Contents lists available at ScienceDirect



Palaeogeography, Palaeoclimatology, Palaeoecology



journal homepage: www.elsevier.com/locate/palaeo

Impact of climate and sea level changes on the ventilation of intermediate water and benthic foraminifer assemblages in the Gulf of Lions, off South France, during MIS 6 and 7

Aleix Cortina ^{a,*}, Francisco Javier Sierro ^a, Beatriz González-Mora ^a, Alessandra Asioli ^b, José Abel Flores ^a

^a Department of Geology, University of Salamanca, Plaza de la Merced sn, 37008 Salamanca, Spain

^b Istituto di Geoscienze e Georisorse del C.N.R.-UOS di Padova, Via G. Matteotti 30 35137 Padova, Italy

ARTICLE INFO

Article history: Received 11 December 2010 Received in revised form 21 May 2011 Accepted 7 June 2011 Available online 22 June 2011

Keywords: Benthic foramimifer Planktic foraminifer Bottom ventilation Mediterranean Sea Sea level

ABSTRACT

Benthic and planktic foraminifer assemblages together with oxygen stable isotope were studied in the PRGL1 borehole (Promess1), drilled on the upper slope of the Gulf of Lions, with a view to reconstruct the impact of climate changes on surface and bottom waters between MIS7 and MIS6. Foraminifer species were grouped by R-mode principal components analysis. We obtained 3 factors in benthic assemblages that were related to eutrophic, mesotrophic and oxygenated environments. In the planktic foraminifer assemblages four factors were considered that explained the changes of sea surface temperature, productivity and turbulence in the water column. Variations in the terrestrial organic carbon supply associated with eustatic sea level changes mainly controlled oxygen consumption and the benthic communities. During MIS7, the benthic communities were mainly mesotrophic owing to the low supply of terrestrial organic carbon because the coastline was distant from the slope. However, during MIS6 the sea level drop caused a rapid progradation of the River Rhone prodelta and dramatically increased the supply of terrestrial organic carbon, resulting in a pronounced increase in eutrophic foraminifers. Apart from the effect of the river discharge, which contributed to the reduced oxygen content, we recognized periods of intense bottom ventilation during MIS 6 and, to a lesser extent, in the substadial stages of MIS 7. The ventilation events are well matched by higher turbulence and convection in the water column during cold episodes associated with an intensification of the northwesterlies. In contrast, during the short, millennial scale warming events of MIS6 the stratification of the water column rapidly reduced bottom ventilation. These results are consistent with those reported in previous studies that point to enhanced dense-water formation in the Gulf of Lions during cold stages.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Ventilation of the deep Mediterranean Sea is mainly driven by winter changes in wind intensity in the region of the Gulf of Lions which triggers dense deep-water formation (Millot, 1990). Subsequently, these changes play an important role in controlling the distribution of deep-sea benthic microfaunas that are adapted to different oxygen concentrations. Studies carried out in recent years have revealed that the rates of deep water ventilation were higher during glacial periods and lower during interglacials (Cacho et al., 2000, 2006; Kuhlemann et al., 2008; Sierro et al., 2009). However, little is known about the changes in the oxygenation of intermediate waters and the benthic microfaunal assemblages living in these water masses.

* Corresponding author. Tel.: +34 923 294497; fax: +34 923 294514.

E-mail addresses: acortina@usal.es (A. Cortina), sierro@usal.es (F.J. Sierro), mora@usal.es (B. González-Mora), alessandra.asioli@igg.cnr.it (A. Asioli), flores@usal.es (J.A. Flores). In the present study we analyzed the benthic foraminifer assemblages from the PRGL1 borehole, drilled on the upper slope of the Gulf of Lions continental margin, in order to determine the main paleoceanographic and paleoclimatic changes that occurred in this region between 133 and 248 kyr ago. The location of this site not far from the shelf-break, means that it has potential for recording past changes in productivity and ventilation in the upper part of the water column (its paleodepth during glacial maximum was only 170 m) as well as changes in sediment and organic carbon supply from the Rhone River. Currently, the river mouth and the fine-grained prodeltaic sediments, which are rich in organic carbon, are being deposited near the coast, about 70 km away from the upper slope. However, during glacial periods the prodelta was very close to the shelf break (Jouet et al., 2006), changing the substratum and food availability of the benthic communities living there.

To date, few studies have reviewed the benthic foraminifer assemblages of the Gulf of Lions area (Schmiedl et al., 2000; Fontanier et al., 2008; Mojtahid et al., 2009), and none of them has focused on MIS 6 and 7. Schmiedl et al. (2000) described the distribution pattern and microhabitat of living benthic foraminifers from two upper

^{0031-0182/\$ –} see front matter 0 2011 Elsevier B.V. All rights reserved. doi:10.1016/j.palaeo.2011.06.005

bathyal stations differing mainly in total organic carbon and the bottom oxygen content. Fontanier et al. (2008) reported the ecological distribution of living benthic foraminifers obtained from 6 stations at different depths between 350 m and 2000 m. Those stations had different conditions of total organic carbon, sources of organic carbon and oxygen concentrations. Mojtahid et al. (2009) focused their study on comparing the density and variability of living benthic foraminifer assemblages with the quality of organic matter $(\delta^{13}C \text{ and } C/N\text{-ratios})$. Regarding planktic foraminifers, one of the most important studies for the Mediterranean Sea was conducted by Pujol and Grazzini (1995), who based on samples of living assemblages collected along a NW-SE transect established the current general patterns of distribution in winter and spring. Few studies have compared planktic and benthic foraminifer assemblages in the Gulf of Lions (Vénec-Péyre, 1990; Melki et al., 2009). Vénec-Peyré (1990) used benthic and planktic foraminifer abundances to demonstrate the importance of sedimentary processes in controlling the composition and distribution of recent thanatocenoses. Melki et al. (2009) using benthic and planktic foraminifer abundances explained the links between surface water temperature, salinity, primary productivity and deep-water masses in rapid fluctuations over the past 28 kyr.

1.1. Regional settings

The Gulf of Lions is situated in the north-western part of the Mediterranean Sea. The general surface circulation is mainly driven by the Northern Current (NC), which is divided into two branches: the main branch, flowing through the open sea along the Catalan-Balearic Sea, and the secondary branch, which circulates along the edge of the continental shelf (Millot, 1990). The secondary branch is composed of surface layers of the main current that spread onto the continental shelf (Lapouyade and De Madron, 2001). Owing to seasonal stratification and the wind system, the current oscillates in magnitude and direction over the year, doubling its magnitude during winter in comparison with the summer (Béthoux, 1984).

The Gulf of Lions is an area of dense deep-water formation. Cold northwesterly winds (the Mistral and Tramontana) blowing through the passages between the Pyrenees, the Massif Central and the Alps cool the surface water, which, as a result of its increasing density, sinks. The sinking speed can reach values of up to 10 cm/s in large areas of open sea (up to tens of square kilometers) (Millot, 1990). Another event that involves deep-water formation in the Gulf of Lions occurs on the continental shelf and is usually referred to as Dense Shelf Water Cascading (DSWC). DSWC is produced during winters when dry and cool northwesterly wind events are prolonged. Despite the gain in buoyancy induced by fresh water input from rivers, the surface water of the continental shelf increases its density and sinks (Canals et al., 2006; Palanques et al., 2006). DSWC has been observed in several areas (Ivanov et al., 2004; Vilibic et al., 2004). It appears as a predominant mechanism controlling both the annual and interannual variability of shelf water export in several places (Béthoux et al., 2002; Dufau-Julliand et al., 2004; Guarracino et al., 2006). Dense waters flow down the continental slope until they reach their hydrostatic equilibrium level, contributing to the formation of Winter Intermediate Water (WIW) (Dufau-Julliand et al., 2004) and even to a renewal of deep waters in the Mediterranean basin (Béthoux et al., 2002; Canals et al., 2006). WIW is also formed outside the continental shelf when North Atlantic Water (NAW) is cooled without any intense mixing with the waters below (Millot, 1999).

Owing to its negative water budget (precipitation–evaporation<0), the Mediterranean Sea has an anti-estuarine circulation, resulting in oligotrophic conditions across most of it (Béthoux, 1979). However, there are some regions with eutrophic conditions due to their particular hydrographic conditions (i.e., the Gulf of Lions). The Gulf of Lions is one of the most productive areas in the Western Mediterranean Sea owing to vertical mixing in winter, upwelling events, and the nutrient input from the Rhône (Lefevre et al., 1997). At a large scale, the northwesterly wind induces upwelling, that spreads out over 2/3 part of the gulf (in the NE), and downwelling over 1/3 part (in the SW) (Millot, 1982). Consequently, northwesterly wind is responsible of downwelling and upwelling processes simultaneously. Regarding productivity levels, the Gulf can be divided into four parts (Lefevre et al., 1997). The first one is the oligotrophic area of the Gulf of Marseilles, which is not influenced by the Rhône plume. Second is the area influenced by the Rhône plume. Third is the zone situated to the west of the Rhône, where the borehole studied is located. In this area the effect of the Rhône plume is less important due to the dilution of nutrients caused by the NC and the Mistral (e.g. wind effect on shape and extension of river plume; Morel and André, 1991). Fourth is the area located south of the NC (southern branch), where productivity is high due to the frontal zone (e.g. the transition area between the NC and the southern area) (Sournia et al., 1990).

2. Material and methods

During the Promess1 campaign (summer 2004), a borehole (PRGL 1–4) was drilled in the Gulf of Lions (42.690 N, 3.838 E) (Fig. 1) at the interfluve of the Boucart and Herault canyons at a water depth of 298 m in order to study the sea level changes and climatic variability of the Western Mediterranean Basin. This area is very suitable for the preservation of continuous sedimentary paleoclimatic records because there is a good balance between the sedimentation rates and the accommodation space and because it is not strongly influenced by the Rhône deltaic system and is very distant from the Catalonian Margin, where erosive processes have been documented (Rabineau et al., 2005).

2.1. Benthic and planktic foraminifer samples

Although the borehole has a total depth of 300 m, here we present data from 73.500 to 129.607 mbsf (meters below sea floor), corresponding to marine isotopic stages 6 and 7, accordingly to age model from Sierro et al. (2009). At the laboratory, the core was sampled at 10 cm intervals (1 cm thick slices). A subsample of approximately 15 g was taken, dried in an oven and weighed. Then, the subsample was washed over a sieve with a 63- μ m mesh to discard the mud fraction. Following this, it was dried and separated with a sieve of 150- μ m mesh. The fraction larger than 150 μ m was used to count the benthic and planktic foraminifers.

According to age model (Sierro et al., 2009) the average resolution of the benthic and planktic foraminifer samples was approximately 1 kyr. The samples were split up until at least 300 benthic foraminifers and 400 planktic foraminifers had been counted. This could not be achieved in the case of the planktic foraminifers for all the samples, especially in glacial periods, due to the high river input that decreased their accumulation rates. Consequently, for the quantitative study we only took into account samples with more than 100 individuals, since it is very satisfactory procedure for paleoceanographic studies, which base their interpretation on species with a proportion of at least 5% of the assemblage (e.g. this case) (Fatela and Taborda, 2002). Benthic foraminifer genus was identified according to Loeblich and Tappan (1988). Subsequently a total of 129 species were recognized using Ellis and Messina (2007). Fourteen planktic foraminifer species were identified using the taxonomic concepts of Hemleben et al. (1989).

2.2. Statistical analyses

In order to constrain the relationship between planktic and benthic foraminifers we applied an R-mode Principal Component Analysis using STATISTICA (StatSoft, Inc, version 7, 2004). Although Q-mode analysis is frequently used in micropaleontological studies for grouping and assessing the relationship between assemblages and physical parameters, we decided to use an R-model in order to avoid



Fig. 1. A. Map of the Western Mediterranean Sea. Black arrows represent approximate steady current paths based on Millot (1999). B. Magnification of the study area taken from Jouet et al. (2006). The present day morphology and the sand distribution on the continental shelf (Aloïsi, 1986) illustrating the last deglacial sea-level rise.

errors in the analysis deriving from the fact that not all the variables were highly correlated. This is important, because unlike the Q factor analysis this method does not group species that are highly correlated but does group cases. Thus, to determine in which factor each species is more important it is necessary to consider its position within the factor, as ranked from factor scores.

It should be remarked that the statistical distributions of the benthic and planktic foraminifer assemblages are not normal but lognormal. Consequently, to improve the correlations between variables when Principal Component Analysis was performed a log10 (x + 1)transform was applied, where x is the percentage data, and 1 was added because the logarithm of 0 cannot be computed. Besides

Table 1

Factor scores and explained variance of the most important species of benthic foraminifers resulting from R-mode principal component analysis. Three factors were extracted, explaining a total variance of 80.1%.

Factor 1B		Factor 2B		Factor 3B		
Explained variance = 38.7%		Explained variance = 16.3%		Explained variance = 25.1%		
Species	Factor scores	Species	Factor scores	Species	Factor scores	
Melonis barleeanum Uvigerina peregrina Cibicidoides pachyderma Bulimina inflata Cassidulina laevigata Bulimina marginata Trifarina angulosa Globocassidulina subglobosa Textularia articulata	3.91684 3.53463 3.17650 3.15283 2.85459 2.68140 2.66617 2.56960 1.93571	Trifarina angulosa Cassidulina laevigata Quinqueloculina seminulum Miliolinella subrotunda Pyrgo oblonga Cibicidinella foliorum Lobatula lobatula Gavelinopsis praegeri Astrononion stelligerum	4.44388 3.99755 3.75286 3.22584 3.06149 2.62957 2.45404 1.37728 1.34720	Brizalina dilatata Bulimina marginata Bulimina aculeata Cassidulina laevigata Gyroidinoides umbonatus Sphaereodina bulloides	7.05786 5.03226 3.74731 2.95620 1.59493 1.41555	
Planulina ariminensis Bulimina aculeata Sigmoilopsis schlumbergeri Brizalina alata Gyroidina neosoldanii	1.65548 1.61935 1.57641 1.45113 1.38947	Brizalina dilatata Triloculina tricarinata Miliolinella sp4 Pullenia quadriloba Miliolinella elongata	1.12819 1.09950 1.07760 1.03190 1.02684			

normalizing the data, in our analysis this transformation increased the importance of the species that were less abundant.

2.3. Paleoproductivity estimates

The benthic foraminifer accumulation rate (BFAR: number of tests $cm^{-2} kyr^{-1}$) was used as a proxy for organic matter flux. A direct relationship between BFAR and organic matter flux has been demonstrated in open ocean settings (Herguera and Berguer, 1991). Although conditions in our study area are typical of upper-slope environments we used this proxy since it was the most reliable tool we had to assess organic matter fluxes. The BFAR was calculated as follows:

 $BFAR = X * S * D * W^{-1}$

where,

X I	Number	of tests.

- S Sedimentation rates (cm kyr $^{-1}$).
- D Density $(g cm^{-3})$.
- W Weight (g).

All parameters were measured, except density, which is only an approximation. We assumed that density would remain fairly constant along the core, and to calculate it we used Gamma ray density. The general density value was 1.95 g cm^{-3} , with a standard deviation of 0.08 (n = 25581), showing that the values along the core remained nearly constant.

3. Results

3.1. Principal component analysis of benthic foraminifer assemblages

The results of the principal component analysis of the benthic foraminifer fauna are summarized in Table 1. Three principal component factors were extracted, explaining a total variance of 80.2%.

Factor 1B, explaining 38.7% of the variance, is mainly composed of *Melonis barleeanum, Uvigerina peregrina, Cibicidoides pachyderma*, and *Bulimina inflata*. The comparison of factor loadings with the record of δ^{18} O in *Globigerina bulloides* (Sierro et al., 2009) revealed that the highest values were reached during MIS 7, especially during the

warmest periods (7.1, 7.3 and 7.5) (Fig. 2). Although 1B remained as the predominant factor during MIS 7, its loadings are lower in the glacial substages (7.2 and 7.4). These periods were dominated by high abundances of *Melonis barleeanum*, which replaced the other main species. When MIS 6 is reached this factor tends to decrease from the beginning to the end.

For Factor 2B (16.3% of the variance), the main species are *Trifarina angulosa*, *Cassidulina laevigata*, *Quinqueloculina seminulum*, *Miliolinella subrotunda* and *Pyrgo oblonga*. The highest values of Factor 2B are seen between 140 and 155 kyr. During MIS 6, the loadings were higher at intervals in which Factor 3B was less significant. Moreover, it became more important in glacial substages of MIS 7, when Factor 1B decreased but 2B only dominated the association in glacial substage 7.2 because in 7.4 Factor 1B remained predominant (Fig. 2).

Factor 3B, with an explained variance of 25.1%, mainly comprises *Brizalina dilatata, Bulimina marginata* and *Bulimina aculeata*. Significant loadings were found only during MIS 6, in periods with the lowest values of Factor 2B. The trend from the beginning of MIS 6 is to increase upward, replacing Factor 1B (Fig. 2).

3.2. Principal component analysis of planktic foraminifer assemblages

The results of the principal component analysis of the planktic foraminifer assemblages are summarized in Table 2. Four factors were extracted, explaining a total variance of 94.4%. In Factor 1P, explaining a variance of 34%, the main species are Globorotalia inflata and Globigerinoides ruber. Loadings were higher during MIS 7, reaching maximum values during the warmest events (7.1, 7.3 and 7.5). This factor (1P) shows a similar behavior to that of Factor 1B in the benthic foraminifer analysis and tends to decrease from the beginning to the end of MIS 6 (Fig. 3). However, Factor 1P dominated during short periods in MIS 6 coinciding with lighter values in the δ^{18} O record. In Factor 2P, explaining a variance of 16.1%, the most abundant species are Turborotalita quinqueloba, Globorotalia scitula and Globigerinita glutinata. This factor was only important during MIS 6, especially around 140 Kyr and 155 Kyr, in agreement with the higher loadings of Factor 2B. The main species in Factor 3P (21.3% of variance explained) is Globigerina bulloides. It was significant in glacial substage 7.2, and in the coldest events along MIS 6. Finally, Neogloboquadrina pachyderma (dex.) is the main species in Factor 4P and explains a variance of 23%. Its values were higher during warm events in MIS 6 and at glacial substage 7.2.

Fig. 2. Factor loadings of 3 factors obtained by R-mode principal component analysis of the benthic foraminifer assemblages. The percentages of the most important species for each factor are also represented. δ^{18} O values of *G. bulloides* shells (Sierro et al., 2009).



Table 2

Factor scores and explained variance of the planktic foraminifers resulting from R-mode principal component analysis. Four factors were extracted, explaining a total variance of 94.4%.

Factor 1P		Factor 2P	Factor 3P		Factor 4P		
Explained variance = 34%		Explained variance = 16.1%		Explained variance = 21.3%		Explained variance = 23%	
Species	Factor scores	Species	Factor scores	Species	Factor scores	Species	Factor scores
Globorotalia inflata	2.747698	Turborotalita quinqueloba	2.905322	Globigerina bulloides	3.04544	Neogloboquadrina pachyderma (dex.)	2.44760
Globigerinoides ruber (white)	1.687807	Globorotalia scitula	1.950089	Globigerinita glutinata	2.33059	Globigerina bulloides	1.62487
Neogloboquadrina pachyderma (dex.)	1.616835	Globigerinita glutinata	1.814010	Globorotalia inflata	0.10186	Turborotalita quinqueloba	1.16335
Globigerina bulloides	1.228059	Neogloboquadrina pachyderma (dex.)	0.395946			Neogloboquadrina pachyderma (sin.)	0.45866
Orbulina universa	0.190897	× ,				Neogloboquadrina pachyderma (int.)	0.28462

3.3. Paleoproductivity estimates

We used the BFAR as a proxy to estimate paleoproductivity (Herguera and Berger, 1991). The general trend of the BFAR was to increase from the beginning to the end of MIS 6 (Fig. 4B). However, this general trend was broken by a minimum at around 151 kyr, corresponding to the maximum value of Factor 2B (Fig. 2). Moreover, two maxima were seen around 135 kyr and 182 kyr. In order to compare Factor 3B with BFAR, we used log10 (BFAR), since the BFAR values were much higher than those of Factor 3B. When contrasting log10 (BFAR) with Factor 3B, a positive correlation emerged (r=0.7, p<0.0001) (Fig. 4A).

4. Discussion

4.1. Environmental conditions on the seafloor

As reported above, the main taxa in Factor 1B are Melonis barleeanum, Uvigerina peregrina, Cibicidoides pachyderma and Bulimina inflata. In several studies, M. barleeanum and U. peregrina have been described as mesotrophic species, living with moderate organic matter fluxes (Corliss, 1991; Schönfeld, 1997; Jorissen et al., 1998; De Rijk et al., 2000; Fontanier et al., 2002; Licari et al., 2003; Eberwein and Mackensen, 2006). Furthermore, these species have been related to upper-slope environments in the Mediterranean Sea, characterized by a labile organic-matter flux of 2.5 g cm $^{-2*}$ yr $^{-1}$ (Altenbach et al., 1999; De Rijk et al., 2000), which has been considered as the boundary between oligotrophic to mesotrophic environments. Although M. barleeanum was present during the interglacial substages of MIS7, it reached its highest abundances during glacial substages 7.2 and 7.4 (Fig. 2). The environmental conditions during these glacial substages were different from those of the interglacial substages, and the extraction of a fourth factor would explain this, but as it accounted for less of 5% of the variance we decided do not take it into consideration. Moreover, both the high abundances of M. barleeanum and the high loadings of Factor 1B throughout MIS 7 suggest that conditions were relatively similar along the different substages. B. inflata is an opportunistic and shallow infaunal species (Rohling et al., 1997; Abu-Zied et al., 2007). Accordingly, M. barleeanum, U. peregrina and B. inflata can be considered as shallow infaunal species related to mesotrophic environments. By contrast, C. pachyderma is an epifaunal opportunistic species (Schmiedl et al., 2000; Abu-Zied et al., 2007) and usually lives in a more oligotrophic context. The presence of species described as mesotrophic (e.g. U. peregrina, M. barleeanum and B. inflata) coexisting with C. pachyderma suggests an environment with a moderate flux of organic matter that did not remain steady throughout the year. These characteristics are typical of modern conditions in the dilution area of the Gulf of Lions, in which blooms are not constant and are restricted to spring and early fall (Pujol and Grazzini, 1995; Lefevre et al., 1997; Riigual-Hernández et al., 2010).

Paleoceanographic studies carried out at the same core (Sierro et al., 2009) revealed the existence of condensed layers (CLs), characterized by prominent peaks in the fraction $>63 \,\mu\text{m}$. These layers, which are rich in biogenic material, were deposited at times of slow sedimentation rates during interglacial periods with high sea levels, when the coastline was very distant from the shelf break and there was enough space on the shelf to accommodate the prodeltaic muds and coastal sediments supplied by the river. The high concordance of Factor 1B with the CLs (Fig. 5) corroborates the notion that this factor was important during warmer periods. However, the extremely low sedimentation rates during the formation of these CLs may result in a strong mixing of hundreds of generations of benthic foraminifers that could mask the record of abrupt climate events. In fact, Factor 1B shows the lowest differences between the main and secondary species (Table 1), although this is probably an artifact due to the mixing of generations. In spite of the low sedimentation rates, Factor 1B is linked to warm periods and the species are well differentiated. Hence, we refer this benthic factor as being characteristic of warm periods, a moderate flux of organic matter, and with low sedimentation rates, and we shall refer to it as the "Mesotrophic Factor" (Table 3).

Factor 2B comprises Trifarina angulosa, Cassidulina laevigata, *Quinqueloculina seminulum, Miliolinella subrotunda* and Pyrgo oblonga. *Trifarina angulosa* is the main species in this factor. High percentages are recorded from current-swept passages (Hayward et al., 1994) and deep high-energy environments on the outer shelf and upper slope (Mackensen et al., 1985). It is adapted to strong water turbulence of varying intensity (Schönfeld, 2002). Cassidulina laevigata is considered to be an opportunistic species (Gooday, 1986; Gooday and Lambshead, 1989; Rasmussen et al., 2002). Its high average (mean = 19%, Std = 8.7) along MIS 6 and MIS 7 and its presence in all factors with moderate-to-high factor scores (Table 1) suggest opportunistic behavior. Hence, this species will not be taken into account in the interpretation of this factor. Quinqueloculina seminulum, M. subrotunda and P. oblonga belong to the Suborder Miliolina, in which most of its species are characterized as settling in oligotrophic environments, with high oxygen concentrations and elevated ventilation (Nolet and Corliss, 1990; den Dulk et al., 1998). In the Ionian Basin, Schmiedl et al. (1998) found M. subrotunda to be related to oligotrophic conditions. Moreover, there are several studies that have reported Q. seminulum in environments with high oxygenation rates (Nolet and Corliss, 1990; den Dulk et al., 1998; Jannink et al., 1998; Moodley et al., 1998; Jorissen, 1999; Van der Zwaan et al., 1999; den Dulk et al., 2000). According to Schönfeld (2002), both T. angulosa and the miliolid taxa seem to be the only ones adapted to winnowing and redeposition environments. Therefore, it will be referred to as the



Fig. 3. Factor loadings of 4 factors obtained by R-mode principal component analysis of the planktic foraminifer assemblages. The percentages of the most important species for each factor are also represented. δ¹⁸O values of *G. bulloides* shells (Sierro et al., 2009). Orange bands represent periods when the warmest factor (Factor 1P) dominated the assemblages.



Fig. 4. Relationship between Factor 3B and BFAR. A. Linear simple regression log10 (BFAR) vs. Factor 3B loadings. B. Comparison between Factor 3B loadings and log10 (BFAR).

"Oxygenated Factor" (Table 3). This factor was important during cold events (Fig. 2) when the mouth of the Rhône was near our core site and, in theory, the high organic matter flux should have been triggering a low-oxygen environment. This indicates that another process drove the presence of oxygenated waters at the bottom and changed conditions that would otherwise have been typical of high organic and low oxygen contents.

The main species in Factor 3B is Brizalina dilatata and, to a lesser extent, Bulimina marginata and Bulimina aculeata (Table 1). Brizalina dilatata is generally considered to be a proxy for high organic matter input, sometimes combined with dysoxic conditions (Gooday, 1993; Jorissen, 1999). It prefers shallow intermediate infaunal microhabitats (Corliss, 1991; Barmawidjaja et al., 1992; de Stigter et al., 1998; Jannink et al., 1998). In the Mediterranean region today, this species is particularly abundant in the low-oxic to suboxic environments of the Marmara Sea (Alavi, 1988). In addition, B. dilatata occurs in a wide range of mesotrophic to eutrophic settings (Barmawidjaja et al., 1992; Jorissen et al., 1995; De Rijk et al., 2000; Schmiedl et al., 2000). Bulimina marginata is considered to tolerate low oxygen conditions (Risdal, 1963). It is found in deltaic areas associated with high organic levels, for instance the discharge area of the Mississippi River and the northern Adriatic Shelf, which undergo annual, spring and summer hypoxia because of the high nutrient input from the River Po (Sen Gupta and Machain-Castillo, 1993). Moreover, Olausson (1961) found that the abundance of B. aculeata in the Levantine Basin of the eastern Mediterranean was correlated with relatively high carbon values. This species is present on the Portuguese continental shelf (Levy et al., 1993) and on the "Grande Vasiere" (part of the French Atlantic continental shelf characterized by the accumulation of muddy–silty sediments mainly originated from the Loire and the Garonne) (Duchemin et al., 2005). In a recent study in the Gulf of Lions, it has been related to high levels of organic matter (Mojtahid et al., 2009). Following the TROX model (Jorissen et al., 1995), the number of benthic foraminifers is higher at high values of organic matter and low oxygen concentrations. Therefore, the dominating species in Factor 3B, together with their relationship with the BFAR (Fig. 4), suggest that this factor was important during periods of high organic flux and low-oxygen conditions, coinciding with the proximity of the mouth of the Rhône during MIS 6. Consequently, it will be referred to as the "Eutrophic Factor" (Table 3).

4.2. Environmental conditions in the water column

Factor 1P is mainly composed of *Globorotalia inflata* and *Globigerinoides ruber*. *Globorotalia inflata* is considered to be a transitional species between subpolar and subtropical waters (Bé, 1977). In the Mediterranean Sea, it is a typical winter deep-dwelling species, requiring vertical mixing and a cool, homogeneous water column (Pujol and Grazzini, 1995). *Globigerinoides ruber* is characteristic of subtropical areas, although it is also found in tropical waters with temperatures above 14 °C (Bé, 1977). It occurs throughout the Mediterranean at the end of summer, and it dominates the winter assemblage in the Levantine basin (Pujol and Grazzini, 1995). Accordingly, the presence of *G. inflata*, characteristic of a cool, mixed water column, and *G. ruber*, which appears in warm and stratified environments, suggests that the loadings of this factor were important in warm episodes similar to modern conditions, with summer stratification and winter mixing of the water column. This factor will thus be referred to as the "Warm Factor" (Table 3).

According to the ecology of the dominant species associated with Factors 2P, 3P and 4P, these can be considered cold factors. For this reason it is noticeable certain degree of anticorrelation between Factor 1P and Factor 4P and to a lesser extent with Factor 3P (Fig. 3). In Factor 2P, the main species are Turborotalita guingueloba, Globorotalia scitula and Globigerinita glutinata. Turborotalita quinqueloba is a shallowdwelling species characteristic of polar and subpolar areas (Bé, 1977). It can be associated with a certain degree of turbulence and productivity since it is characteristic of the Polar front (Johanneseen et al., 1994). However, currently it is scarce in the Mediterranean Sea (Pujol and Grazzini, 1995). Globorotalia scitula is generally associated with cool waters (Bé and Hutson, 1977; Hemleben et al., 1989). In glacial times this species was widespread in the Mediterranean but was conspicuously absent during the Holocene and Eemian (Rohling et al., 2002), suggesting that it can be used as a cool water indicator. As mentioned above, G. glutinata is a surface-dwelling species considered to be eurytopic (Lourens et al., 1992). It is not related either to temperature or sea surface productivity (Bé and Hutson, 1977). The main species in this factor are consistent with the principal species comprising the SFDZ (small foraminifer dominance zone) defined by Perez-Folgado et al. (2003) in core samples from the Alboran Sea during the last 70 kyr. This interval defines a period during MIS 3 characterized by sharp fluctuations in the abundance of the main species. In that study the strong variability associated with these species and the turbulence linked to T. quinqueloba imply stressful conditions in the mixed layer due to an excess of turbulence that could have prevented high productivity. Accordingly, we consider this factor as an indicator of cold conditions with strong turbulence in the mixed layer, and hence it will be referred to as the "Turbulence Factor" (Table 3).

Factor 3P is mainly controlled by *Globigerina bulloides* and, to a lesser extent, by *Globigerinita glutinata*. *Globigerinita glutinata* is considered a eurytopic species (Lourens et al., 1992). *Globigerina bulloides* mainly occurs in cold subpolar water (Bé and Tolderlund,



Fig. 5. Relationship between Factor 1B and Condensed Layers (CLs) described by Sierro et al. (2009). A. Factor 1B loadings (Mesotrophic factor). B. Sea level curve (m) (Waelbroeck et al., 2002). C. Sedimentation rates of PRGL 1–4 (m kyr⁻¹). D. % Fine sand (62–150 μm) (Sierro et al., 2009). Gray bands represent condensed layers defined on the basis of % fine sand by Sierro et al. (2009).

1971), in upwelling areas (Kroon and Ganssen, 1989), and in boundary currents (Bé, 1977). In the Mediterranean Sea, it is associated with cold, productive events (Bárcena et al., 2004; Hernández-Almeida et al., 2011). It therefore has higher loadings during the coldest events in MIS 6 and in glacial substage 7.2, coinciding with low sea levels, lower temperatures and the proximity of the mouth of the Rhône (Fig. 3). It will therefore be referred to as the "Cold-productive Factor" (Table 3), associated with some degree of turbulence in the mixed layer.

Factor 4P is controlled by *Neogloboquadrina pachyderma* (dex) and to a lesser extent by *Globigerina bulloides*. *Neogloboquadrina pachyderma* (dex.) occurs from subpolar to tropical regions, but is most prolific when sub-thermocline temperatures are colder than 12 °C (Bé and Tolderlund, 1971). It is often considered a deepdwelling species, living close to or below the thermocline (Fairbanks and Wiebe, 1980). In the Mediterranean Sea, it is associated with the DCM (Deep Chlorophyll Maximum) in cold, productive areas (Pujol and Grazzini, 1995). The presence in this factor of G. bulloides also indicates cold high-productivity water. The difference between Factor 3P and Factor 4P is the predominance of Factor 4P in periods of relatively warmer times than Factor 3P (Fig. 3). In the Mediterranean, N. pachyderma (dex.) usually disappears during the coldest events and therefore in some cases it has been grouped with the temperate foraminifers (Sierro et al., 2009). This is corroborated by the presence of *N. pachyderma* in warm Factor 1P, in which it is ranked in third position (Table 1). Another reason for this behavior is linked to the presence or absence of a thermocline and the formation of a seasonal DCM (Pujol and Grazzini, 1995). Accordingly, henceforth Factor 4P will be referred to as the "Temperateproductive Factor" (Table 3). Although it is possible to infer that this factor is typical of temperate, productive water, it is not possible to determine whether the presence of N. pachyderma (dex.) was due

Table 3

Summary of benthic and planktic foraminifer factors extracted by R-mode principal component analysis. For each factor, we provide the most important species, their names and qualitative environmental characteristics. The qualitative range is defined as follows: ++++ Very high +++ High ++ moderate + low.

Factors	Species	Name	Environment		Factors	Species	Name	Environment			
			Oxygen	Organic matter	Turbulence				Turbulence	Productivity	Temperature
Factor 1B	M. barleeanum U. peregrina C. pachyderma B. inflata	Mesotrophic	++	++	++	Factor 1P	G. inflata G. ruber	Warm	+	+	++++
Factor 2B	T. angulosa C. laevigata Q. seminulum M. subrotunda P. oblonga	Oxygenated	+++ +	+++	++++	Factor 2P	T. quinqueloba G. scitula G. glutinata	Turbulence	++++	++	++
Factor 3B	B. dilatata B. marginata B. aculeata	Eutrophic	+	+++ +	+	Factor 3P	G. bulloides	Cold- productive	+++	++++	+
						Factor 4P	N. pachyderma (dex)	Temperate- productive	++	+++	++

mainly to temperature or to the seasonal stratification of the water column.

4.3. Changes in environmental conditions in the Gulf of Lions along MIS 6 and 7 inferred from benthic and planktic assemblages

During cold stages, high productivity in surface waters in response to a high rate of nutrient supply at times of intense northwesterlies, together with increases in river organic matter and nutrient fluxes owing to low sea levels, contributed the development of an oxygen minimum zone in the subsurface waters flowing along the upper slope. However, wind intensity also favored vertical mixing and hence the oxygen supply to the bottom. Accordingly, the ventilation of the bottom waters on the upper slope would have been the result of the balance between oxygen consumption to oxidize the organic matter flux and the oxygen supply due to deep mixing, especially in winter.

4.3.1. Sea level oscillations

Global sea level reconstructions for MIS 7 and 6 record oscillations of the order of 120 m from MIS 7.5 to the glacial maximum in MIS 6 (Waelbroeck et al., 2002). Consequently, the coastline and the prodeltaic deposits laid down by the Rhône migrated seaward, causing a strong impact on the bottom conditions prevailing on the upper slope. During MIS 7.5, the global sea level was very similar to the present one, and therefore the coastline position was not very different from today's. The mouth of the Rhône and the organic-rich prodeltaic deposits were very distant from the outer continental shelf and the upper slope. With a distant coastline, the input of riversupplied nutrients and organic carbon was very low—hence bottom conditions on the upper slope were very similar to those existing today—and the benthic microfauna was controlled by mesotrophic conditions (Factor 1B) (Fig. 6). Because MIS 7.5 was a warm interglacial period, the planktic foraminifers associated with Factor 1P, typically thriving in temperate-to-warm subtropical waters, are abundant in the sediments. Summer stratification and milder winters did not favor strong vertical mixing in the water column and the rising of nutrients from intermediate waters was limited. This, combined with the low nutrient input from the rivers, resulted in low productivity and low organic carbon export to the seafloor.

In contrast, MIS 6 was characterized by a progressive growth of the northern Hemisphere ice-sheets and the subsequent fall of global sea levels typical of glacial stages. The coastline, the mouth of the Rhône, and the fine-grained prodeltaic deposits gradually shifted to the outer shelf, finally reaching the upper slope. The high input of organic carbon associated with the delta, as well as the high supply of nutrients, increased the productivity of surface waters and the flux of organic carbon to the seafloor. Consequently, a significant increase in the BFAR is recorded in the sediments (Fig. 4), together with a major change in the benthic foraminifer assemblages, which shifted from mesotrophic to eutrophic. During this glacial period, the high abundance of *Globigerina bulloides*, (factor 3P) indicates upwelling and deep vertical mixing in the Gulf of Lions and, as a result, a high organic flux to the sea floor, reinforcing the organic supply by the Rhone.

In conclusion, a positive relationship can be found between the occurrence of mesotrophic conditions on the seafloor and the prevalence of warm surface waters in the Gulf of Lions during periods of high sea levels, and there is a relationship between eutrophic conditions and cold-more eutrophic periods at lowstand times.



Fig. 6. Sea level oscillations. Orange bands represent periods when the warmest planktic factor (Factor 1P) dominated the association. A. Sea level curve (m) (Waelbroeck et al., 2002). B. Eutrophic conditions at the seafloor (Factor 3B loadings). C. Warm conditions in the water column (Factor 1P loadings). D. Mesotrophic conditions at the seafloor (Factor 1B loadings). E. δ¹⁸O values of *G. bulloides* shells (Sierro et al., 2009).



Fig. 7. Effect of millennial climate oscillations on bottom ventilation between 140 and 160 kyr. Orange bands represent periods when the warmest planktic factor (Factor 1P) dominated the association. Blue bands represent periods when the oxygenated benthic factor (Factor 2B) dominated the association. A. Cold-productive conditions in the water column (Factor 3P loadings). B. Turbulent conditions in the water column (Factor 2P loadings). C. Oxygenated conditions at the seafloor (Factor 2B loadings). D. Warm conditions in the water column (Factor 1P loadings). E. Eutrophic conditions at the seafloor (Factor 3B loadings), F. δ^{18} O values of *G. bulloides* shells (Sierro et al., 2009).

4.3.2. Effect of millennial climate oscillations on bottom ventilation

Although MIS 6 was mainly characterized by the prevalence of organic-rich sediments dominated by eutrophic benthic foraminifers during a period of low sea level, the rate of bottom ventilation seems to be high, as may be inferred from the high abundance of oxygenated species. This elevated oxygenation of the seafloor is especially evident in the period between 140 and 160 kyr ago, although, ventilation was repeatedly interrupted by short, millennial-scale events of low oxygenation during warm events (Fig. 7). The warming of surface waters during the glacial period immediately led to stratification of the water column, preventing bottom ventilation. A low rate of oxygen supply, together with a high oxygen consumption linked to the enhanced discharge of organic carbon by the Rhône, led to rapid eutrophication with strong repercussion on the benthic fauna. As shown in Fig. 7D, warm and stratified waters interrupt ventilation events, consistent with the presence of eutrophic assemblages on the bottom (Fig. 7E). Since sea level changes at these time-scales were probably very small, we believe that the main cause of bottom water ventilation on the upper slope were abrupt climate oscillations. Previous studies have related cold stadial events to enhanced deep water ventilation for the last 50 kyr due to a reinforcement of the northwesterlies flowing over the Western Mediterranean Deep Water (WMDW) source area in the Gulf of Lions (Cacho et al., 2000; Sierro et al., 2005; Cacho et al., 2006). Moreover, using a 3D model with paleoproxy data from sea surface to alpine altitudes, Kuhlemann et al. (2008) suggested frequent polar cold-air incursions into the northwestern Mediterranean during the Last Glacial Maximum, enhancing WMDW formation. Although due to its location, our core does not

record the WMDW, events of DSWC falling down the slope, or downwelling processes, ought to be recorded, since they were caused by northwesterly winds (Ulses et al., 2008). Both processes changed bottom conditions, bringing more oxygen and turbulence. The benthic foraminifer species adapted to eutrophic or mesotrophic environments, depending on the proximity of the river mouth, would have been replaced by those adapted to turbulent and oxygenated environments (Fig. 7).

These results agree with those of Martrat et al. (2004) for the same period in the Alboran Sea. The time period ranging from 140 to 155 kyr had the lowest alkenone-based temperatures of both MIS 6 and 7. Moreover, the relative proportion of heptatriatetraenone to total alkenones, a biomarker that can be used as a tracer of cold and/or low salinity waters, had maximum values. Thus, the increases in ventilation matched colder episodes recorded in the Alboran Sea. This corroborates our hypothesis that millennial ventilation events were intensified during colder periods.

Enhanced bottom ventilation was associated with an increased abundance of *Globigerina bulloides* and *Turborotalita quinqueloba* in surface waters, linked either to intense convection and high productivity or to high turbulence in the water column. The relationship between enhanced bottom ventilation and the high productivity of surface water seems to be contradictory, but the strong mixing of surface waters that stimulated fertility and the flux of organic carbon to the bottom also increased the rate of oxygen supply to the sea floor. In these cases, the rate of oxygen supply seems to be higher than the rate of oxygen consumption to oxidize the organic matter input (e.g. river and water column). The relationship of bottom ventilation with *T. quinqueloba* is more logical, since this species is characteristic of cold, turbulent waters and lower productivity. The only exception is found at around 139 kyr, when cold-high productivity waters at the surface (Factor 3P) (Fig. 3) did not correspond to oxygenated bottom waters but to eutrophic conditions (Factor 3B) (Fig. 6D). We believe this would have been due to two simultaneous processes. The increase in productivity in the mixed layer, together with the fact that the sea level was at its lowest level (Fig. 6B), suggests that the high input of organic matter from the river would have accelerated the rates of oxygen consumption, balancing the oxygen supply from surface waters.

During MIS 7, the only ventilation event in glacial substage 7.2 (Factor 2B) (Fig. 2) was related to the predominance of coldproductive conditions in the water column (Factor 3P) (Fig. 3). Although an increase in oxygenated species on the bottom occurred during glacial substage 7.4, they were not the major components of the association, which was dominated by mesotrophic fauna. This result is consistent with an increase in the cold-productive planktic species, although the warm-water, interglacial species were more abundant.

Fresh organic matter coming from the mixed layer associated with the coldest and more productive periods was of higher quality for the benthic communities than detrital organic carbon discharged by the river, owing to its lower C/N ratio (De Rijk et al., 2000). However, our results suggest that the greater quantity of detrital organic carbon at times of low sea levels had a stronger influence on the benthic communities because of its stronger impact on oxygen consumption than the higher quality fresh organic matter. As mentioned above, cold-productive periods were associated with eutrophic seafloor events only when the sea level was lower. Moreover, during MIS 6 highly eutrophic conditions were only reached during warm periods (Fig. 7). Consequently, high loads of organic matter coming from the river, together with the stability of the bottom conditions, preventing winnowing and redeposition, strongly influenced the benthic foraminifer assemblages.

5. Conclusions

Here we have used benthic and planktic foraminifer assemblages to reconstruct past conditions in high resolution in the Gulf of Lions during MIS 6 and 7. Changes in sea level, water temperatures and wind intensity were the main parameters governing the benthic and planktic foraminifer assemblages.

The high sea level during MIS7 and the distance from the coastline reduced the input of organic carbon by rivers. The stratification of the water column, which was favored by the prevalence of warm waters at the surface, resulted in a lower oxygen supply to the bottom. All these oceanic conditions favored the development of mesotrophic benthic foraminifers very similar to those living today on the upper slope. In contrast, during MIS 6 the proximity of the river mouth and the strong input of terrestrial organic carbon rapidly changed bottom conditions due to the high rates of oxygen consumption that favored the growth of eutrophic benthic foraminifers. However, the intensification of cold, northwesterly winds cooled the surface waters and promoted vertical convection in the water column, which stimulated productivity and at the same time enhanced the oxygenation of the sea floor. Even though the input of both the more refractory terrestrial organic carbon and the fresh organic carbon was at its maximum at times of low sea level and cold climates, benthic species adapted to highly oxygenated conditions were abundant. This contradictory behavior can only be explained in terms of the high oxygen input from surface waters due to the strong mixing of the water column. In these periods the rate of oxygen supply due to intense vertical convection was higher than the rate of oxygen consumption. Our results are in agreement with previous studies for the deep sea Mediterranean that have also linked cold periods to a reinforcement of the northwesterlies flowing over the Gulf of Lions.

Well ventilated conditions at the seafloor during MIS 6 were repeatedly interrupted by short, millennial-scale events of low bottom water oxygenation, typically associated with a warming of surface waters. Species living in well-oxygenated waters were replaced by eutrophic benthic foraminifers, accompanied by an increase in warm-water planktic species due to the stratification of the water column in response to the warming of surface waters.

Acknowledgments

The authors are grateful to Dr. Guillermo Francés and Dr. Ann Holbourn who reviewed this manuscript. This work was funded by the Spanish "Ministerio de Ciencia e Innovación" MICINN project CGL2006-10593 and GRACCIE (CONSOLIDER-INGENIO CSD 2007-00067), the regional Government of Castilla y León project GR34, and by a MEC FPI Grant (BES-2007-17602) awarded to Aleix Cortina.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10. 1016/j.palaeo.2011.06.005.

References

- Abu-Zied, R.H., Keatings, K.W., Flower, R.J., 2007. Environmental controls on foraminifera in Lake Qarun, Egypt. Journal of Foraminiferal Research 37, 136–149. Alavi, S.N., 1988. Late Holocene deep-sea benthic foraminifera from the Sea of Marmara.
- Marine Micropaleontology 13, 213–237.
 Aloïsi, J.C., 1986. Sur un modèle de sédimentation deltaîque: contribution à la connaissance des marges passives. Thèsis de doctorat d'Etat Thesis, Université de Perpignan, Perpignan, 162 pp.
- Altenbach, A.V., Pflaumann, U., Schiebel, R., Thies, A., Timm, S., Trauth, M., 1999. Scaling percentages and distributional patterns of benthic foraminifera with flux rates of organic carbon. Journal of Foraminiferal Research 29, 173–185.
- Bárcena, M.A., Flores, J.A., Sierro, F.J., Perez-Folgado, M., Fabres, J., Calafat, A., Canals, M., 2004. Planktonic response to main oceanographic changes in the Alboran Sea (Western Mediterranean) as documented in sediment traps and surface sediments. Marine Micropaleontology 53, 423–445.
- Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S., Van der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the Northern Adriatic Sea. Journal of Foraminiferal Research 22, 297–317.
- Bé, A.W.H., 1977. An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), Oceanic Micropaleontology. Academic Press, pp. 1–100.
- Bé, A.W.H., Hutson, W.H., 1977. Ecology of planktonic foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean. Micropaleontology 23, 369–414.
- Bé, A.W.H., Tolderlund, D.S., 1971. Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Oceans. In: Funnel, B.M., Riedel, W.R. (Eds.), The Micropaleontology of Oceans. Cambridge Univ. Press, London, pp. 105–149.
- Béthoux, J.P., 1979. Budgets of the Mediterranean Sea their dependence on the local climate and on the characteristics of the Atlantic waters. Oceanologica Acta 2, 157–163.
- Béthoux, J.P., 1984. Paleoceanographic changes in the Mediterranean-Sea in the last 20,000 years. Oceanologica Acta 7, 43–48.
- Béthoux, J.P., de Madron, X.D., Nyffeler, F., Tailliez, D., 2002. Deep water in the western Mediterranean: peculiar 1999 and 2000 characteristics, shelf formation hypothesis, variability since 1970 and geochemical inferences. Journal of Marine Systems 33, 117–131.
- Cacho, I., Grimalt, J.O., Sierro, F.J., Shackleton, N., Canals, M., 2000. Evidence for enhanced Mediterranean thermohaline circulation during rapid climatic coolings. Earth and Planetary Science Letters 183, 417–429.
- Cacho, I., Shackleton, N., Elderfield, H., Sierro, F.J., Grimalt, J.O., 2006. Glacial rapid variability in deep-water temperature and delta O-18 from the Western Mediterranean Sea. Quaternary Science Reviews 25, 3294–3311.
- Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., Fabres, J., 2006. Flushing submarine canyons. Nature 444, 354–357.
- Corliss, B.H., 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. Marine Micropaleontology 17, 195–236.
- De Rijk, S., Jorissen, F.J., Rohling, E.J., Troelstra, S.R., 2000. Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera. Marine Micropaleontology 40, 151–166.
- de Stigter, H.C., Jorissen, F.J., Van der Zwaan, G.J., 1998. Bathymetric distribution and microhabitat partitioning of live (Rose Bengal stained) benthic foraminifera along a

shelf to bathyal transect in the southern Adriatic Sea. Journal of Foraminiferal Research 28, 40–65.

- den Dulk, M., Reichart, G.J., Memon, G.M., Roelofs, E.M.P., Zachariasse, W.J., Van der Zwaan, G.J., 1998. Benthic foraminiferal response to variations in surface water productivity and oxygenation in the northern Arabian Sea. Marine Micropaleontology 35, 43–66.
- den Dulk, M., Reichart, G.J., van Heyst, S., Zachariasse, W.J., Van der Zwaan, G.J., 2000. Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea. Palaeogeography Palaeoclimatology Palaeoecology 161, 337–359.
- Duchemin, G., Jorissen, F.J., Andrieux-Loyer, F., Le Loc'h, F., Hily, C., Philippon, X., 2005. Living benthic foraminifera from "La Grande Vasiere", French Atlantic continental shelf: faunal composition and microhabitats. Journal of Foraminiferal Research 35, 198–218.
- Dufau-Julliand, C., Marsaleix, P., Petrenko, A., Dekeyser, I., 2004. Three-dimensional modeling of the Gulf of Lion's hydrodynamics (northwest Mediterranean) during January 1999 (MOOGLI3 Experiment) and late winter 1999: Western Mediterranean Intermediate Water's (WIW's) formation and its cascading over the shelf break. Journal of Geophysical Research-Oceans 109.
- Eberwein, A., Mackensen, A., 2006. Regional primary productivity differences off Morocco (NW-Africa) recorded by modern benthic foraminifera and their stable carbon isotopic composition. Deep-Sea Research Part I-Oceanographic Research Papers 53, 1379–1405.
- Ellis, Messina Catalogue of Foraminifera, 2007. DVD Material. Micropaleontology press.
- Fairbanks, R.G., Wiebe, P.H., 1980. Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance. Science 209, 1524–1526.
- Fatela, F., Taborda, R., 2002. Confidence limits of species proportions in microfossil assemblages. Marine Micropaleontology 45, 169–174.
- Fontanier, C., Jorissen, F.J., Licari, L., Alexandre, A., Anschutz, P., Carbonel, P., 2002. Live benthic foraminiferal faunas from the Bay of Biscay: faunal density, composition, and microhabitats. Deep-Sea Research Part I-Oceanographic Research Papers 49, 751–785.
- Fontanier, C., Jorissen, F.J., Lansard, B., Mouret, A., Buscail, R., Schmidt, S., Kerherve, P., Buron, F., Zaragosi, S., Hunault, G., Ernoult, E., Artero, C., Anschutz, P., Rabouille, C., 2008. Live foraminifera from the open slope between Grand Rhone and Petit Rhone Canyons (Gulf of Lions, NW Mediterranean). Deep-Sea Research Part I-Oceanographic Research Papers 55, 1532–1553.
- Gooday, A.J., 1986. Meiofaunal foraminiferans from the bathyal Porcupine Seabight (northeast Atlantic): size structure, standing stock, taxonomic composition, species diversity and vertical distribution in the sediment. Deep-Sea Research Part a– Oceanographic Research Papers 33, 1345–1355.
- Gooday, A.J., 1993. Deep-sea benthic foraminiferal species which exploit phytodetritus: characteristic features and controls on distribution. Marine Micropaleontology 22, 187–205.
- Gooday, A.J., Lambshead, P.J.D., 1989. Influence of seasonally deposited phytodetritus on benthic foraminiferal populations in bathyal northeast Atlantic: the species response. Marine Ecology-Progress Series 58, 53–67.
- Guarracino, M., Barnier, B., Marsaleix, P., de Madron, X.D., Monaco, A., Escoubeyrou, K., Marty, J.C., 2006. Transfer of particulate matter from the northwestern Mediterranean continental margin: variability and controlling factors. Journal of Marine Research 64, 195–220.
- Hayward, B.W., Hollis, C.J., Grenfell, H., 1994. Foraminiferal associations in Port Pegasus. Stewart Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 28, 69–95.
- Hemleben, C., Spindler, M., Anderson, O.R., 1989. Modern Planktonic Foraminifera. Springer, New York.
- Herguera, J.C., Berger, W.H., 1991. Paleoproductivity from benthic foraminifera abundance: glacial to postglacial change in the west-equatorial Pacific. Geology 19, 1173–1176.
- Hernández-Almeida, I., Bárcena, M.A., Flores, J.A., Sierro, F.J., Sanchez-Vidal, A., Calafat, A., 2011. Microplankton response to environmental conditions in the Alboran Sea (Western Mediterranean): one year sediment trap record. Marine Micropaleontology 78 (1–2), 14–24.
- Ivanov, V.V., Shapiro, G.I., Huthnance, J.M., Aleynik, D.L., Golovin, P.N., 2004. Cascades of dense water around the world ocean. Progress in Oceanography 60, 47–98.
- Jannink, N.T., Zachariasse, W.J., Van der Zwaan, G.J., 1998. Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea). Deep-Sea Research Part I-Oceanographic Research Papers 45, 1483–1513.
- Johanneseen, T., Jansen, E., Flatoy, A., Ravelo, A.C., 1994. The relationship between surface water masses, oceanographic fronts and paleoclimatic proxies in surface sediments of the Greenland, Iceland, Norwegian Seas. NATO ASI Ser.
- Jorissen, F.J., 1999. Benthic foraminiferal successions across Late Quaternary Mediterranean sapropels. Marine Geology 153, 91–101.
- Jorissen, F.J., de Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. Marine Micropaleontology 26, 3–15.
- Jorissen, F.J., Wittling, I., Peypouquet, J.P., Rabouille, C., Relexans, J.C., 1998. Live benthic foraminiferal faunas off Cape Blanc, NW-Africa: community structure and microhabitats. Deep-Sea Research Part I-Oceanographic Research Papers 45, 2157–2188.
- Jouet, G., Berné, S., Rabineau, M., Bassetti, M.A., Bernier, P., Dennielou, B., Sierro, F.J., Flores, J.A., Taviani, M., 2006. Shoreface migrations at the shelf edge and sea-level changes around the Last Glacial Maximum (Gulf of Lions, NW Mediterranean). Marine Geology 234, 21–42.

- Kroon, D., Ganssen, G., 1989. Northern Indian Ocean upwelling cells and the stable isotope composition of living planktonic foraminifers. Deep-Sea Research Part a-Oceanographic Research Papers 36, 1219–1236.
- Kuhlemann, J., Rohling, E.J., Krumrei, I., Kubik, P., Ivy-Ochs, S., Kucera, M., 2008. Regional synthesis of Mediterranean atmospheric circulation during the last glacial maximum. Science 321, 1338–1340.
- Lapouyade, A., De Madron, X.D., 2001. Seasonal variability of the advective transport of particulate matter and organic carbon in the Gulf of Lion (NW Mediterranean). Oceanologica Acta 24, 295–312.
- Lefevre, D., Minas, H.J., Minas, M., Robinson, C., Williams, P.J.L., Woodward, E.M.S., 1997. Review of gross community production, primary production, net community production and dark community respiration in the Gulf of Lions. Deep-Sea Research Part II—Topical Studies in Oceanography 44, 801–832.
- Levy, A., Mathieu, R., Poignant, A., Rossetmoulinier, M., Ubaldo, M.D., Ambroise, D., 1993. Recent foraminifera from the continental margin of Portugal. Micropaleontology 39, 75–87.
- Licari, L.N., Schumacher, S., Wenzhofer, E., Zabel, M., Mackensen, A., 2003. Communities and microhabitats of living benthic foraminifera from the tropical East Atlantic: impact of different productivity regimes. Journal of Foraminiferal Research 33, 10–31.
- Loeblich, A.R., Tappan, H., 1988. Foraminiferal Genera and Their Classification. Springer, New York.
- Lourens, L.J., Hilgen, F.J., Gudjonsson, L., Zachariasse, W.J., 1992. Late Pliocene to early Pleistocene astronomically forced sea surface productivity and temperature variations in the Mediterranean. Marine Micropaleontology 19, 49–78.
- Mackensen, A., Sejrup, H.P., Jansen, E., 1985. The distribution of living benthic foraminifera on the continental slope and rise off southwest Norway. Marine Micropaleontology 9, 275–306.
- Martrat, B., Grimalt, J.O., Lopez-Martinez, C., Cacho, I., Sierro, F.J., Flores, J.A., Zahn, R., Canals, M., Curtis, J.H., Hodell, D.A., 2004. Abrupt temperature changes in the Western Mediterranean over the past 250,000 years. Science 306, 1762–1765.
- Melki, T., Kallel, N., Jorissen, F.J., Guichard, F., Dennielou, B., Berne, S., Labeyrie, L., Fontugne, M., 2009. Abrupt climate change, sea surface salinity and paleoproductivity in the western Mediterranean Sea (Gulf of Lion) during the last 28 kyr. Palaeogeography Palaeoclimatology Palaeoecology 279, 96–113.
- Millot, C., 1982. Analysis of Upwelling in the Gulf of Lions. Elsevier Oceanography Series. Elsevier, pp. 143–153.
- Millot, C., 1990. The Gulf of Lions' hydrodynamics. Continental Shelf Research 10, 885–894.
- Millot, C., 1999. Circulation in the Western Mediterranean Sea. Journal of Marine Systems 20, 423–442.
- Mojtahid, M., Jorissen, F., Lansard, B., Fontanier, C., Bombled, B., Rabouille, C., 2009. Spatial distribution of live benthic foraminifera in the Rhone prodelta: faunal response to a continental-marine organic matter gradient. Marine Micropaleontology 70, 177–200.
- Moodley, L., Van der Zwaan, G.J., Rutten, G.M.W., Boom, R.C.E., Kempers, A.J., 1998. Subsurface activity of benthic foraminifera in relation to porewater oxygen content: laboratory experiments. Marine Micropaleontology 34, 91–106.
- Morel, A., André, J.M., 1991. Pigment distribution and primary production in the Western Mediterranean as derived and modeled from Coastal Zone Color Scanner observations. Journal of Geophysical Research 96, 12685–12698.
- Nolet, G.J., Corliss, B.H., 1990. Benthic foraminiferal evidence for reduced deep-water circulation during sapropel deposition in the eastern Mediterranean. Marine Geology 94, 109–130.
- Olausson, E., 1961. Studies of deep sea cores. Reports of the Swedish Deep Sea Expedition, 1947–48.
- Palanques, A., de Madron, X.D., Puig, P., Fabres, J., Guillen, J., Calafat, A., Canals, M., Heussner, S., Bonnin, J., 2006. Suspended sediment fluxes and transport processes in the Gulf of Lions submarine canyons. The role of storms and dense water cascading. Marine Geology 234, 43–61.
- Perez-Folgado, M., Sierro, F.J., Flores, J.A., Cacho, I., Grimalt, J.O., Zahn, R., Shackleton, N., 2003. Western Mediterranean planktonic foraminifera events and millennial climatic variability during the last 70 kyr. Marine Micropaleontology 48, 49–70.
- Pujol, C., Grazzini, C.V., 1995. Distribution patterns of live planktic foraminifers as related to regional hydrography and productive systems of the Mediterranean Sea. Marine Micropaleontology 25, 187–217.
- Rabineau, M., Berné, S., Aslanian, D., Olivet, J.L., Joseph, P., Guillocheau, F., Bourillet, J.F., Ledrezen, E., Granjeon, D., 2005. Sedimentary sequences in the Gulf of Lion: a record of 100,000 years climatic cycles. Marine and Petroleum Geology 22, 775–804.
- Rasmussen, T.L., Backstrom, D., Heinemeier, J., Klitgaard-Kristensen, D., Knutz, P.C., Kuijpers, A., Lassen, S., Thomsen, E., Troelstra, S.R., van Weering, T.C.E., 2002. The Faroe-Shetland Gateway: Late Quaternary water mass exchange between the Nordic seas and the northeastern Atlantic. Marine Geology 188, 165–192.
- Rigual-Hernández, A.S., Bárcena, M.A., Sierro, F.J., Flores, J.A., Hernández-Almeida, I., Sanchez-Vidal, A., Palanques, A., Heussner, S., 2010. Seasonal to interannual variability and geographic distribution of the silicoflagellate fluxes in the Western Mediterranean. Marine Micropaleontology 77, 46–57.
- Risdal, 1963. Foraminiferfaunaen i en del sedimentkjerner fra indre Oslofjord. Norges Geologiske Undersoekels 224, 5–90.
- Rohling, EJ., Jorissen, F.J., de Stigter, H.C., 1997. 200 year interruption of Holocene sapropel formation in the Adriatic Sea. Journal of Micropalaeontology 16, 97–108.
- Rohling, E.J., Cane, T.R., Cooke, S., Sprovieri, M., Bouloubassi, I., Emeis, K.C., Schiebel, R., Kroon, D., Jorissen, F.J., Lorre, A., Kemp, A.E.S., 2002. African monsoon variability during the previous interglacial maximum. Earth and Planetary Science Letters 202, 61–75.

- Schmiedl, G., Hemleben, C., Keller, J., Segl, M., 1998. Impact of climatic changes on the benthic foraminiferal fauna in the Ionian Sea during the last 330,000 years. Paleoceanography 13, 447–458.
- Schmiedl, G., de Bovee, F., Buscail, R., Charriere, B., Hemleben, C., Medernach, L., Picon, P., 2000. Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. Marine Micropaleontology 40, 167–188.
- Schönfeld, J., 1997. The impact of the Mediterranean Outflow Water (MOW) on benthic foraminiferal assemblages and surface sediments at the southern Portuguese continental margin. Marine Micropaleontology 29, 211–236.
- Schönfeld, J., 2002. A new benthic foraminiferal proxy for near-bottom current velocities in the Gulf of Cadiz, northeastern Atlantic Ocean. Deep-Sea Research Part I-Oceanographic Research Papers 49, 1853–1875.
- Sen Gupta, B.K., Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. Marine Micropaleontology 20, 183–201.
- Sierro, F.J., Hodell, D.A., Curtis, J.H., Flores, J.A., Reguera, I., Colmenero-Hidalgo, E., Bárcena, M.A., Grimalt, J.O., Cacho, I., Frigola, J., Canals, M., 2005. Impact of iceberg melting on Mediterranean thermohaline circulation during Heinrich events. Paleoceanography 20, PA2019, doi:10.1029/2004PA001051.
- Sierro, F.J., Andersen, N., Bassetti, M.A., Berne, S., Canals, M., Curtis, J.H., Dennielou, B., Flores, J.A., Frigola, J., Gonzalez-Mora, B., Grimalt, J.O., Hodell, D.A., Jouet, G., Perez-

Folgado, M., Schneider, R., 2009. Phase relationship between sea level and abrupt climate change. Quaternary Science Reviews 28, 2867–2881.

- Sournia, A., Brylinski, J., Dallot, S., Le Corre, P., Leveau, M., Prieur, L., Froget, C., 1990. Fronts hydrologiques au large des cotes francaises: Les sites-ateliers du programme Frontal. Oceanologica Acta 13, 413–438.
- Ulses, C., Estournel, C., Puig, P., de Madron, X.D., Marsaleix, P., 2008. Dense shelf water cascading in the northwestern Mediterranean during the cold winter 2005: quantification of the export through the Gulf of Lion and the Catalan margin. Geophysical Research Letters 35.
- Van der Zwaan, G.J., Duijnstee, I.A.P., den Dulk, M., Ernst, S.R., Jannik, N.T., Kouwenhoven, T.J., 1999. Benthic foraminifers: proxies or problems? A review of paleocological concepts. Earth-Science Reviews 46, 213–236.
- Vénec-Péyre, M.T., 1990. Contribution of foraminifera to the study of Recent sedimentation in the Gulf of Lions (western Mediterranean Sea). Continental Shelf Research 10, 869–883.
- Vilibic, I., Grbec, B., Supic, N., 2004. Dense water generation in the north Adriatic in 1999 and its recirculation along the Jabuka Pit. Deep-Sea Research Part I-Oceanographic Research Papers 51, 1457–1474.
- Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Science Reviews 21, 295–305.