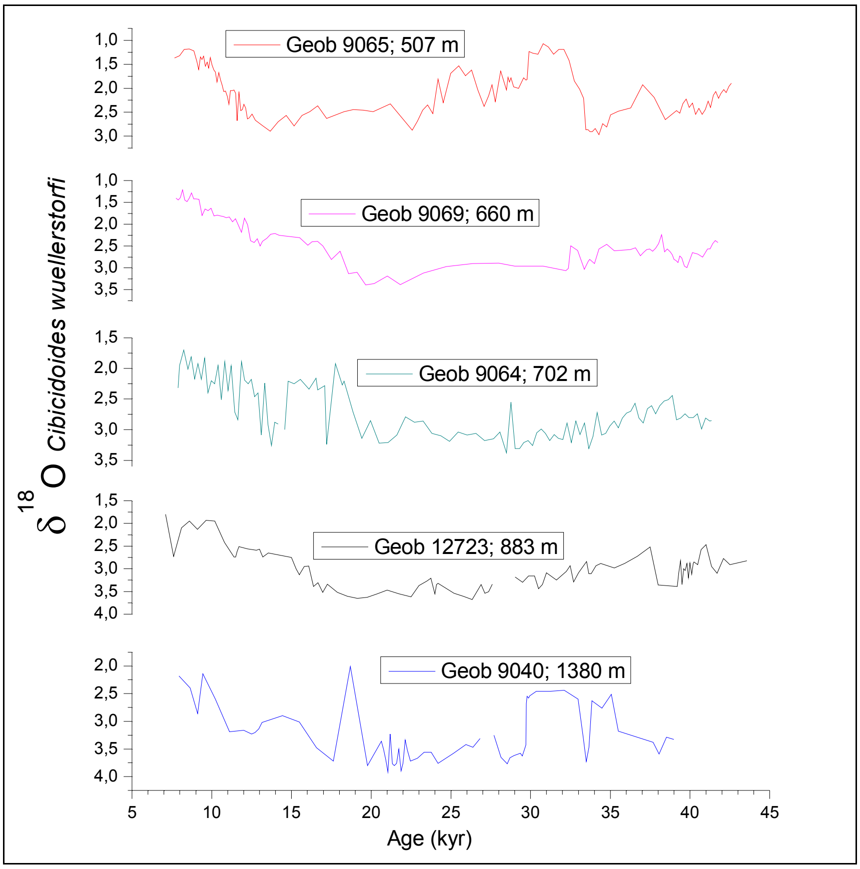

Figure 4. $\delta^{18}O$ values of benthic foraminifera (*Cibicidoides wuellerstorfi*).

Grain size

Grain-size is of relevance for the present study, it was measured to depict the hydrodynamic changes from sediment composition and thereby address the MOW's strength variability. The mean grain size (Fig. 7) indicates changes in the strength of the prevailing bottom current; it varies between 10.25 and 20.72 µm and shows clear millennial-scale variability with higher values, especially during the Younger Dryas and the last glacial maximum inception.

DISCUSSION

Determination of the MOW depth

Present day oceanographic circulation in the Gulf of Cadiz (GoC) is dominated by the exchange of water masses between the Atlantic Ocean and the Mediterranean Sea (Ochoa & Bray 1991). Flowing westwards through the strait of Gibraltar, the MOW prevails in the northern Gulf where it flows between ~ 500 and 1400 m water depth above the North Atlantic Deep Water (NADW) (Ambar *et al.* 1999, Baringer & Price 1999). For the southern GoC along the Moroccan Atlantic margin, Pelegrí *et al.* (2005) suggest the presence of MOW at 800 m. Eberwein & Mackensen (2008) showed that water mass stratification during the LGM off Morocco was similar to present-day conditions, accordingly, and by analogy with modern water mass stratification pattern, we suggest that the shallower cores (Geob 9065, Geob 9069, Geob 9064) which were retrieved at water depths of 507 m, 669 m and 702 m, respectively, can be interpreted as deposits of NACW formation. The benthic isotopic signal of Geob 12723 (water depth of 883 m) may reflect the variation of the ambient isotope values of MOW mass through time and the isotopic record of the core Geob 9040 raised from a water depth of 1380 m can be attributed to NADW formation.

The δ^{13}C of the glacial MOW (Geob12723) is characterized by a mean of 1.2 ‰, in the Holocene we denote lower values of δ^{13}C with a mean of 0.96 ‰.

The mean benthic δ^{13}C of NADW (Geob9040) is found to be 0.66 ‰ in the glacial and 1.08 ‰ during the Holocene (Fig. 5).

The comparison of our benthic δ^{13}C record with published values in nearby locations reveals that the δ^{13}C values of glacial MOW and NADW perfectly match with data from sites along the Portuguese continental margin (Schönfeld & Zahn 2000) to southern sites between Cape Ghir (31°N) and Cape Yubi (27.5°N), where glacial MOW is characterized by a mean δ^{13}C of 1.15 ± 0.13 ‰. NADW is described by a mean δ^{13}C of 0.44 ± 0.16 ‰ (Eberwein & Mackensen 2008). This supports the overall water mass stratification in Moroccan Atlantic margin as argued by Zahn & Mix (1991) and Sarnthein *et al.* (1994).

Besides, and as indicated above, the benthic δ^{18}O values of the core Geob 12723 exhibit a glacial–Holocene shift of ~ 1.87 ‰, relatively bigger than the next shallower cores. Regarding the ice volume effect (~1.2 ‰; Labeyrie *et al.* 1987), which indicates that this shift exceeds the sea level rise related value by about 0.67 ‰ and therefore reveals that the glacial waters were either about 3.04 °C colder (a δ^{18}O increase of 0.22 ‰ is equivalent to a 1°C cooling; Visser *et al.* 2003) or saltier than the Holocene ones. This may be due to the intrusion, at intermediate depth, of Mediterranean Outflow Water, marked by higher salinity which may influence oxygen isotope signal at this level.

To verify if our cores are really the deposits of the NACW, the MOW and the NADW formations, we refer to the benthic δ^{13}C variations of the core 15669 (34°53.5', 7°07.1'; 2022 m water depth, Zahn *et al.* 1987), which was retrieved from the NADW ambient water mass, and that of the core MD99-2339 (35.88°N, 7.53°W; 1170 m water depth; Voelker *et al.* 2006]) that have been interpreted to reflect the advection of the MOW.

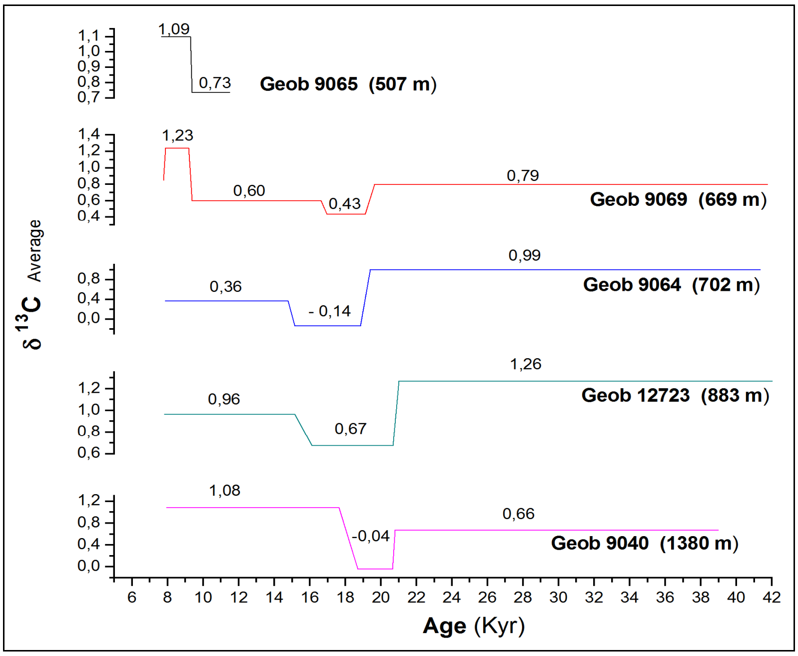

Figure 5. δ^{13}C average values of benthic foraminifera (*Cibicidoides wuellerstorfi*).

For the core Geob 9040 representing probably the NADW formation, a gradient was computed using the benthic $\delta^{13}C$ signal of the core 15669. Knowing that this core represents pure NADW as a prevailing water mass deposition (Zahn *et al.* 1987), this gradient will allow us to check if the $\delta^{13}C$ of the core Geob 9040 can effectively be considered as representative of the NADW water mass.

In the following, the term of $\Delta\delta^{13}C$ is used to indicate the difference between the values of the benthic records. The $\Delta\delta^{13}C_{Geob9040\text{-}15669}$ shown in (Fig. 6a) for reference displays positive and negative values indicating changes in the contribution of the NADW to our core location (1380 m). From 18 to 40 kyr B.P., a negative gradient or slightly close to zero indicates as was expected of the NADW formation. An intriguing finding in our data set is the positive gradient before 18 kyr, this highlights that the MOW reached this location during this period.

As indicated above, the core Geob 12723 was retrieved from a water mass depth characterized probably by MOW spreading; accordingly, its benthic $\delta^{13}C$ record was compared with the $\delta^{13}C$ signature of the MOW provided by the core MD99-2339 (Voelker *et al.* 2006). The Figure 6b shows that the $\Delta\delta^{13}C_{Geob12723\text{–}MD99\text{-}2339}$ remains, most of the time, close to zero indicating almost exclusive presence of the MOW at the core Geob 12723 location.

By analogy with the modern water masses stratification, we suggest that the water depths shallower than 800 m are characterized by the oceanic sinks of the MOW and or the NACW. Hence, and in order to determine accurately which water mass flows at the sampling sites of the cores Geob 9064, Geob 9069 and Geob 9065, gradients between the $\delta^{13}C$ values of these cores and the core MD99-2339 were calculated.

The $\Delta\delta^{13}C_{Geob9064\text{–}MD99\text{-}2339}$ exhibits almost continuously null values (Fig. 6c), by analogy to the core Geob 12723, this pattern suggests the presence of nearly pure MOW at the location of the core Geob 9064 (702 m). At shallower depths, the $\Delta\delta^{13}C_{Geob9069\text{–}MD99\text{-}2339}$ and the $\Delta\delta^{13}C_{Geob9065\text{–}MD99\text{-}2339}$ display positive, null and negative values (Fig. 6d, e) and thereby depict changes in the spreading of the NACW and the MOW water masses. Positive gradients are seen during the time interval between 8 to 25 kyr B.P. at 507 m water depth (Geob 9065) and between 8 and 9 kyr at 669 m (Geob 9069). They indicate a significantly presence of the NACW water mass at this water depths during these periods of time. In contrast, during most of glacial time, the null and negative gradients suggest stronger influence of the MOW water mass.

Reconstruction of the MOW advection

The $\delta^{13}C$ values of Mediterranean deep water are regulated by the strength of deepwater formation in the Gulf

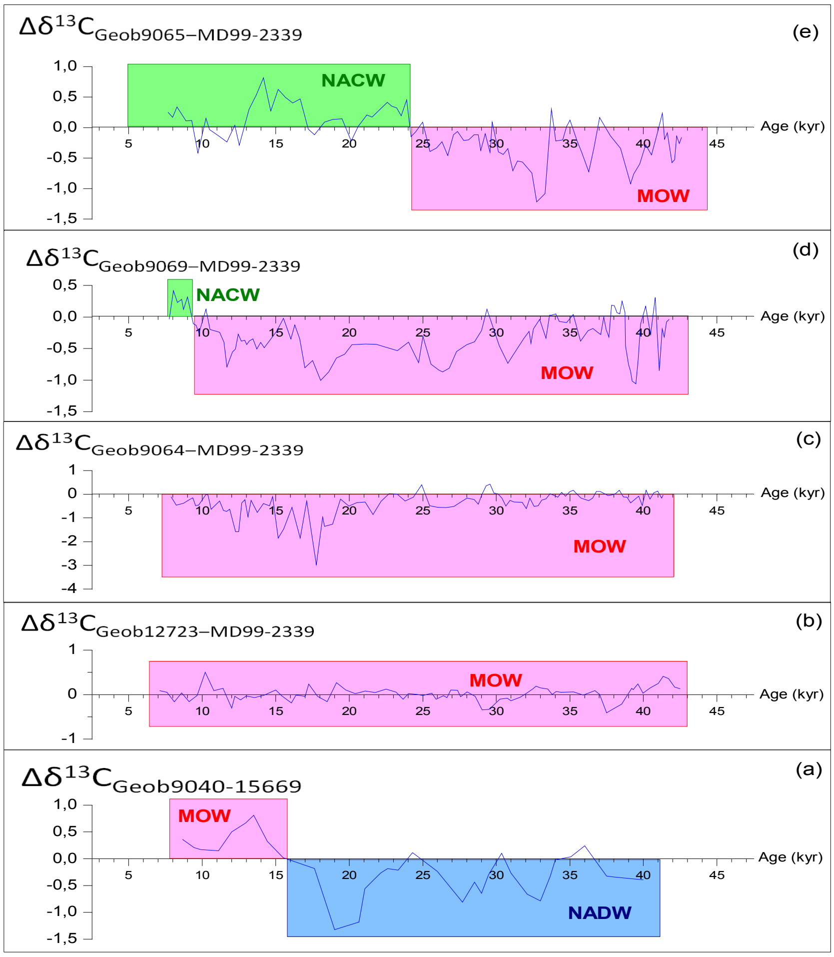

Figure 6. Gradients generated from the difference between the benthic $\delta^{13}C$ records of our cores and the cores MD99-2339 (Voelker *et al.* 2006) and 15669 (Zahn *et al.* 1987).

of Lions, the flux of organic carbon to the floor, and the rate of water exchange with the Atlantic (Béthoux *et al.* 1998, Pierre 1999, Gómez 2003).

Slower rates of deepwater convection and/or higher export productions would lead to decreasing values of $\delta^{13}C$ in bottom waters (Pierre 1999). In contrast, higher $\delta^{13}C$ values should be recorded at times of vigorous deepwater convection or lower carbon export. Of these two factors, the strength of Mediterranean deepwater formation probably contributed more to the $\delta^{13}C$ variability, because surface productivity and export production are relatively low in the Mediterranean (Béthoux *et al.* 1998, Gómez 2003). Thus, heavier benthic $\delta^{13}C$ values are more related to ventilation than to nutrient levels and therefore indicate a vigorous deep convection in the Gulf of Lions (Sierro *et al.* 2005).

In addition, Zahn *et al.* (1987) assumed that the variation in intermediate water $\delta^{13}C$ values are related to changes in advection rates of MOW. We can therefore deduce that during glacial time, the heavy values of the benthic carbon isotope record in the core Geob 12723 (Fig 7) indicate significantly increased influence of the MOW on the North Atlantic circulation (Curry & Lohmann 1985, Duplessy *et al.* 1988a). This explains why glacial MOW was traced to 20°N (Zahn *et al.* 1987), and even as far south as to 30°S (Bickert & Mackensen 2004).

During the Last Glacial Maximum time slice which is defined as the time interval between 26.500 and 19.000 years ago (Clark *et al.* 2009) with its center at 21 kyr B.P. (Mix *et al.* 2001), the variation in ice volume and the resulting sea level changes are assumed to have a great influence on the volume of the MOW core. In this study, the generated gradients (Fig. 6) indicate that throughout the LGM significantly lower influence of the MOW was recorded (Fig. 8), during this time, the lower sea level implied less space in the strait of Gibraltar, thus we argue for a reduced outflow volume during the colder time.

Interestingly, the most positive benthic $\delta^{13}C$ are recorded in core Geob 12723 during the Last Glacial Maximum (LGM) (Fig. 7) and a restricted exchange through the strait of Gibraltar due to the progressive sea level lowering (Schönfeld & Zahn 2000, Matthiesen & Haines 2003). So, even with a narrowed geometry of the strait of Gibraltar caused by low sea level and hence a strong decrease in the outflow volume (Béthoux 1984, Bryden & Stommel 1984, Rohling & Bryden 1994, Matthiesen & Haines 1998), the glacial outflow is estimated at 0.39 Sv compared with 0.86 Sv today, Mediterranean water flowed into the Gulf of Cadiz during the LGM.

In addition, a reduced cross section might have enhanced the MOW current velocity, theoretically aided by stronger winds during glacial time (e.g., Gasse 2000; Kohfeld & Harrison 2001, Goudie & Middleton 2001). The increased MOW strength is further corroborated by stronger bottom currents, indicated by the deposition of biggest grain-size especially in the LGM inception (Fig. 7).

The grain-size excursions were especially abrupt during the Younger Dryas (YD) and Dansgaard-Oeschger (D-O) stadials (Fig. 7) and were marked by a prominent increase suggesting that in addition to the enhanced MOW flow known during the cold climatic intervals (Faugères *et al.* 1986, Vergnaud-Grazzini *et al.* 1989, Cacho *et al.* 2000, Sierro *et al.* 2005, Llave *et al.* 2006, Rogerson *et al.* 2006a, Voelker *et al.* 2006, Toucanne *et al.* 2007 Rogerson *et al.* 2012), strong deepwater convection can be inferred. Off NW Africa salinities spiked during most HEs (Heinrich Events) (Kiefer 1998), the inflow of salt-enriched subtropical Atlantic waters into the western Mediterranean increased surface water density and facilitated deep convection in the Gulf of Lions (Voelker *et al.* 2006). Furthermore, low sea-surface temperatures (Cacho *et al.* 1999), intense north-westerly winds, and dry, cool conditions on land (Combourieu-Nebout *et al.* 2002, Sanchez-Goni *et al.* 2002, Moreno *et al.* 2005) facilitated an increased formation of WMDW (Western Mediterranean Deep Water) in the Gulf of Lions during D-O stadials and Heinrich events (Rohling *et al.* 1998, Cacho *et al.* 2000, Sierro *et al.* 2005, Voelker *et al.* 2006).

Besides, during the LGM, the MOW has sunk relatively deeper than during older ages (Fig. 8), according Schönfeld & Zahn (2000), the deeper glacial MOW advection was caused by increased density, as a result of higher salinity and lower temperature of Mediterranean waters during the LGM, result argued by the highest $\delta^{18}O$ values recorded at this period of time. The earlier glacial times are marked by lower $\delta^{18}O$ values suggesting either lower salinity and/or higher temperature, accordingly the MOW became less dense and the deep advection has shifted upwards.

The Early Holocene and the warm Dansgaard-Oeschger interstadials are characterized by lower $\delta^{13}C$ values and decrease in $\delta^{18}O$ record (Fig. 7) when local climate conditions increased sea surface temperatures and reduced salinity (Cacho et al., 2000; Sierro et al., 2005) resulting in reduced density gradient between Atlantic inflow and Mediterranean outflow (Sierro et al., 2005) and therefore weaker MOW advection (e.g., Huang et al., 1972; Diester-Haass, 1973; Bethoux, 1979a; Thunell et al., 1984 ; Vergnaud Grazzini et al., 1986 ; Zahn et al., 1987; Grousset et al., 1988; Sanchez- Goni et al., 2002; Schönfeld, 2002; Moreno et al., 2005; Toucanne et al., 2007). These periods are coincident with low grain size values (Fig. 7) which hint to a reduction of the MOW flow strength.

The weakening in the MOW strength was coupled with a hydrographic change in the water mass stratification, the generated gradients highlight an oceanic sink of the NACW (Fig. 8), the NADW was not traceable in our location. This evidence would indicate that fresher entrains the dense Mediterranean water to flow deeply, replacing hence the NADW water mass.

Nowadays, usually most of the MOW is flowing around Iberia northward into the NE Atlantic with an average of 2.17 Sv, and relatively little is spreading south to the Moroccan margin, the southward and westward transport are close to zero except for the periods 1950 to 1955 and 1985 to 2005, when the westward transport is about 1 Sv (Bozec *et al.* 2011). Our results showed that the MOW flowed southward (hitting our cores sites) during colder stages, indicating that the direction towards the MOW was flowing has changed, this suggestion is argued by Rogerson *et al.* (2012) results, which show opposite fluctuations in flow activity between the Last Glacial Maximum and the present day.

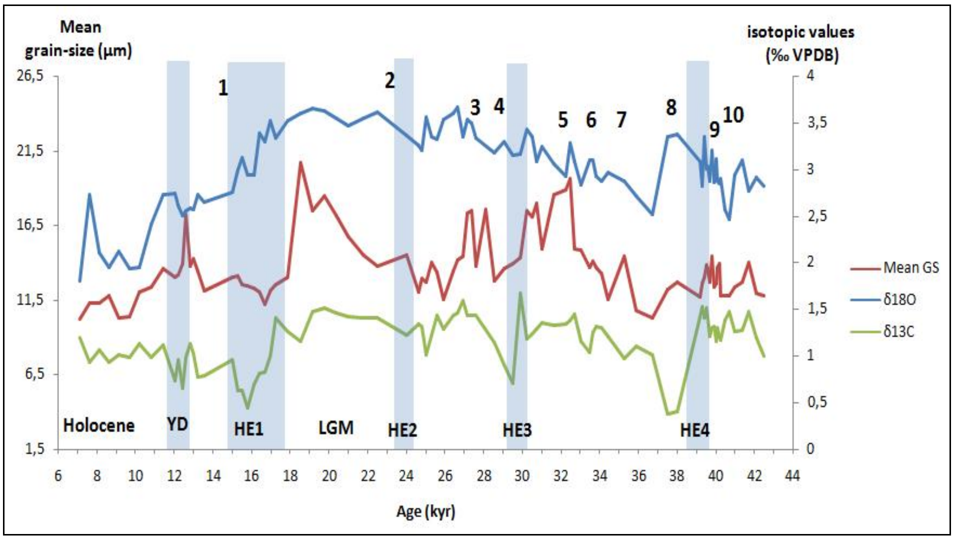

Figure 7. Mean grain-size record and benthic isotope data of the core Geob 12723. (YD: Younger Dryas; HE: Heinrich Events; LGM: Last Glacial Maximum; Numbers above The δ^{18}O record indicate Dansgaard-Oeschger interstadials).

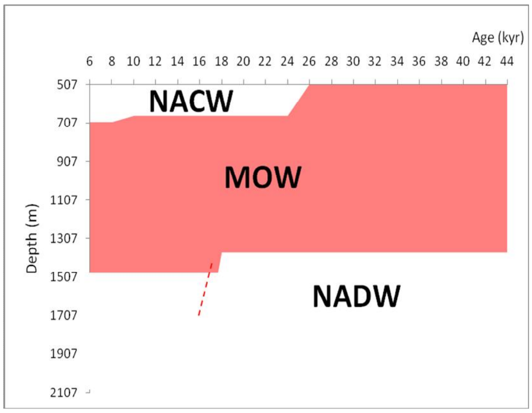

Figure 8. Diagram (deduced from Fig. 6) illustrating the variation through time of the MOW core thickness.

CONCLUSION

The records of the gradients generated from the benthic stable isotopes of sediments retrieved from the Larache offshore suggest that unlike today, the MOW was spreading south to the Moroccan margin during at least the last 40 kyrs.

The conceptual view of past spreading path of the MOW is supplemented in this study by the determination of the upper and lower boundaries. Our results revealed the presence of nearly pure MOW at depth ranged between 702 and 803 m, the upper and lower boundaries varied through time between 507 and 1380 m.

The variations in the mean grain-size data provide further evidence with respect to the seesaw in the MOW velocity for the period that extend back to 40 kyrs with increased strength during the Younger Dryas (YD) and Dansgaard-Oeschger (D-O) stadials.

ACKNOWLEDGEMENTS

At the end of this study, I (first author) would like to thank Pr. Dierk Hebbeln for the invitation and the supervision in his laboratory, and through him all the Marum scientific team. The Journal reviewers Pr. Abdellah EL HMAIDI and an anonymous are equally thanked for their corrections and commentaries.

Also, I am very grateful for the financial support of the DAAD (German Academic Exchange Service) and CNRST (National Center for Scientific and Technical Research, Rabat, Morocco) without which the work reported here would not have been possibly for me to carry out.

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Manuscrit reçu le 28/10/2014
Version révisée acceptée le 25/03/2015
Version finale reçue le 22/10/2015
Mise en ligne le 02/11/2015