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Live benthic foraminiferal faunas from the French Mediterranean Coast: Towards a new biotic index of environmental quality

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Abstract:

In this study, living (Rose Bengal stained) foraminiferal faunas from 31 stations along the entire French Mediterranean Sea coast except Corsica have been analysed. In the context of the Water Framework Directive, the aim was to develop a biotic index to evaluate the benthic ecosystem quality. Therefore, different faunal parameters (diversity indices, wall structure proportion, and indicative species groups) have been tested to determine their relevance as indicators of environmental conditions. The best results are obtained with a biotic index based on the relative proportion of stress-tolerant taxa. For ecosystem quality evaluation, it is essential to distinguish between natural and anthropogenic eutrophication phenomena. In order to do so, we applied a correction on our biotic index, using the expected percentage of stress-tolerant species in natural environments, in function of sediment grain size (percentage <63 µm). Finally, a comparison of the different faunal parameters calculated for two different sediment intervals (0–1 and 0–4 cm) indicates clearly that the analysis of the uppermost centimetre of the sediment is sufficient to obtain relevant information needed for bio-monitoring purposes.

Highlights

► Development of a biotic index based on benthic foraminiferal faunas. ► Discriminate between natural and anthropogenic eutrophication. ► Relevance of foraminiferal parameters for the development of biotic index. ► Inventory of living benthic foraminiferal faunas of the French Mediterranean coast. ► Restrict faunal analysis to the first cm of sediment for bio-monitoring studies.

Keywords: Coastal Mediterranean Sea ; Foraminiferal faunas ; Indicative species ; Tolerant species ; Biotic index ; Water Framework Directive

1. Introduction

Due to their strategic location at the interface of marine and terrestrial areas, coastal ecosystems have been impacted by human activities since the advent of human societies. Anthropogenic impact in coastal marine ecosystems has multiple origins, such as urban sewage, industrial and agricultural activities or fisheries, and results in environmental problems, such as eutrophication, oxygen deficiency, chemical pollution or physical disturbance. Awareness of recent changes in ecological conditions in many coastal seas has fostered a need to assess increasing anthropogenic pressures and their consequences on sediment and water quality, and to suggest measures to reverse this trend. In this context, the European commission implemented the Water Framework Directive (WFD, Directive 2008/56/EC) with the aim to obtain (or to maintain) a “good status” for all the European waters by 2015. The WFD defines the ecological status as the quality of the structure and functioning of ecosystems and is assessed using different planktonic and benthic indicators (e.g. phytoplankton, macro-algae, angiosperms, fish faunas and soft substrate benthic invertebrate fauna) (Devlin et al., 2007).

The study of the benthic macrofauna is the traditional tool for benthic ecological quality assessment and bio-monitoring studies, since macrofauna responds in a predictable way to anthropogenic and natural stress (Pearson and Rosenberg, 1978). Environmental managers need an easily interpretable ecological quality status based on quantitative data. Numerous biotic indicator methods were developed for macrofauna (see review in Diaz et al., 2004) based either on diversity indices (e.g. Shannon index, Pielou, 1975) or on indices based on the relative proportions of faunal groups with different ecological characteristics. Some of the latter methods are based on groups with different feeding strategies (e.g. ITI, Word, 1979), whereas others distinguish several classes of pollution-sensitive versus opportunistic, pollution-tolerant, species (e.g. AMBI, Borja et al., 2000; BENTIX, Simboura and Zenetos, 2002; BOPA, Gomez Gesteira and Dauvin, 2002, Dauvin and Ruellet, 2007; BQI, Rosenberg et al., 2004).

More recently, benthic foraminiferal faunas have been increasingly used as bio-indicators of anthropogenic pollution. Initially, foraminifera were mainly studied in fossil records for biostratigraphic and paleoenvironmental purposes. The interest for the living organisms greatly expanded when researchers started to study their ecology in the 1960‟s. Because of their short life cycle (3 months to 2 years, Murray, 1991), these organisms are able to respond rapidly to environmental changes, with a change in diversity and in species composition. Such rapid adaptive responses have been observed in response to changes in the quantity and quality of organic supplies (e.g. Altenbach and Sarnthein, 1989; Corliss and Emerson, 1990; Corliss, 1991; Herguera and Berger, 1991; Rathburn and Corliss, 1994; Jorissen et al., 1995, 1998; De Rijk et al., 2000; Licari et al., 2003), in oxygen conditions (e.g. Sen Gupta and Machain-Castillo, 1993 ; Gooday, 1994 ; Jorissen et al., 1995 ; Gooday et al., 2000), pH (e.g. Murray, 1989), salinity and temperature (e.g. Murray, 2006). Moreover, foraminifera are ubiquitous in marine environments, inhabiting transitional to abyssal areas and tropical to polar latitudes (review in Murray, 2006). Foraminifera are abundant in marine sediments, even in deep-sea environments where they commonly represent more than 50% of the total biomass (Gooday et al., 1992). The high number of individuals sampled with a little quantity of sediment assures the robustness of data analysis and limits the impact of sampling on the seafloor. Furthermore, foraminiferal taxonomy is easy compared to the identification of macrofauna, since only a single biological group is considered, instead of several phyla. Although foraminifera represent only a part of the trophic niches and guilds, the ecological characteristics of the different species are different enough to obtain reliable information about the environmental conditions, as it has been shown in a wide range of papers on benthic foraminiferal ecology (e.g. Gooday and Rathburn, 1999; Jorissen et al., 2007; Murray, 2006). Finally, the main advantage of foraminifera is the conservation of a large part of their tests (shells) in the sediment after their death. The study of dead faunas at different depths in the sediment can give important information about the natural conditions which existed before a site became polluted. This is especially useful in case of the absence of an environmental baseline study (Alve, 1995). Comparison of living faunas and pre-impact faunas can also yield essential information about individual species ecological strategies. For example, opportunistic species which have colonised the area, or sensitive species which disappear from the area after the onset of pollution, can easily be recognised. As such, the comparison of live and dead faunas can ensure that lists with species ecological characteristics correctly translate the behaviour of the various species at the study site.

All these advantages make foraminifera an innovative and very interesting tool for bio-monitoring studies of anthropogenic impact (reviews in Alve, 1995; Nigam et al., 2006; Frontalini and Coccioni, 2011). The first studies using foraminifera as indicators of environmental quality appeared in the 1960‟s (Resig, 1960; Watkins, 1961; Bandy et al., 1964, 1965; Seiglie, 1968, 1971; Clark, 1971). Today, numerous studies use foraminifera as bio-indicators of different types of pollution such as eutrophication (e.g. Platon et al., 2005; Mojtahid et al., 2008; Hyams-Kaphzan et al., 2009), heavy metals (e.g. Alve, 1991; Armynot du Châtelet et al., 2004; Frontalini et al., 2008; Bergamin et al., 2009; Cherchi et al., 2009; Coccioni et al. 2009; Frontalini et al., 2009; Romano et al., 2009; Vilela et al., 2011), urban sewage (e.g. Burone et al., 2006; Teodoro et al., 2010), oil drilling activities (e.g. Durrieu et al., 2006; Mojtahid et al. 2006; Duchemin et al. 2008; Jorissen et al., 2009; Denoyelle et al., 2010), oil spills (e.g. Morvan et al., 2004) or aquaculture (e.g. Bouchet et al., 2007). However, no standardised protocols for sampling and sampling treatment have been defined until recently (Schönfeld et al., 2012) so that direct comparison of the various studies is very difficult, if not impossible. However, a careful observation of the faunal patterns described in these studies allows identifying different types of species behaviour in response to pollution. Just as for macrofauna, some studies tried to develop biotic indices, either based on faunal diversity (e.g. Bouchet et al., 2012) or on the proportion of indicative species (e.g. Mojtahid et al. 2006; Jorissen et al., 2009).

In the present study, we analyse living (Rose Bengal stained) foraminiferal faunas from the French Mediterranean Sea coast (except Corsica) in the context of the WFD, with the aim to evaluate the ecosystem quality. The study area represents more than 1000 km of coastal zone for which the presence of anthropogenic stress parameters is badly known. There are no point sources of pollution close to sampling stations, and there are no well-defined reference stations exempt of any anthropogenic impact either. Therefore, we first analysed the various faunal parameters (faunal density, diversity and faunal composition) that could be used for the evaluation of the environmental quality. Next, we tried to take into account the natural variability of the system in order to distinguish between the impact of this natural variability and a putative anthropogenic impact. Unfortunately, our study was performed prior to the establishment of a standardised sampling and sampling treatment protocol by the FOBIMO group (Schönfeld et al., 2012), and therefore does not follow all recommendations made in this paper. However, by comparing the faunal data for the 0-1 cm and 0-4 cm sediment levels, we tested the possibility to restrict faunal analyses to the topmost centimetre, as recommended by Schönfeld et al. (2012). By studying only the topmost centimetre, the time needed for picking the foraminifera would be largely reduced, making the method better adapted for cost-efficient bio-monitoring studies. This study represents the first crucial step for the development of a new biotic index based on benthic foraminiferal faunas. In order to be used routinely in future surveys, the presented index will need to be tested in cases with a strong pollution gradient and in other geographic areas. Since it is the first large scale study of living foraminiferal faunas along the entire French Mediterranean coast (except Corsica), the results of the present study can also serve as a global inventory and a baseline for future studies.

2 Material and methods

2.1 Regional setting of the study area

The Mediterranean Sea is generally considered as a semi-enclosed oligotrophic basin. Low salinity surface water from the Atlantic Ocean enters the Mediterranean Sea through the Strait of Gibraltar and creates the Liguro-Provencal Current (LPC) which flows along the French Mediterranean coast, from Italy to Spain through the Gulf of Lion (Millot and Taupier-Letage, 2005; Pairaud and Desmare, 2011). The LPC can develop small scale gyres, depending of the background stratification or external forcing that can influence the shelf circulation.

There is a clear difference in the continental shelf characteristics along the Mediterranean French coast. The continental shelf in front of the Provence Alpe Côte d‟Azur region is relatively narrow, less than 1 mile wide (Pairaud and Desmare, 2011). East of Toulon, an area with rocky sea floor is interrupted by several small embayments containing more fine-grained sediments, such as the Bay of Villefranche, between Villefranche and Nice. On the western side of the French Mediterranean coast, the continental shelf of the Gulf of Lion is wide (up to 40 miles; Bassetti et al., 2006) and consists of a large crescent shaped area incised by submarine canyons (Berné and Gorini, 2005). The bottom sediment distribution displays a mid-shelf mud belt and the inner and outer shelf regions with mixed sandy to muddy deposits (Aloisi et al., 1973).

The Gulf of Lions is also strongly influenced by the Rhône River input (Raimbault and Durrieu de Madron, 2003). With a mean annual discharge of 1700m^3/s (Thill et al., 2001), the Rhône is one of the main sources of freshwater and organic carbon for the Mediterranean Sea (Pont, 1997; Sempéré et al., 2000). The Rhône River has a mean sediment discharge of about 9.9±6.4 10^9 Kg/yr (Sempéré et al., 2000; Pont et al., 2002), accounting for 80% of the riverine input to the Gulf of Lions (Durrieu de Madron et al., 2000). The Rhône prodelta is characterized by silty muds with high organic carbon content (1–2%; Durrieu de Madron et al., 2000) and very high sediment accumulation rates. Also smaller coastal rivers (e.g. the Têt and Hérault Rivers) can significantly contribute to the sediment budget in this area (Kim et al., 2006).

Finally, this part of the Mediterranean Sea is characterised by endemic *Posidonia* seagrass meadows. In our study area, *Posidonia* meadows are located in front of Banyuls-sur-Mer (Blanc-Vernet, 1969, 1984; Vénec-Peyré and Le Calvez, 1981, 1988; Vénec-Peyré, 1984) and form a continuous band from the east side of the Rhône prodelta to the Italian frontier (Boudouresque et al., 2006).

2.2 Sampling strategy

From March 26th to April 9th 2009, 31 stations were sampled for the study of benthic foraminiferal faunas along the French Mediterranean coast on board of the research vessel "Europe" (Figure 1, Appendix A). The location of the stations was chosen according to the WFD criteria, i.e. within one mile from the coastline and at least one station per water body (i.e., a coherent geographic area based on physical (e.g. hydrodynamic, sedimentological) criteria influencing biological activities).

2.3 Foraminiferal sampling methods

Surface sediment was sampled using a Reineck box corer, which was subsampled with plexiglass cores (diameter 7.1cm). Only station Cerbère could be sampled with an interface corer (Gemax twin corer, core diameter 8.8cm).

On board, cores were sliced horizontally, every half centimetre from the surface to 2cm depth, every centimetre between 2 and 6cm depth, and every two centimetres from 6 to 10cm depth. Sometimes, cores were too short to sample until 10cm depth. For stations Gruissan, Lavandou and Faraman, it was not possible to take a core in the Reineck box (e.g. because of the presence of many pebbles), and the first centimetre of the surface was sampled with a spoon. In this case, after homogenization, 50cm^3 of sediment was subsampled for foraminiferal analyses.

After sampling, sediments were stored in plastic bottles filled with a mixture of ethanol (95%) and Rose Bengal stain (1g/l). Rose Bengal is commonly used to obtain a rapid overview of the living faunas. It stains the cytoplasm of foraminifera alive at the time of sampling (Walton, 1952), or which died in a recent past (weeks to months, Bernhard, 1988; Corliss and Emerson, 1990), and in which the non degraded proteins are still stainable. Ethanol allows preserving stained cellular tissues for a prolonged period of time. Samples were gently shaken to obtain a homogeneous mixture and were transported to the laboratory for further processing.

2.4 Foraminiferal analyses

In the laboratory, sediment samples treated with Rose Bengal were sieved through 150 and, if necessary, 500µm mesh screens. For our study, only the > 150µm or 150-500µm fraction was analysed, depending on the station. The >500µm size fraction was removed when the sediment contained large quantities of vegetal detritus, shell fragments or coarse sand, which complicated foraminiferal picking. The >500µm fraction was checked on some occasions and no living foraminifera were found. We consider therefore that in our study area, the results obtained for the 150-500µm size fraction are comparable with those of the >150µm fraction. Also Bouchet et al. (2012) observed that the number of individuals >500µm in their samples from the Norwegian Skagerrak coast was minimal. Unfortunately, our foraminiferal analyses were performed prior to the establishment of the methodological recommendations of the FOBIMO group (Schönfeld et al., 2012). The main differences between our methodology and the one described by the FOBIMO group is the use of the >150µm instead of the >125µm size fraction, and the absence of replicate cores, which could not be sampled due to time constraints.

Rose Bengal stained foraminifera were wet-picked in 50% ethanol under a binocular microscope (Leica MZ95). Only specimens showing a clear pink colour (or red, depending on the species) in all but the last chambers were considered as living fauna. If necessary, opaque porcelaneous and agglutinated specimens were broken to check for the presence of protoplasm. Next, foraminifera were arranged on micropaleontological slides, identified on species level using taxonomic handbooks, and counted.

In order to study the vertical distribution (and microhabitats) of living foraminifera in the sediment, 14 stations have been analysed until at least 4cm depth in sediment (station Toulon Grande Rade has only been sampled until 3cm) and a maximum of 10cm depth. The faunal parameters from the 0-4cm sediment interval have been compared to those obtained for the 0-1cm interval, to determine whether the study of deeper sediment intervals (time-consuming and therefore more expensive) yields important complementary information. An important aim of the present study was to determine whether the study of the 0-1cm sediment interval is sufficient to describe the quality of the benthic ecosystem, if so, supporting one of the recommendations of the FOBIMO group (Schönfeld et al., 2012).

2.5 Foraminiferal parameters

For each station and studied sediment interval (i.e., 0-1cm or 0-4cm), we calculated the following faunal parameters: 1) total foraminiferal density (standardised for a 50cm² sediment surface), 2) specific richness, and 3) the respective proportion of the three principal foraminiferal groups (perforate, porcelaneous and agglutinated foraminifera). To describe the diversity of the foraminiferal faunas, we used the Shannon-Wiener H index (Hayek and Buzas, 1997) and the Equitability J index (Pielou, 1966) which are defined by the following equations:

$$H = -\sum\left(\left(\frac{n_i}{N}\right) \times \ln\left(\frac{n_i}{N}\right)\right) \qquad \text{and} \qquad J = \frac{H}{\ln(S)}$$

where n_i is the number of individuals of species i, N is the total number of individuals, and S is the total number of species at the considered station. The Shannon-Wiener index links the number of species to the assemblage density whereas the Equitability index focuses particularly on the distribution of individual densities between the different species (it distinguishes between samples with comparable densities for all species or samples with a dominance of one or a few species).

Because foraminiferal abundances are very different between stations, we also calculated (using PAST software, Hammer and Harper, 2005) the expected number of species from a sub-sample of 50 individuals taken from the population of all the individuals (ES_{50}). The concept of expected number of species (ES) was first introduced by Sanders (1968) but its computation was modified by Hurlbert (1971). It is computed as:

$$ES_{50} = 1 - \sum_{i=1}^{s} \frac{(N - N_i)!(N - 50)!}{(N - N_i - 50)!N!}$$

where N is the total abundance of individuals at the considered station, N_i is the abundance of the ith species at the considered station, and s is the number of species at the considered station. ES_{50} was not calculated when absolute density was lower than 50 individuals.

After testing the data for normal distribution (Shapiro-Wilk test adapted to small size samples, $n<50$), we used parametric (Student test) or non parametric (Wilcoxon test) statistical analyses for paired samples in order to compare the data obtained for 0-1cm and 0-4cm sediment intervals. Differences were considered significant when $p<0.05$.

We also studied the vertical distribution of the various taxa in the first centimetres of sediment. Foraminiferal microhabitats are controlled by physical, chemical and biological processes (Corliss, 1985; Buzas et al., 1993; Jorissen et al., 1995). The microhabitat concept allows a better understanding of the food and oxygen needs of each species. Therefore we calculated the Average Living Depth (ALD_x) for the total fauna of the core as follows (Jorissen *et al.*, 1995):

$$ALD_x = \sum_{i=1,x} \frac{(n_i \times D_i)}{N}$$

in which ALD_x is the average living depth (in cm) of the fauna in a core of x centimetres depth; n_i is the number of specimens in the sediment interval i; D_i is the midpoint of the sediment interval i (in cm); and N is the total number of individuals for all levels.

2.6 Environmental parameters

Pore water oxygen profiles were measured on board under *in situ* temperature conditions using a cathode-type mini-electrode (100 or 500µm tips, Unisense©) (Revsbech 1983; Helder and Bakker 1985; Revsbech and Jørgensen 1986) for Reineck cores with a well preserved sediment water interface with overlying bottom waters. These analyses were generally duplicated and allowed to determine the maximum oxygen penetration depth (OPD) in the sediment.

During the oceanographic cruise, in addition to sediment for foraminiferal analysis, sediment was also sampled for grain size and total organic matter analyses. Grain size analysis was conducted using a Malvern® Mastersizer 2000 laser microgranulometer. Organic matter content corresponds to ash free dry weight. Weight-loss after combustion (450°C, 5H) of lyophilised samples is measured.

3 Results

3.1 Sediment characteristics

The large difference in the continental shelf features between the eastern and western French Mediterranean coast has an important impact on the sediment characteristics observed at our sampling stations.

The 31 stations sampled have been chosen according to the Water Framework Directive strategy, and are systematically positioned within 1 mile from the coast line. Because of this sampling policy and the heterogeneity of the French Mediterranean coast, there is a clear difference in the average water depth of the stations from the western part of our study area (18m on average) compared to those from the east (40m on average). The limit between the two areas is approximately positioned between the stations Fos and Carry (Figure 2a, Appendix B).

The grain size analyses show a clear difference between western and eastern stations (Figure 2c-d-e, Appendix B). Stations west of Carry contain a low proportion of sand >250µm, with the exception of the stations Collioure and Cerbère, which are located at the most western part of the French coast. Conversely, the eastern stations show a high proportion of medium (250-

500µm) and coarse (500-1000µm) sands, with the exception of some stations (e.g. Marseille Jetée, Ile Embiez, Nice, Menton). There is a significant positive correlation between the percentage of the >500µm fraction and water depth (r=0.50, p<0.05; Appendix C), which underlines the difference in sediment characteristics along the French Mediterranean coast. Conversely, stations located close to the Rhône river mouth (Fos, Carteau, Beauduc) show a high proportion of clay and silt particles (<63µm), in response to a continuous input of fine-grained sediment from the Rhône river.

The organic matter content (Figure 2b, Appendix B) has been analysed on the total sediment, without any pre-treatment. Consequently, this organic matter is not only composed of marine phytoplankton detritus and of river-supplied continental organic matter, but also by much larger debris of macro-algae and seagrass (roots, leaves). The feeding strategies of foraminifera are various, from detritivory on labile or also more refractory organic matter, to carnivory and bactivory (review in Murray et al. 2006). In our study area, marine and continental sedimentary organic matter can probably serve as food for the benthic foraminifera, which is probably not the case for the seagrass debris. In fact, the trophic state of marine sediments is not only dependent on the absolute quantities of organic matter deposited on the sea floor, but it is also a function of its biochemical composition and nutritional quality for consumers (Pusceddu et al., 2009). Several studies (e.g. Mateo et al., 2006; Østergaard Pedersen et al., 2011) have shown that the roots, rhizomes, and leaf sheaths of *Posidonia* decompose very slowly due to their high content of lignin, cellulose, and phenolic compounds (Harrison, 1989; Klap et al., 2000), which are not readily degraded by microbes (Godshalk and Wetzel, 1978). Therefore the large amounts of *Posidonia* leaves and roots found at several stations in our study area, resulting in very high OM values in some stations, cannot be considered as readily available food for benthic organisms. Consequently, it appears impossible to use the OM percentages as measure of the trophic level or as an indicator of anthropogenic pressure. There is no clear west-east trend in the OM percentage (Figure 2b), but there is a statistically significant positive correlation between the OM content and the percentage of clay/silt (<63µm) particles (r=0.42, p<0.05; Appendix C), as was observed previously in other coastal areas (e.g. Jorissen, 1987, 1988; Fontanier *et al.*, 2008). Large quantities of macro-algae and seagrasses (e.g. detritus of *Posidonia* roots) observed in the sediment collected at stations east of Fos explain the abnormally high OM percentages found in some stations with coarse sediments (e.g. Ile Maire, Porquerolles, Ile Levant).

Summarising, natural environmental characteristics appear to be very different between the western stations (lower water depth, fine sediment, enriched in sedimentary organic matter) and the eastern stations (higher water depth, coarser sediment, and sometimes abundant plant remains) in our study area. The faunal assemblages that are colonising these different types of environments will therefore be very different naturally. This bias will have to be taken into account when trying to construct a bio-indicator method based on the foraminiferal faunas. However, it is very probable that this strong west-east dichotomy will equally affect the macrofaunal distribution.

3.2 Diversity and density of the living fauna

Living foraminiferal densities standardised for 50cm² are highly variable among stations (Figure 3a, Appendix B). For the 0-1cm sediment interval (31 stations considered), the total number of foraminifera varies between 22 specimens/50cm² for station Faraman and 2091 specimens/50cm² for station Grau du Roi. For the 0-4cm sediment interval (14 stations considered), total densities vary between 387 and 2526 specimens/50cm² for stations Ile Maire and Grau du Roi, respectively. The very low densities found at stations Faraman, Lavandou and Porquerolles (22, 43 and 51 specimens/50cm², respectively) could result from the loss of a large part of the superficial sediment before the Reineck core reached the deck of the ship.

The stations Leucate, Villefranche and Menton exhibit a particularly strong difference in densities between both studied sediment intervals (0-1 and 0-4cm), indicating the presence of abundant live foraminiferal faunas in deeper sediment layers. In most other stations, this difference is smaller.

Diversity indices are relatively high at all studied stations (Appendix B). Species richness in the first centimetre of sediment varies between 20 (station Agde Est) and 73 species (station Monaco) (Figure 3b). The Shannon-Wiener index (Figure 3c) varies between 1.9 (station Grau du Roi) and 3.7 (station Monaco). The Equitability index (Figure 3d), which gives information about the dominance of one or more taxa, varies between 0.53 (station Grau du Roi) and 0.96 (station Marseille Grande Rade). According to these indices, biodiversity seems to increase to the eastern part of the French Mediterranean coast, where the depth of the sampling stations is more important. There is indeed a statistically significant positive correlation between the diversity indices and water depth (r=0.79 for ES_{50}, r=0.74 for

Shannon-Wiener index, r=0.66 for specific richness, and r=0.52 for Equitability index, $p<0.05$ for all correlations; Appendix C).
The expected number of species from a sub-sample of 50 individuals (ES_{50}, Figure 3e) exhibits smaller differences between stations compared to uncorrected species richness. In general, stations with relatively low total faunal densities (e.g. Cerbère, Marseille Grande Rade or Porquerolles) deviate less from the overall trend. This observation confirms the good performance of the ES_{50} index in case of samples with large differences in faunal density, which is also the case for the Shannon-Wiener and Equitability indices.

The comparison of the diversity indices for the 0-1cm and 0-4cm intervals shows first that on average 8 additional species (a maximum of 16 species), have been found when the 1-4cm interval is added (Figure 3b). However, the difference in Shannon-Wiener and ES_{50} indices between the 2 considered depth intervals is relatively small (Figure 3c and 3d). Species exclusively found in the 1 to 4cm sediment interval are represented by few specimens; the density differences between the 0-1 and 0-4cm levels highlighted in Figure 3a are mainly resulting from an increase in the density of species that also occur in the first centimetre of the sediment. The statistical comparison of the diversity indices of both intervals shows a significant difference for the specific richness (t=-7.05, p=0.000) and Shannon index (t=-2.71, p=0.02), but no significant differences for the Equitability index (t=1.53, p=0.15) and ES_{50} (t=-1.12, p=0.28).

3.3 Vertical distribution of total living foraminiferal faunas

Oxygen profiles have been measured at 11 stations. In fact, overlying water, essential for oxygen profiles, was not always available when we used a Reineck corer. A typical example of an oxygen profile obtained at station Carteau is shown in Appendix D. Oxygen saturation is 93% in the bottom waters and starts to decrease at the sediment-water interface. The oxygen concentration in the interstitial waters decreases rapidly within the first millimetres of the sediment to reach anoxic conditions at 6mm.

The vertical distribution of living foraminifera is controlled by the oxygen penetration depth in the sediment, the grain size, the availability of labile organic matter and by macrofaunal bioturbation, the latter parameter modifying the former three (e.g. Corliss, 1985; Shirayama, 1984; Corliss and Emerson, 1990).

The vertical distribution of foraminiferal faunas was studied at 14 stations. In order to group these 14 stations in function of sediment grain size, we performed a cluster analysis (using the Ward method) using the different measured grain size fractions (percentages of particles <63µm, 63-125µm, 125-250µm, 250-500µm and >500µm). As a result, we obtained two groups of stations: group A with muddy to silty sediments, and group B with sandy sediments. In table 1, it can be seen that the average living depth (ALD_5/ALD_6) of the live foraminiferal fauna is considerably higher for the sandy stations (group B) than for the clayey-silty stations (group A) (Figures 4 and 5).

For the stations of group A, with clayey-silty sediment (Figure 4), faunas present a maximum density in the first centimetre of the sediment (often in the first half centimetre) followed by a noticeable decrease downcore, more or less sharp. Group A stations are characterised by a relatively shallow average living depth (ALD_5/ALD_6), from 1.0 to 1.6cm (Table 1). These stations have a relatively high OM content, between 1.68 and 7.52% (4.34% on average). There is a strong negative correlation between the <63µm particle size fraction and the ALD_x of the total fauna ($r=-0.57$, $p<0.03$). Generally, silty-clayed marine environments are characterised by weak hydrodynamics allowing the deposition of organic matter (Tyson, 1995) and its adsorption on clay particles (Hedge and Keil, 1995). Fine grained substrates can therefore often be considered as eutrophic to mesotrophic environments.
The strong surface maximum, together with poor faunas in deeper sediment layers found at these stations is typical for eutrophic environments with limited oxygen penetration depth (a maximum OPD of 14mm for stations where oxygen profiles were performed) (Jorissen et al., 1995).

Also for the stations of group B (Figure 5), the foraminiferal vertical distribution is generally characterised by a density maximum in the first centimetre of sediment. However, unlike group A, densities remain high in deeper sediment layers. Consequently, the ALD_5/ALD_6 of these stations is much higher (between 1.4 and 2.7cm, 2.1cm on average; Table 1).
For some stations (e.g. Agde Est, Leucate), the faunal density and composition are almost the same in every sediment layer down to 5cm. The stations of group B are generally characterised by a lower OM, of 2.5% on average (1.37-3.99%).
Unfortunately, no oxygen measurements could be performed for the stations of group B. However, the abundant faunas in deeper sediment layers suggest that oxygen penetration is

considerably deeper here than at the stations of group A, where oxygen penetration varies from 6 to 14 mm (Table 1).

3.4 Species composition of living foraminiferal faunas

In total, 40 major species (>5% in at least one station, 150-500µm) have been identified: 20 perforate, 8 porcelaneous and 12 agglutinated taxa (Table 2, see Plates 1-2-3-4 in Supplementary material 1, Supplementary material 2 for standardised counting data and Supplementary material 3 for the taxonomical list of major species).

The relative densities of these major species do not show a statistically significant difference between the 0-1 and 0-4cm levels (Appendix E). This result indicates that the percentages of the dominant taxa of the first centimetre can be considered as representative for the whole fauna. The following discussion is therefore uniquely based on the 0-1 cm level.

Among the 40 major species, 10 are very common in the study area, and are present in more than 70% of the stations: 2 perforate taxa (*Ammonia beccarii, Buccella granulata*), 4 porcelaneous taxa (*Adelosina longirostra, Quinqueloculina aspera, Q. seminula, Triloculina trigonula*) and 4 agglutinated taxa (*Eggerella scabra, Lagenammina* spp.*, Reophax fusiformis, Textularia agglutinans*). More specifically, *Eggerella scabra* is clearly the most common species since it is present in 26 of the 31 stations; 15 stations with relative densities over 5% and 7 stations where it represents more than 30% of the total fauna.

On the contrary, some stations are characterised by a strong relative abundance of species that are not frequently found at other stations. For example, *Elphidium crispum* is dominant at the station Grau du Roi where it represents 54.6% (1142 specimens per 50cm²). This species shows only very low abundances (less than 15 specimens) in 13 other stations and is absent in the rest of the stations. Station Leucate presents also a peculiar faunal composition compared to other studied stations with high relative densities of *Nonion depressulum* (18.4%) and *Nonionella turgida* (16.1%), these species being very scarce in other locations except at Grau du Roi. Leucate is also characterised by a relative abundance of 6.7% of *Leptohalysis scotti*, which appears only with single individuals in 3 other stations.

The analysis of the correlations between the available environmental data and the relative densities of the major species is given in Appendix F. Since our study concerns a very large area with strongly contrasting environmental characteristics, it may be expected that also the faunal composition will show large differences between stations. For example, the positive correlation of *Nonion depressulum* and *Nonionella turgida* with the 63-125µm grain size fraction is mainly determined by their high percentages at station Leucate, which is characterised by 53% of very fine sand (63-125µm). At other stations with similar sediment grain size (e.g. Ile Embiez, Agde Ouest), these taxa are much less frequent or absent. Consequently, it becomes difficult to work with individual (marker) species and to observe clear relations between single species percentages and environmental parameters. It is therefore more relevant to define groups of species with a similar distribution, which will respond in the same way to the environmental parameters.

Several trials with Q- and R-mode multivariate statistics (Principal Component Analysis, cluster analysis) to construct species clusters only yielded very inconclusive results. Q-mode PCA results show that *Elphidium crispum* and *Eggerella scabra* are responsible for most of the variability in the dataset when considering the two first PCA axes (see Supplementary material 4). This is due to the strong dominance of *E. crispum* at station Grau du Roi and the high relative densities of *E. scabra* at a number of stations. These species also stand out in the R-mode PCA. The other species cluster together, and do not form clear species groups, even not when considering the next axes. Faunal clusters systematically contain a mix of species with different ecological characteristics, and were therefore very difficult to interpret ecologically (see Supplementary material 5). For this reason, we preferred to test three a priori groupings, based on 1) wall structure, 2) life position (epiphytic species), and 3) literature observations on tolerance/sensitivity with respect to eutrophication.

3.5 Species groups indicative of environmental quality

According to the comparison between 0-1cm and 0-4cm sediment intervals for density, diversity and species composition (see paragraph 5.1 for more details), we considered only data from the first centimetre of the sediment for the study of groups of indicative species of environmental quality.

3.5.1 Species groups according to wall structure

A ternary diagram (Figure 6, after Murray, 1973) presents the contribution of the 3 main groups (defined by wall structure) to the foraminiferal faunas (of the 0-1cm level): perforate, porcelaneous and agglutinated species (see also Appendix B). Station Collioure is the only one showing a majority of porcelaneous taxa (Figure 6, upper blue triangle). The faunas of stations Toulon Grande Rade, Marseille Grande Rade, Ile Plane, Porquerolles, Marseille Jetée, Carry, Fos and Grau du Roi are composed in majority of perforate foraminifera (Figure 6, lower right red triangle) whereas stations Nice, Agde Est and Ouest, Gruissan, Sète and Ile Embiez are characterised by a dominance of agglutinated tests (between 54 and 71%; Figure 6, lower left green triangle). At station Beauduc, where porcelaneous taxa are almost absent, equal amounts of perforate and agglutinated taxa are found. The remaining stations don‟t show a clear dominance of one of the groups.

We performed a canonical correspondence analysis to compare the available environmental parameters (grain size fractions, OM content and water depth) with the percentage of the three wall structure groups. The result shows that the five distinguished grain size fractions are distributed in a horse shoe pattern (Figure 7). The percentage of porcelaneous taxa is plotted in the same area as medium sand (250-500µm), and is opposed to the percentages of clay and silt. In fact, there is a significant positive correlation between the percentage of porcelaneous taxa and the fine and medium sand fractions (for 125-250µm, $r=0.57$, $p<0.05$; for 250-500µm, $r=0.55$, $p<0.05$) and a negative correlation with the clay/silt fraction ($r=-0.71$, $p<0.05$; Appendix C). The percentage of perforate foraminifera plots in the same area as OM content and water depth; there is indeed a positive correlation between their percentage and the percentage of clay/silt ($r=0.42$, $p<0.05$) and with the OM content ($r=0.50$, $p<0.05$; Appendix C). Finally, the percentage of agglutinated taxa plots together with the 63-125µm fraction showing a positive correlation ($r=0.47$, $p<0.05$). This group anti-correlates with coarse sand (>500µm, $r=-0.52$, $p<0.05$). In general, the distribution of this group seems to be opposite to the one of the perforate taxa ($r=-0.74$, $p<0.05$; Appendix C).

3.5.2 Species group according to life position (epiphytic species)

To constitute the epiphytic species group (i.e. capable to live fixed on algae), we selected the species classified in morphotypes A and B as defined by Langer (1993). These morphotypes have been defined according to the different modes of surface attachment and the feeding strategies. Morphotype A represents stationary, permanently attached species which secrete an organic substance to glue to seagrass leaves or algal blades (e.g. *Planorbulina mediterranensis*). Morphotype B represents temporary attached species which have a trochospiral shape with apertures facing the substrate (e.g. *Rosalina globularis*). Morphotypes C and D are not considered in our group of epiphytic species since they can also live in areas without seagrass or algae considering their permanently motile behaviour (e.g. elphidiids, porcelaneous species). The epiphytic species identified in our samples are *Asterigerinata mamilla, Cibicides lobatulus, Gavelinopsis praegeri, Hanzawaia boueana, Neoconorbina terquemi, Planorbulina mediterranensis, Rosalina bradyi, R. globularis, Rosalina vilardeboana* and other *Rosalina* species (e.g. Jorissen, 1987; Kitazato, 1988; Langer, 1993; Barmawidjadja et al., 1995; Schönfeld, 2002; Murray, 2006; Buosi et al., 2012). These epiphytic species are indicative of the presence of vegetation in the vicinity of the sampling station and generally of a good ventilation of bottom waters. According to Van der Zwaan *et al*. (1999), many epiphytic species are sensitive to oxygen-limited conditions and would be competitive in oligotrophic environments. They are mainly found in sandy sediments (Pujos, 1976; Spindler, 1980; Bizon and Bizon, 1984; Jorissen, 1987; Murray, 1991; Villanueva Guimerans and Cervera Currado, 1999; Mendes et al., 2004; Mojtahid et al., 2006) and some of these species, such as *Cibicides lobatulus* and *Gavelinopsis praegeri,* can tolerate high energy environments (Coppa and Di Tuoro, 1995; Guimerans and Currado, 1999; Schönfeld, 2002; Panieri et al., 2005; Martins et al., 2007; Milker et al., 2009). In our study area, the *Posidonia* meadows provide abundant niches for these foraminiferal species; the rhizomes act as sediment traps and the leaves are often colonised by motile or (temporarily) fixed epiphytic foraminifera (Vénec-Peyré, 1984; Langer, 1993).

We calculated the cumulative percentage of epiphytic species for the 0-1cm interval of the 31 studied stations (Figure 8a, Appendix B). Figure 8a highlights again the clear difference between western shallow stations and eastern deeper stations (limit between Fos and Carry), with the exception of Antibes Nord and Nice were epiphytic species are absent. As illustrated by the CCA analysis (Figure 9), there is a positive correlation between the percentage of epiphytic species and water depth ($r=0.53$, $p<0.05$), medium and coarse sediment (for 250-500µm, $r=0.40$, $p<0.05$; for >500µm, $r=0.80$, $p<0.05$). On the other side, there is a negative correlation with fine sands (63-125µm; $r=-0.50$, $p<0.05$; Appendix C).

3.5.3 Species groups according to tolerance/sensitivity to organic enrichment

According to the literature, we defined two species groups: 1) a group of “stress-tolerant” species, with a high percentage being indicative of stressed conditions, such as eutrophication or abundant supplies of fine-grained sediments, and 2) a group of sensitive species, which are supposed to be indicative of a good overall quality of the ecosystem, and which should disappear when environmental conditions become more stressful.

Ten stress-tolerant taxa were identified on the basis of literature evidence: *Bulimina* spp., *Cancris auriculus*, *Nonion scaphum, Nonion depressulum, Nonionella turgida, Nonionella stella*, *Pseudoeponides falsobeccarii, Rectuvigerina phlegeri, Valvulineria bradyana* and the agglutinated *Leptohalysis scotti* (see Plate 2 in Supplementary material 1). The observations presented in the literature which supported our decision to place these 10 taxa in the tolerant group are listed in Appendix G.

The group of sensitive species (see Plate 3 and 4 in Supplementary material 1) includes all porcelaneous species and all epiphytic species. In addition, we also included other motile epiphytic species (morphotypes C and D according to Langer, 1993) such as *Elphidium* species (*Elphidium crispum, E. granosum* and *E. poeyanum*), *Reussella spinulosa* and *Spirillina* spp.. According to the literature that supports our choice to group all these species sensitive to stressed conditions (see Appendix G for literature references on which this grouping was based), a poor representation of this group in the total fauna would be indicative of enrichment in muddy sediments, eventually leading to low oxygen conditions.

Among the 40 major species identified, 14 species have not been assigned to one of these two groups, either because they are neither sensitive nor stress-tolerant, or due to a lack of well documented studies with clear pollution gradients, or due to contradictory literature data with respect to their ecological characteristics.
The case of *Eggerella scabra* is particularly striking. Although this species has been reported in several articles as being able to tolerate stressed conditions, we did not include it in the group of tolerant species. *Eggerella scabra* is a continental shelf species (e.g. Murray, 1991; Barmawidjaja et al., 1992) that lives in muddy to sandy substrates (Murray, 1986; Alve and Nagy, 1986; Scott et al. 2003) and in various microhabitats, from the oxygenated sediment

surface to the deepest anoxic layers (e.g. Barmawidjaja et al., 1992; Jorissen et al., 1992; Ernst et al., 2002, 2005; Duijnstee et al., 2003, 2004). It appears therefore to be tolerant for hypoxic conditions. For instance, *E. scabra* is common in the Adriatic Sea, in areas where important amounts of degraded organic matter cause oxygen depletion (Donnici and Serandrei-Barbero, 2002). It has also been shown to support extremely polluted environments in Sorfjord, western Norway (Alve, 1991). On the other hand, this species is very common and typical in many apparently unpolluted coastal Mediterranean environments (e.g. Venec-Peyré, 1984; Donnici and Serandrei-Barbero, 2002; Duijnstee et al., 2003; Frontalini and Coccioni, 2008; Mojtahid et al., 2009; Goineau et al., 2012; Sabbatini et al., 2010, 2012). Several authors suggested that this species has a poorer tolerance to stressed conditions than some clear opportunists, although it has a great ability to withstand fluctuations in diverse parameters including an absence of labile organic matter (Scott et al., 2003; Mojtahid et al., 2007; De Nooijer et al., 2008; Sabbatini et al. 2012). Finally, some authors have considered *E. scabra* as an epiphytic species on seagrass (Redois et Debenay, 1996; Debenay, 2000), again suggesting that it can be a dominant faunal element in high quality ecosystems. Because of this strongly contrasting evidence and the high densities of *E. scabra* in most of our studied stations, we decided not to include this species in our stress-tolerant group so that it does not obscure the message given by more clear stress-tolerant species.

Figure 8b-c show the percentages of sensitive and stress-tolerant species in our study area following a West-East transect. In our dataset, the percentage of stress-tolerant species positively correlates with the percentage of fine particles ($r=0.48$, $p<0.05$) and organic matter ($r=0.40$, $p<0.05$; Figure 9 and Appendix C). Conversely, stress-tolerant species are weakly represented in eastern stations, in spite of high organic matter contents measured at some stations (e.g. stations Fréjus and Antibes).

Conversely, sensitive species are negatively correlated with the percentage of fine particles (for <63µm, $r=-0.49$, $p<0.05$; for 63-125µm, $r=-0.44$, $p<0.05$) and positively correlated with coarser particles (for 250-500µm, $r=0.59$, $p<0.05$; for >500µm, $r=0.60$, $p<0.05$; Figure 9 and Appendix C).

4 Discussion

4.1 Representativity of the fauna of the first centimetre of sediment

Ecological studies of recent foraminiferal faunas are usually based on the analyses of the total fauna in the sediment column, down to 5 or 10 cm depth. In fact, the vertical distribution of foraminifera can give information about the ecological strategies of different species or about the environmental conditions. In our study, the fauna of deeper sediment layers allows us to distinguish two types of environments. More eutrophic, silty/clayey stations with a limited oxygen penetration depth have the large majority of the fauna in the topmost centimetre, whereas sandy stations, probably with lower organic matter supplies, show a more even faunal distribution in the first 2 to 5 cm of the sediment.

Although this environmental information is not without interest, the significantly longer picking time required to obtain data from deeper layer makes that the study of the vertical distribution analysis is hardly possible for bio-monitoring studies, in which economical aspects are important, and strict deadlines have often to be respected. Recently, the FOBIMO group recommended therefore to limit foraminiferal bio-monitoring studies to the analysis of the first centimetre of the sediment. This recommendation was supported by the results of Bouchet et al. (2012), who studied the faunal response to various oxygen concentrations in the Norwegian Skagerrak, using diversity indices based on the faunas in the 0-1cm and 0-2cm intervals. It turned out that the results were virtually similar, suggesting that the study of the 0-1 cm was sufficient.

However, before taking the decision to restrict the faunal analysis to the uppermost centimetre, we wanted to verify whether this does not lead to an erroneous or incomplete interpretation of the faunal response to environmental conditions when considering our coastal Mediterranean samples. In our study area, species living exclusively in deeper sediment layers (e.g. Corliss, 1985; Jorissen, 1995) were not observed (Figure 4-5). Buzas et al. (1993) highlighted the fact that the microhabitat succession usually observed in deep water (outer continental shelf and slope) is much less evident on inner continental shelf environments. They explained this difference by the more dynamic nature of coastal areas (sediment disturbance, bioturbation, etc.).

To know if a study restricted to the first centimetre of sediment (generally containing the majority of the living fauna) is sufficient to correctly define the environmental quality, we compared faunal parameters between 0-1 and 0-4cm intervals. Statistical comparison of Equitability indices and ES_{50} show no significant difference between 0-1 and 0-4cm. However, faunal densities are significantly different. For the Shannon index, the statistical test identified significantly higher values for the 0-4cm interval (test based on the sign of the difference). However, the differences are small (average shift between the values from 0-1 and 0-4cm intervals of 0.11), and would not cause major changes in the classification of the stations into the different quality categories. It is also interesting to observe that there are no significant differences in the relative densities of major species which change only slightly between the 0-1 and 0-4cm intervals (Wilcoxon test, Appendix E).

In view of all these results, we conclude that in our study area, the first centimetre of the sediment gives a very good picture of the overall live fauna, its diversity and composition. Therefore, our results fully support the recommendation of the FOBIMO group (Schönfeld et al., 2012).

4.2 Relevance of the various faunal parameters for ecosystem quality evaluation

Ideally, the development of a faunal index of environmental quality should be based on a precise knowledge of pollution sources and intensities in the study area. The analysis of faunal patterns along a well-described pollution gradient makes it possible to distinguish species with various degrees of tolerance, and to identify the faunal parameter(s) or indices that correlate best with the state of the environment, as defined by the concentration of one or more pollutants. Usually, such studies focus on the impact of a single stress parameter on the foraminiferal faunas, such as bottom water oxygen concentration (Bouchet et al., 2012), eutrophication (Mojtahid et al., 2008), or chemical pollution (Frontalini and Coccioni, 2008; Mojtahid et al., 2006). In our study, the geographical area of concern is very wide, pollutants are dispersed in an erratic way, and their concentration is not known. Consequently, we do not dispose of a clear transect following a pollution gradient, and our approach has therefore to be slightly different. We cannot have the ambition to directly develop a biotic index, but instead, we will try to determine which faunal parameters could be relevant to adequately describe the ecosystem health.

4.2.1 Biodiversity indices

According to different diversity indices calculated, biodiversity seems to be higher at the eastern part of the French Mediterranean coast. Unfortunately, because of the strong positive correlation between diversity indices and water depth, it is impossible to say whether the higher values of the diversity indices of the eastern stations indicate a higher overall biodiversity, or whether they are the result of a sampling bias (shift in water depth). Diversity indices give important information about biodiversity and faunal equilibrium at a station. It has been shown that biodiversity indices may be useful to classify the ecosystem quality in strongly polluted conditions (e.g. Bouchet et al., 2012; Armynot du Chatelet et al., 2004). Our study area differs from the severely stressed environments described by these authors, because of the absence of a clear stress parameter, such as oxygen depletion or heavy metal pollution. In fact, the French Mediterranean coast is generally considered as rather oligotrophic (e.g. Bosc et al., 2004). Consequently, a slight eutrophisation of the benthic ecosystem does not necessarily lead to a decreased biodiversity, but could easily cause an increase of the values of diversity indices. Based on several studies of macrofauna along a gradient of organic enrichment, the Pearson-Rosenberg model (also called SAB model, Pearson and Rosenberg, 1978) clearly shows that a slight increase in organic matter content leads first to an increase of the number of species. Several earlier studies show that foraminiferal diversity is decreasing along bathymetric transects in response to lowering of the OM flux towards greater water depth (e.g. Rathburn et al., 1996; Schmiedl et al., 2000; Fontanier et al., 2008). Consequently, we think that in the oligotrophic Mediterranean sea, diversity indices are not an appropriate tool to describe the environmental quality of benthic ecosystems.

4.2.2 Species groups according to wall structure

According to our data (Figure 7, Appendix C) and the literature, porcelaneous taxa have the clearest ecological response to environmental change. They are found abundantly in coarse-grained shallow water environments with a low OM content and oxygen-saturated bottom waters (e.g. Jorissen, 1988; Donnici and Serandrei-Barbero, 2002). Bizon and Bizon (1984) observed that this group is also abundant in sandy sediments on the continental shelf off the Rhône River. In our study, their percentage shows a clear decrease with an increasing percentage of fine sediment (<63µm; Figure 7 and Appendix C). Therefore, samples with a high percentage of porcelaneous taxa should denote stations with rather good environmental quality, whereas the opposite should be true for samples with very low percentages of porcelaneous taxa. For example, stations Collioure, Fréjus and Cap Canaille all show more than 40% of porcelaneous taxa, suggesting healthy environmental conditions. Conversely, stations Grau du Roi, Fos, Carry and Marseille Jetée show very low percentages of porcelaneous specimens (less than 8%), and very high percentages of perforate foraminifera (over 60%) (Figure 6), suggesting that these stations with clayey-silty sediments may be characterised by a slightly degraded ecological state. However, we cannot push the interpretation much further. In fact, wall structure groups present the disadvantage to separate species according to morphological criteria, which do not necessarily correspond exactly to ecological preferences and tolerances (Buzas et al., 1993). When we look in more detail at the species composing the three groups, it appears that some important species do not at all respect the general tendency. For example, some porcelaneous species have been observed to behave as opportunistic species in particular conditions. So has *Quinqueloculina seminula* been described as an early foraminiferal recoloniser of the benthic ecosystem after a gravity flow in the Whittard canyon (Duros et al., 2011) and on an ash layer deposit around Mt. Pinatubo in the South China Sea (Hess and Kuhnt, 1996). Another example is the group of perforate species which includes species that we classified as tolerant to stressed conditions (e.g. *Nonion scaphum, Cancris auriculus*) and epiphytic species which are generally considered as very sensitive to eutrophication.

Summarising, an index based on the cumulative percentages of the three wall structure groups can give a rapid first overall characterisation of the state of the environment, but may in some specific cases lead to erroneous conclusions. It appears therefore that it is more judicious to base a biotic index on groups of indicator taxa which have a similar response to stressed conditions.

4.2.3 Species groups according to life position (epiphytic species)

Our data seem to confirm the literature: epiphytic species are most successful on coarse-grained substrates (Figure 9, Appendix C), where bottom waters are normally well oxygenated. The rather surprising positive correlation with OM content (Appendix C) is probably caused by the presence of abundant larger plant debris in seagrass meadows, leading to anomalously high OM values. High percentages of epiphytes are found in eastern part of the French Mediterranean coast as well as in front of Banyuls-sur-Mer, where *Posidonia* meadows are growing (Gobert et al., 2009). Since *Posidonia* meadows are known to be highly sensitive to human disturbance (Boudouresque et al., 2000, 2006), our observations suggest that high percentages of epiphytic species could indeed be indicative of a good ecosystem quality. However, their absence at stations naturally characterised by more fine-grained substrates and lack of vegetation cover cannot be interpreted as indicative of a bad ecosystem state. It appears therefore that this parameter can emphasize a very good ecosystem state in some cases, but cannot be used to characterise the environmental quality along the entire French Mediterranean coast.

4.2.4 Species groups according to tolerance/sensitivity to organic enrichment

Figure 8c shows a clear increase in the percentage of stress-tolerant species in the stations located around the Rhône River mouth. The Rhône River is the main sediment source in the Gulf of Lions (80%; Durrieu de Madron et al., 2000). Hence, stations located in the vicinity of the delta are influenced by supplies of fine sediment and terrestrial organic matter. However, these stress-tolerant species do not occur in all stations exhibiting high percentages of OM because in several eastern stations these high values reflect the presence of macro-algae detritus, as mentioned earlier.

Sensitive species are less adapted to inhabit muddy to silty substrates which are often characterised by a varying degree of organic enrichment. This enrichment can be entirely natural, or partly, in some cases even entirely anthropogenic. Therefore, a historical disappearance of sensitive species (shown by a comparison of recent and fossil faunas) can highlight either a (natural) shift from more sandy to more muddy sediment, or an increase of anthropogenic organic supplies.

Summarising, the proportions of stress-tolerant and sensitive species can allow us to distinguish two kinds of environments:

1) Faunas characterised by a high percentage of stress-tolerant species and a low percentage of sensitive species are indicative of fine-grained substrates often associated with high organic matter contents. This concerns stations Leucate, Gruissan, Beauduc, Carteau, Fos, Carry, Marseille Grande Rade, Marseille Jetée, Toulon Grande Rade, Monaco and Menton. Often, the predominance of stress-tolerant

taxa is probably the result of natural conditions. However, in some cases it may be due to a superimposed anthropogenic impact.

2) Faunas with a high percentage of sensitive species and a low percentage of stress-tolerant species are indicative of sandy substrates with relatively low organic matter content and well oxygenated bottom waters. Such a situation was encountered at stations Cerbère, Collioure, Agde Ouest, Agde Est, Sète, Grau du Roi, Faraman, Cap Canaille, Ile Plane, Ile Maire, Embiez, Porquerolles, Lavandou, Ile du Levant, Pampelone, Fréjus, Antibes 2, Antibes Nord, Nice and Villefranche.

It appears that the information given by the group of stress-tolerant species is very similar (but opposed) to the information given by the group of sensitive species. However, as shown in Figure 8b, sensitive species are well represented in all stations (from 16 to 76%) whereas the percentage of stress-tolerant species appears to be more discriminative (from 0 to 46%). This difference is essential for the development of a biotic index of ecological quality status. Although the group of stress-tolerant species apparently can inform us about the degree of stress at a particular station, it does not tell us whether this stress results entirely from natural conditions or is partly, or totally, due to an anthropogenic impact. Since the aim of bio-monitoring studies is to evaluate the anthropogenic impact on the ecosystem (excluding natural eutrophication); it is absolutely essential to deconvolve these two parameters.

4.3 Correction for natural eutrophication phenomena

In this study, the analyses of the environmental parameters (water depth, organic matter, grain size fraction) highlighted the clear (natural) environmental differences between 1) stations located on West side of the Rhône River with relatively shallow water depths (18m depth in average) and clayey to fine sandy sediments; 2) stations located in front of the Rhône river mouth and in the Gulf of Fos with clayey sediments enriched in organic matter; and 3) the eastern stations with relatively important water depth (40m depth in average) and coarser sediments. Living foraminiferal faunas of the 31 analysed stations respond clearly to this natural variability of environmental parameters with changes in species composition. Foraminifera (and benthic fauna in general) are largely influenced by sediment grain size. A simple faunal analysis shows large differences between faunas from clayey and sandy substrates. In fact, faunas living on clayed substrates are more adapted to naturally enriched conditions (eutrophisation), often characterised by increased OM concentrations and sometimes seasonal low oxygen concentrations. For this reason stations with muddy substrates tend to show an elevated proportion of stress-tolerant species, even if the concerned ecosystem is exempt from anthropogenic impact.

We think therefore, that it is necessary to define reference conditions in function of grain size distribution, in order to avoid a basic and erroneous interpretation of faunal data that would consider any station with a clayey substrate of bad quality.

In our database, we selected 8 stations (Agde Ouest, Grau du Roi, Beauduc, Cap Canaille, Embiez, Antibes 2, Antibes Nord and Nice) with different proportions of fine grain-sized sediment (<63µm size fraction), which show minimal percentages of stress-tolerant species. These stations were used to define the reference faunas, in other words, the percentages of stress-tolerant species expected to be found in a natural environment with a certain grain-size composition, without any anthropogenic impact (Figure 10). If only very few (1 to 3) reference stations are selected, there is the risk that they do not represent correctly all the environmental conditions of the study area. Our method, based on 8 reference stations, represents a wide range of coarse sand to clayey substrates, with many intermediate conditions being represented. The stations Faraman, Lavandou and Porquerolles, which also present very low percentages of tolerant species were not retained as reference stations because of their low total number of individuals (<51 ind.) which make them statistically less robust.

Knowing the theoretical percentage of tolerant species in reference conditions for each grain size (defined by the equation $\%TS_{ref}$ = exp (0.0302*(%<63µm) + 0.1496)-1)), it is then possible to calculate the standardised percentage of tolerant species ($\%TS_{std}$) using the following formula, for a given grain size composition:

$$\%TS_{std} = \frac{\left(\%TS_x - \%TS_{ref}\right)}{\left(100 - \%TS_{ref}\right)} \times 100$$

where $\%TS_x$ is the percentage of tolerant species at station x, and $\%TS_{ref}$ is the theoretical percentage of tolerant species expected at a station with a certain proportion of <63µm particles, in the absence of anthropogenic impact (c.f. exponential curve equation).

The $\%TS_{std}$, which varies from 0 to 100, describes the increase of the number of stress-tolerant taxa with respect to a reference station with a similar grain-size. Exceptionally, some stations can present a lower percentage of stress-tolerant species than the reference conditions, leading to negative values (Table 3, Figure 10). Values of *%TS*$_{std}$ close to 0 are indicative of a very high environmental quality, whereas values close to 100 would indicate a very high anthropogenic impact.

The standardised percentages of tolerant species for 30 studied stations are presented in Table 3 (except for station Marseille Grande Rade for which we don"t have a grain size analyses). Twenty-one stations out of 30 show a *%TS*$_{std}$ below 10%, suggesting that the ecological quality at these stations is high, close to theoretical reference conditions. The other 9 stations contain a *%TS*$_{std}$ between 10 and 50, indicating that the percentage of stress-tolerant species is higher than would be expected in natural conditions. This concerns particularly the stations Carry, Marseille Jetée and Leucate stations which exhibit a *%TS*$_{std}$ higher than 30%. The benthic foraminiferal faunas of these stations are very probably impacted by human activities.

5 Conclusion

In the literature, the study of foraminiferal faunas along the French Mediterranean coast is rather disperse, with some older studies dealing with total (dead and living individuals) assemblages (Blanc-Vernet, 1969; Bizon and Bizon, 1984; Vénec-Peyré, 1984), and some more recent studies on living foraminifera around the Rhône river mouth (Mojtahid et al., 2009, 2010; Goineau et al., 2011, 2012) Our study of 31 stations presents for the first time a description of living (Rose Bengal stained) foraminiferal faunas along the entire French Mediterranean coast except Corsica.

The comparative study, for 14 stations, of two different sediment intervals, 0-1cm and 0-4cm, clearly shows that the analysis of the uppermost centimetre of sediment is sufficient to obtain relevant information needed for bio-monitoring purposes. In our sandy to silty coastal area, intermediate to deep infaunal species are virtually absent so that the faunal composition of the topmost centimetre is representative of the whole sediment column. This conclusion strongly supports the recommendation of the FOBIMO group (Schönfeld et al., 2012).

Our analysis of the different faunal parameters led us to the conclusion that the use of indicator species, such as stress-tolerant or sensitive species, is more relevant than the use of diversity indices for the evaluation of ecosystem quality, at least in rather oligotrophic areas such as the Mediterranean Sea. Finally, we propose a method to distinguish between natural and anthropogenic eutrophication phenomena by determining the expected percentage of stress-tolerant taxa in natural environments, in function of sediment grain size, and by correcting the observed percentage of stress-tolerant taxa accordingly. This study is a first step towards the development of a foraminiferal index of ecosystem quality for the coastal Mediterranean Sea that could be used in the context of the Marine Strategy Framework Directive (2008/56/EC). Our index has to be tested at other stations, ideally located on a gradient of disturbance. Furthermore, some aspects deserve to be further explored, such as the pertinence of our list of tolerant species in other Mediterranean coastal areas, the potential of the comparison of live and dead faunas to select indicator species, or the relevance of a multimetric index (cf., M-AMBI) combining indicator species and diversity indices.

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FIGURES CAPTION

Figure 1: Localisation of the sampling stations along the French Mediterranean coast.

Figure 2: Environmental parameters for the 31 sampling stations, from west (left side) to east (right side) stations : a) water depth, b) percentage of organic matter, c) percentage of clay and silt (<63µm), d) percentage of very fine to fine sand (63-250µm), and e) percentage of medium to coarse sand (>250µm).

Figure 3: Density and diversity (species number) of living foraminiferal faunas for the 31 sampling stations, from west (left side) to east (right side), considering either 0-1cm (black/diamonds) or 0-4cm (white/squares) sediment intervals: a) living foraminiferal density (number of specimens standardised for 50cm², crosses notify samples for which only the first cm of sediment was analysed), b) species richness, c) Shannon-Wiener index, d) Equitability index, and e) ES_{50}. NB: For station Toulon Grande Rade data are based on a study of the 0-1 and 0-3cm intervals.

Figure 4: Vertical distribution of living foraminiferal faunas for stations of group A. Foraminiferal densities are standardised for $50cm^3$. Major species (>5% of the total fauna of the core) are presented separately from the rest of the species gathered in « others ». NB: x and y axes scales change according to the stations.

Figure 4 and 5 should be in color on both the web and on printed version.

Figure 5: Vertical distribution of living foraminiferal faunas for stations of group B. Foraminiferal densities are standardised for $50cm^3$. Major species (>5% of the total fauna of the core) are presented separately from the rest of the species gathered in « others ». NB: x and y axes scales change according to the stations.

Figure 4 and 5 should be in color on both the web and on printed version.

Figure 6: Ternary diagram representing stations according to the fractions of the 3 main groups of foraminifera (perforate, porcelaneous and agglutinated taxa) in the living fauna in the 0-1cm interval. Stations dominated by perforate foraminifera plot in the red area (lower right triangle), those dominated by porcelaneous taxa in the blue area (upper triangle), and those dominated by agglutinated taxa in the green area (lower left triangle).

Figure 6 should be in color only on the web version, and in black and white on printed version.

Figure 7: Canonical correspondence analysis (Axis 1 vs. Axis 2) performed on environmental parameters and the percentages of the 3 main foraminiferal groups (without considering Marseille Grande Rade and Cap Canaille for which no environmental data were available).

Figure 8: Percentage of indicative species in the sample (0-1cm interval) at each station (West-East transect): a) epiphytic species, b) sensitive species, and c) stress-tolerant species.

Figure 9: Canonical correspondence analysis (Axis 1 vs. Axis 2) performed on environmental parameters and the percentages of the indicative species groups: epiphytic species, stress-tolerant and sensitive species (without considering Marseille Grande Rade and Cap Canaille for which no environmental data were available).

Figure 10: Percentage of stress-tolerant species versus the percentage of particles <63µm in the different stations studied along the Mediterranean coast. The exponential curve is thought to represent the percentage of stress-tolerant species in natural conditions (without anthropogenic influence).

TABLES CAPTION

Table 1: Oxygen penetration depth (OPD) and Average Living Depth (ALD_5/ALD_6) for stations where oxygen profiles were performed and average living depth was calculated for cores of 5 or 6cm length (depending on the slicing) in order to compare the ALD_x of different stations. NB: ALD_3 for Toulon and ALD_4 for Agde Est. Environmental parameters are added to compare with the vertical distribution of foraminifera.

Table 2: List of major species (relative density >5% in at least one of the stations studied between 0-1cm).

Table 3: Values of the standardised percentage of stress-tolerant species. The parameters required for the calculation of the $\%ST_{std}$ are indicated. Data are missing for Marseille Grande Rade due to the lack of particle size measurements at this station.

APPENDICES CAPTION

Appendix A: Localisation (WGS84) and water depth of the stations. The sediment layers analysed for living foraminiferal faunas are indicated.

Appendix B: Environmental parameters and faunal parameters (considering foraminiferal faunas from the >150µm size fraction and 0-1cm sediment interval) calculated for the 31 stations analysed in this study (presented from West to East).

Appendix C: Linear correlations between environmental and faunal parameters (upper right triangle shows p values and lower left triangle shows r values) considering foraminiferal faunas from the >150µm size fraction and 0-1cm sediment interval.

Appendix D: Example of an oxygen profile, measured at station Carteau.

Appendix E: Wilcoxon tests (Z) results and their corresponding probabilities (p) in order to test similarities of major species (>5%) between intervals 0-1 and 0-4cm.

Appendix F: Linear correlation (r) between the relative densities of the major species (see Table 2 for the meaning of species abbreviations) and the environmental parameters available for this study. The statistically significant correlations ($p<0.05$) are indicated in bold.

Appendix G: Evidence from the literature that support our choice to attribute species to stress-tolerant and sensitive (including epiphytic species) groups.

SUPPLEMENTARY MATERIAL

Supplementary material 1: Plates showing MEB pictures of major species.

Plate 1: 1) *Lagenammina* sp. a, Fréjus, 1a: side view, 1b: aperture view; 2) *Lagenammina* sp. b, Marseille Jetée; 3) *Eggerella scabra*, Grau du Roi; 4) *Leptohalysis scotti*, Leucate; 5) *Textularia sagittula*, Marseille Jetée; 6) *Textularia agglutinans*, Marseille Jetée; 7) *Reophax scorpiurus*, Marseille Jetée; 8) *Reophax fusiformis*, Fréjus; 9) *Reophax subfusiformis*, Grau du Roi; 10) *Ammoscalaria pseudospiralis*, Carteau, 9a: front view, 9b: side view; 11) *Quinqueloculina seminula*, Rhône prodelta (station 10, 80m) (Mojtahid et al., 2009); 12) *Triloculina trigonula*, Grau du Roi; 13) *Sigmoilina grata*, Fréjus; 14) *Quinqueloculina aspera,* Agde Est, 13a: side view, 13b: aperture view; 15) *Quinqueloculina bosciana*, Antibes Nord; 16) *Adelosina longirostra*, Calvi, Corsica. NB: scale bar is 100µm.

Plate 2: 1) *Rectuvigerina phlegeri*, Marseille Jetée; 2) *Valvulineria bradyana*, Carteau, 2a: dorsal side, 2b: aperture view, 2c: ventral side; 3) *Cancris auriculus*, Marseille Jetée, 3a: dorsal side, 3b: ventral side; 4) *Nonion scaphum*, Grau du Roi, 4a: side view, 4b: aperture view; 5) *Nonionella turgida*, Leucate, 5a: dorsal side, 5b: aperture view, 5c: ventral side; 6) *Nonion depressulum*, Leucate, 6a: side view, 6b: aperture view; 7) *Pseudoeponides falsobeccarii*, Menton, 7a: dorsal side, 7b: aperture view, 7c: ventral side; 8) *Bulimina aculeata*, Menton. NB: scale bar is 100µm except for 1b where it corresponds to 10µm.

Plate 3: 1) *Asterigerinata mamilla*, Marseille Jetée, 1a: dorsal side, 1b: aperture view, 1c: ventral side; 2) *Hanzawaia boueana*, Marseille Jetée, 2a: dorsal side, 2b: ombilical view; 3) *Planorbulina mediterranensis*, Carry; 4) *Cibicides lobatulus*, Marseille Jetée/Carry, 4a: dorsal side, 4b: aperture view, 4c: ventral side; 5) *Rosalina bradyi*, Santa Manza, Corsica, 5a: dorsal side, 5b: ventral side; 6) *Rosalina globularis*, Marseille Jetée, 6a: dorsal side, 6b: ventral side; 7) *Neoconorbina terquemi*, Pampelone, 7a: dorsal side, 7b: aperture view, 7c: ventral side. NB: scale bar is 100µm.

Plate 4: 1) *Elphidium crispum*, Grau du Roi, 1a: side view, 1b: aperture view; 2) *Elphidium poeyanum* f. *decipiens*, Marseille Jetée, 2a: side view, 2b: aperture view; 3) *Elphidium granosum* f. *lidoense*, Beauduc, 3a: side view, 3b: aperture view; 4) *Astrononion stelligerum*, Fréjus/Toulon Grande Rade, 4a: side view, 4b: aperture view; 5) *Ammonia beccarii* f. *beccarii*, Grau du Roi, 5a: dorsal side, 5b: aperture view, 5c: ventral side; 6) *Ammonia parkinsoniana* f. *tepida*, Beauduc, 6a: dorsal side, 6b: aperture view, 6c: ventral side; 7) *Spirillina* sp., Fréjus; 8) *Buccella granulata*, Agde Est, 8a: dorsal side, 8b: aperture view, 8c: ventral side; 9) *Reusella spinulosa*, Marseille Jetée. NB: scale bar is 100µm.

Supplementary material 2: Number of living (Rose Bengal stained) foraminifera (>150µm) in the first centimetre of sediment standardised for 50cm².

Supplementary material 3: Taxonomical list of the major species identified in this study.

Supplementary material 4: Loadings on the species on the 2 first axis of the PCA performed on the relative densities of the major species (>5%) of the 31 stations (see Table 2 for the meaning of species abbreviations). The percentage of variance explained by the axes is indicated in parenthesis.

Supplementary material 5: Cluster analyses based on the relative densities of major species (>5%) in the 31 stations using paired group algorithm and correlation similarity measures (see Table 2 for the meaning of species abbreviations).

Table 1

	Station	OPD (mm)	ALD5/ ALD6 (cm)	Depth (m)	%OM	%<63µm	%63-125µm	%125-250µm	%250-500µm	%>500µm
Group A										
	Grau	7	1.0	15	3.28	**67.92**	25.86	6.21	0.00	0.00
	Toul	-	1.1	43	7.52	**50.90**	11.59	4.84	2.82	29.85
	Cart	6	1.3	10	5.91	**80.80**	13.07	6.14	0.00	0.00
	Mjet	14	1.4	41	5.41	**51.91**	19.80	19.78	7.61	0.90
	Nice	12	1.4	30	2.21	**46.12**	**28.47**	17.79	6.80	0.81
	Bduc	-	1.6	14	1.68	**87.52**	10.75	1.73	0.00	0.00
Group B										
	Colli	-	1.4	23	1.37	2.89	13.86	**39.90**	**33.74**	9.62
	AgdE	-	1.8	21	1.57	8.45	27.56	**56.99**	6.99	0.00
	Maire	-	2.0	40	3.31	4.82	4.26	11.22	23.28	**56.42**
	Vfran	-	2.0	42	3.99	14.66	12.25	18.11	**22.75**	**32.22**
	Leuc	-	2.2	22	1.72	19.73	**53.10**	24.61	2.41	0.14
	Carry	-	2.3	48	3.54	**26.28**	14.25	17.57	17.72	**24.18**
	Ment	-	2.3	51	1.73	28.26	**37.50**	**32.75**	1.49	0.00
	Pamp	-	2.7	42	2.78	19.10	6.06	11.39	**23.95**	**39.49**

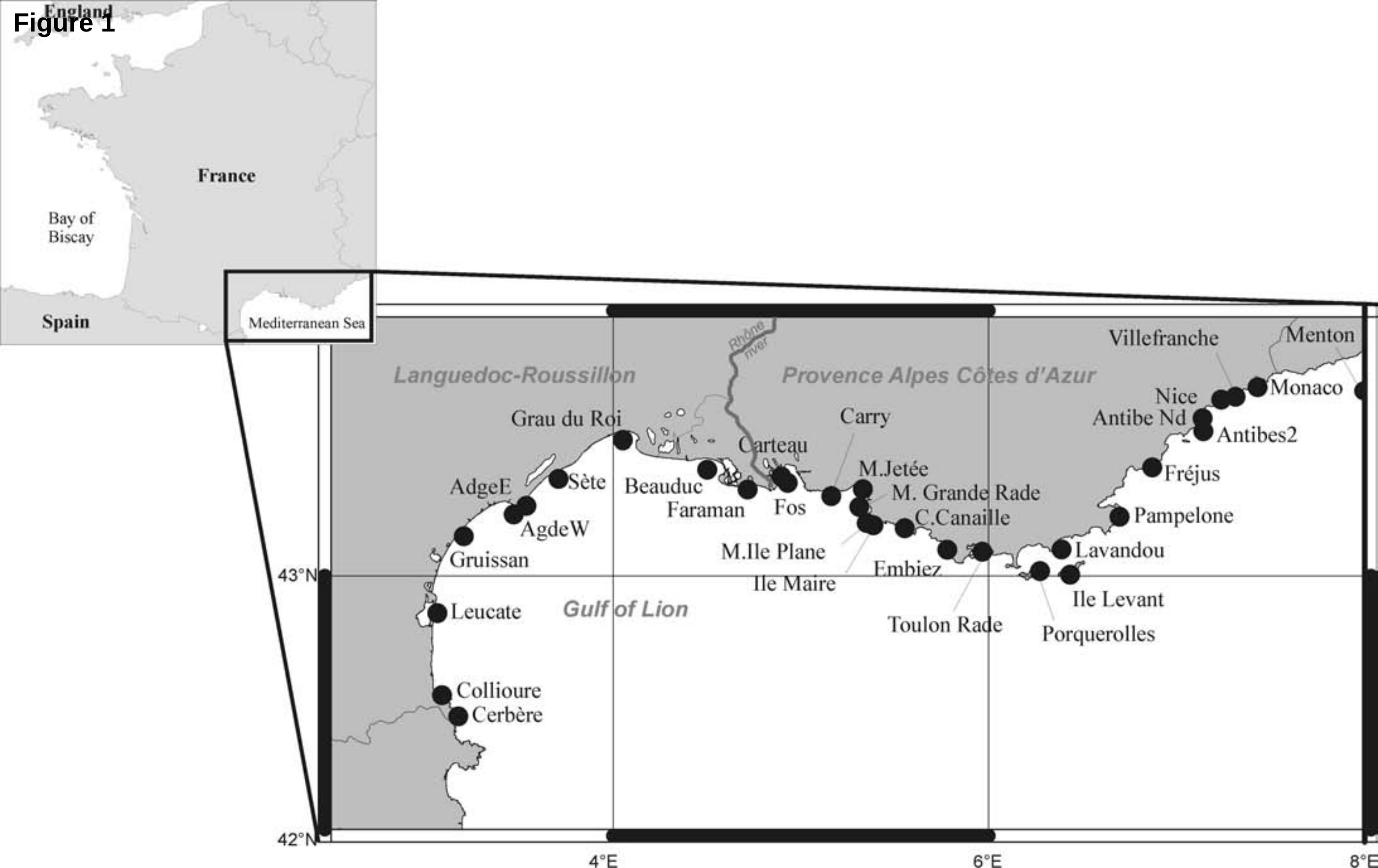
Table 2

Perforate species		**Porcelaneous species**		**Agglutinated species**	
Name	Abbrev.	Name	Abbrev.	Name	Abbrev.
Ammonia beccarii f. *beccarii*	*Abecc*	*Adelosina longirostra*	*Along*	*Ammoscalaria pseudospiralis*	*Apseudo*
Asterigerinata mamilla	*Amami*	*Biloculinella irregularis*	*Birreg*	*Eggerella scabra*	*Escab*
Astrononion stelligerum	*Astel*	*Quinqueloculina aspera*	*Qasp*	*Lagenammina* sp. a	*LagenamA*
Buccella granulata	*Bgran*	*Quinqueloculina bosciana*	*Qbosc*	*Lagenammina* sp. b	*LagenamB*
Bulimina aculeata	*Bacul*	*Quinqueloculina costata*	*Qcost*	*Leptohalysis scotti*	*Rscot*
Cancris auriculus	*Cauri*	*Quinqueloculina seminula*	*Qsemi*	*Psamosphaera fusca*	*Pfusc*
Cibicides lobatulus	*Cloba*	*Sigmoilina grata*	*Sgrata*	*Reophax fusiformis*	*Rfusif*
Elphidium crispum	*Ecris*	*Triloculina trigonula*	*Ttrigo*	*Reophax micaceus*	*Rmica*
Elphidium granosum	*Egran*			*Reophax scorpiurus*	*Rscorp*
Elphidium poeyanum f. *decipiens*	*Epoey*			*Reophax subfusiformis*	*Rsubfus*
Hanzawaia boueana	*Hboue*			*Textularia agglutinans*	*Taggl*
Neoconorbina terquemi	*Nterq*			*Textularia sagittula*	*Tsagit*
Nonion depressulum	*Ndepres*				
Nonion scaphum	*Nscap*				
Nonionella turgida	*Nturg*				
Planorbulina mediterranensis	*Pmedit*				
Rectuvigerina phlegeri	*Rphle*				
Rosalina globularis	*Rglob*				
Spirillina sp.	*Spiril*				
Valvulineria bradyana	*Vbrad*				

Table 3

Stations	**%TS*x***	**% <63 µm**	**%TS*ref***	**%TS*std***
	% tolerant species, station x	% <63µm particles	% tolerant species, theoretical reference conditions	Standardised % tolerant species
Cerb	1.90	4.56	0.3	1.6
Colli	2.67	2.89	0.3	2.4
Leuc	46.28	19.73	1.1	45.7
Gruis	11.11	42.36	3.2	8.2
AgdW	2.21	18.70	1.0	1.2
AgdE	2.42	8.45	0.5	1.9
Sete	6.54	30.35	1.9	4.7
Grau	7.07	67.92	8.0	-1.1
Bduc	17.79	87.52	15.3	2.9
Fara	0.00	6.16	0.4	-0.4
Cart	35.06	80.80	12.3	25.9
Fos	24.93	73.57	9.7	16.9
Carry	34.77	26.28	1.6	33.7
Mrade	16.13			
Mjet	39.84	51.91	4.6	37.0
Plane	9.26	13.18	0.7	8.6
Maire	11.11	4.82	0.3	10.8
Ccan	0.36	13.25	0.7	-0.4
Embi	5.10	28.30	1.7	3.4
Toul	22.47	50.90	4.4	18.9
Porq	0.00	10.83	0.6	-0.6
Lav	2.33	25.56	1.5	0.8
Levan	5.08	6.47	0.4	4.7
Pamp	8.85	19.10	1.1	7.9
Fréj	2.82	17.35	1.0	1.9
Antib2	0.78	36.56	2.5	-1.8
AntibN	0.00	1.62	0.2	-0.2
Nice	3.00	46.12	3.7	-0.7
Vfran	6.93	14.66	0.8	6.2
Monac	19.51	56.83	5.5	14.9
Ment	21.96	28.26	1.7	20.6

Figure 1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Spain
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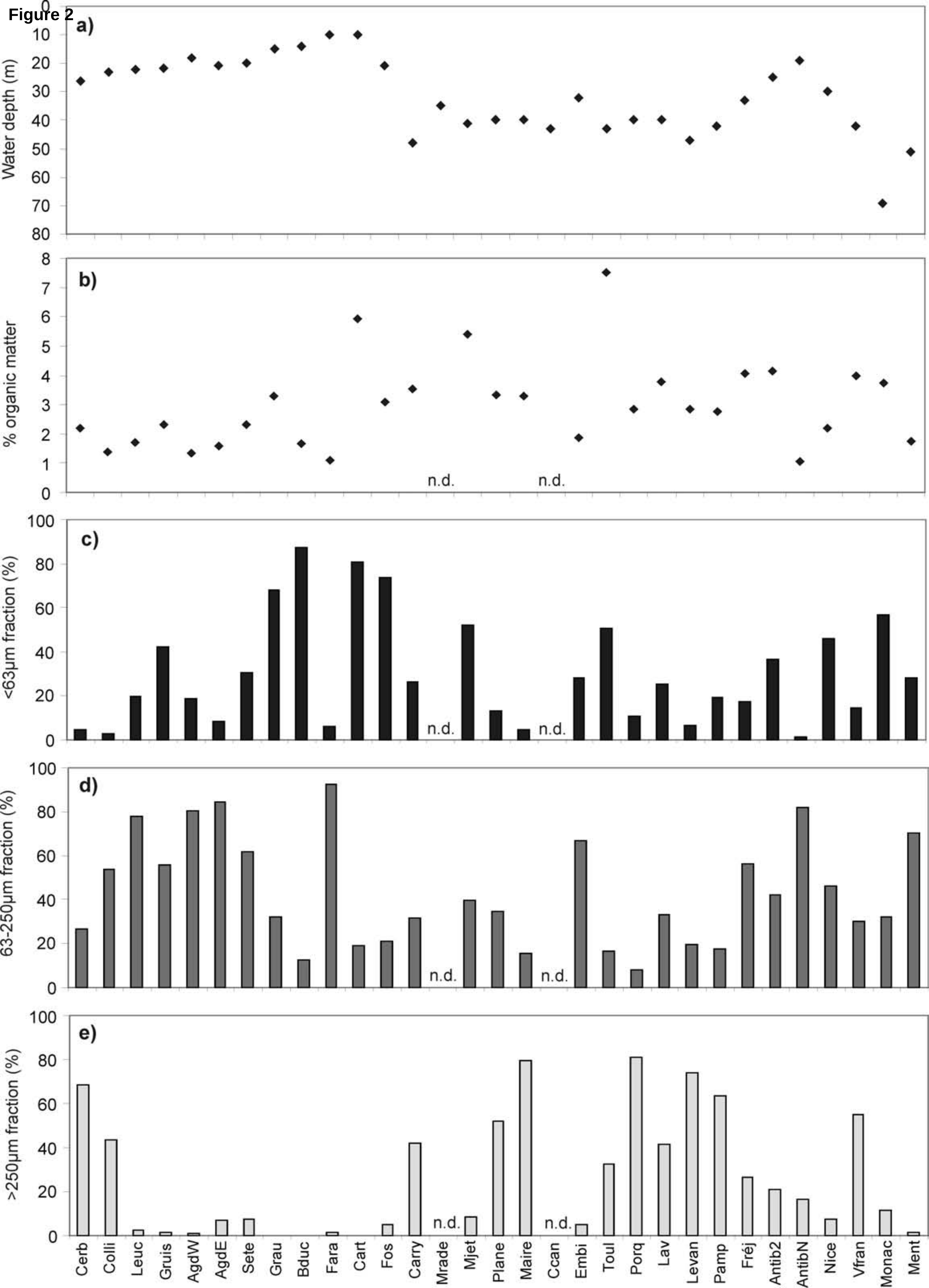
Provence Alpes Côtes d'Azur
Rhône river
Gulf of Lion
Grau du Roi
AdgeE
Sète
AgdeW
Gruissan
Leucate
Collioure
Cerbère
Beauduc
Faraman
Carteau
Fos
Carry
M.Jetée
M. Grande Rade
C.Canaille
M.Ile Plane
Ile Maire
Embiez
Toulon Rade
Porquerolles
Ile Levant
Lavandou
Pampelone
Fréjus
Antibe Nd
Antibes2
Nice
Villefranche
Monaco
Menton
43°N
42°N
4°E
6°E
8°E

Figure 2


a)
Water depth (m)
0
10
20
30
40
50
60
70
80
b)
% organic matter
0
1
2
3
4
5
6
7
8
n.d.
n.d.
c)
<63µm fraction (%)
0
20
40
60
80
100
n.d.
n.d.
d)
63-250µm fraction (%)
0
20
40
60
80
100
n.d.
n.d.
e)
>250µm fraction (%)
0
20
40
60
80
100
n.d.
n.d.
Cerb
Colli
Leuc
Gruis
AgdW
AgdE
Sete
Grau
Bduc
Fara
Cart
Fos
Carry
Mrade
Mjet
Plane
Maire
Ccan
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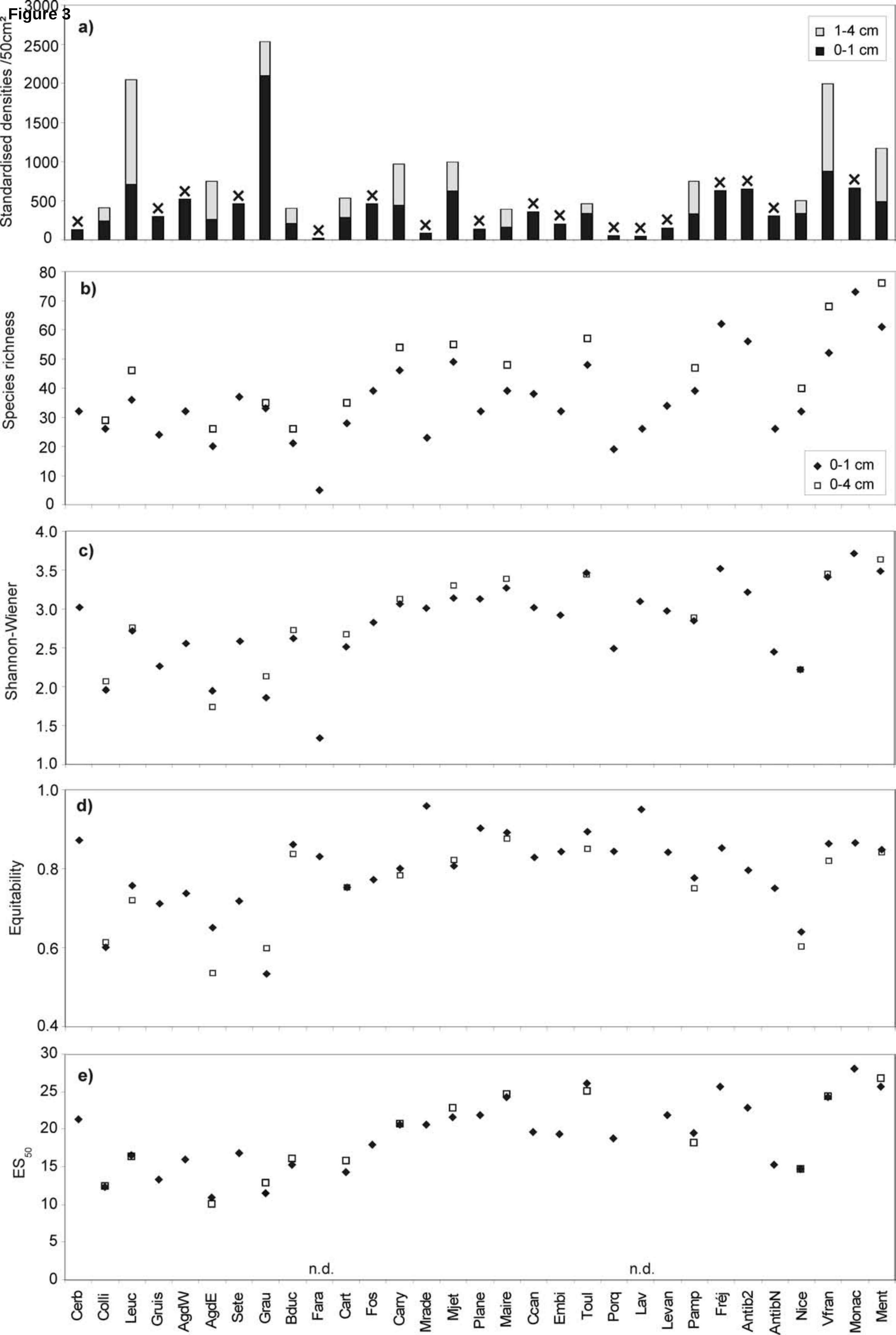
Lav
Levan
Pamp
Fréj
Antib2
AntibN
Nice
Vfran
Monac
Ment

Figure 3


a)
Standardised densities /50cm²
0
500
1000
1500
2000
2500
3000
1-4 cm
0-1 cm
b)
Species richness
0
10
20
30
40
50
60
70
80
0-1 cm
0-4 cm
c)
Shannon-Wiener
1.0
1.5
2.0
2.5
3.0
3.5
4.0
d)
Equitability
0.4
0.6
0.8
1.0
e)
ES_{50}
0
5
10
15
20
25
30
n.d.
n.d.
Cerb
Colli
Leuc
Gruis
AgdW
AgdE
Sete
Grau
Bduc
Fara
Cart
Fos
Carry
Mrade
Mjet
Plane
Maire
Ccan
Embi
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Lav
Levan
Pamp
Fréj
Antib2
AntibN
Nice
Vfran
Monac
Ment

Figure 4

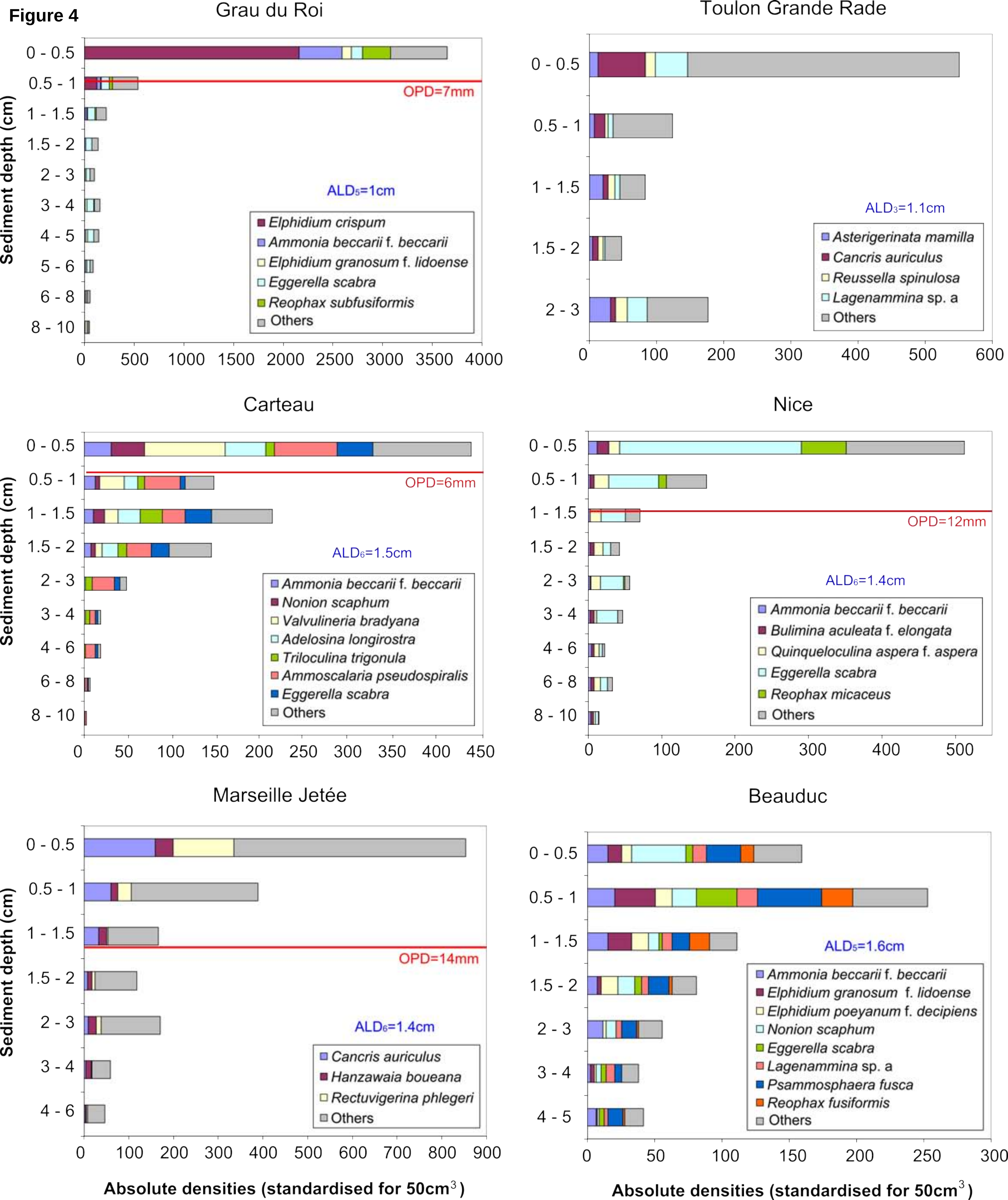

Grau du Roi
Sediment depth (cm)
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 8
8 - 10
OPD=7mm
ALD5=1cm
Elphidium crispum
Ammonia beccarii f. beccarii
Elphidium granosum f. lidoense
Eggerella scabra
Reophax subfusiformis
Others
0
500
1000
1500
2000
2500
3000
3500
4000
Toulon Grande Rade
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
ALD3=1.1cm
Asterigerinata mamilla
Cancris auriculus
Reussella spinulosa
Lagenammina sp. a
Others
0
100
200
300
400
500
600
Carteau
Sediment depth (cm)
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 6
6 - 8
8 - 10
OPD=6mm
ALD6=1.5cm
Ammonia beccarii f. beccarii
Nonion scaphum
Valvulineria bradyana
Adelosina longirostra
Triloculina trigonula
Ammoscalaria pseudospiralis
Eggerella scabra
Others
0
50
100
150
200
250
300
350
400
450
Nice
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 6
6 - 8
8 - 10
OPD=12mm
ALD6=1.4cm
Ammonia beccarii f. beccarii
Bulimina aculeata f. elongata
Quinqueloculina aspera f. aspera
Eggerella scabra
Reophax micaceus
Others
0
100
200
300
400
500
Marseille Jetée
Sediment depth (cm)
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 6
OPD=14mm
ALD6=1.4cm
Cancris auriculus
Hanzawaia boueana
Rectuvigerina phlegeri
Others
0
100
200
300
400
500
600
700
800
900
Absolute densities (standardised for 50cm3)
Beauduc
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 5
ALD5=1.6cm
Ammonia beccarii f. beccarii
Elphidium granosum f. lidoense
Elphidium poeyanum f. decipiens
Nonion scaphum
Eggerella scabra
Lagenammina sp. a
Psammosphaera fusca
Reophax fusiformis
Others
0
50
100
150
200
250
300
Absolute densities (standardised for 50cm3)

Figure 5 part1

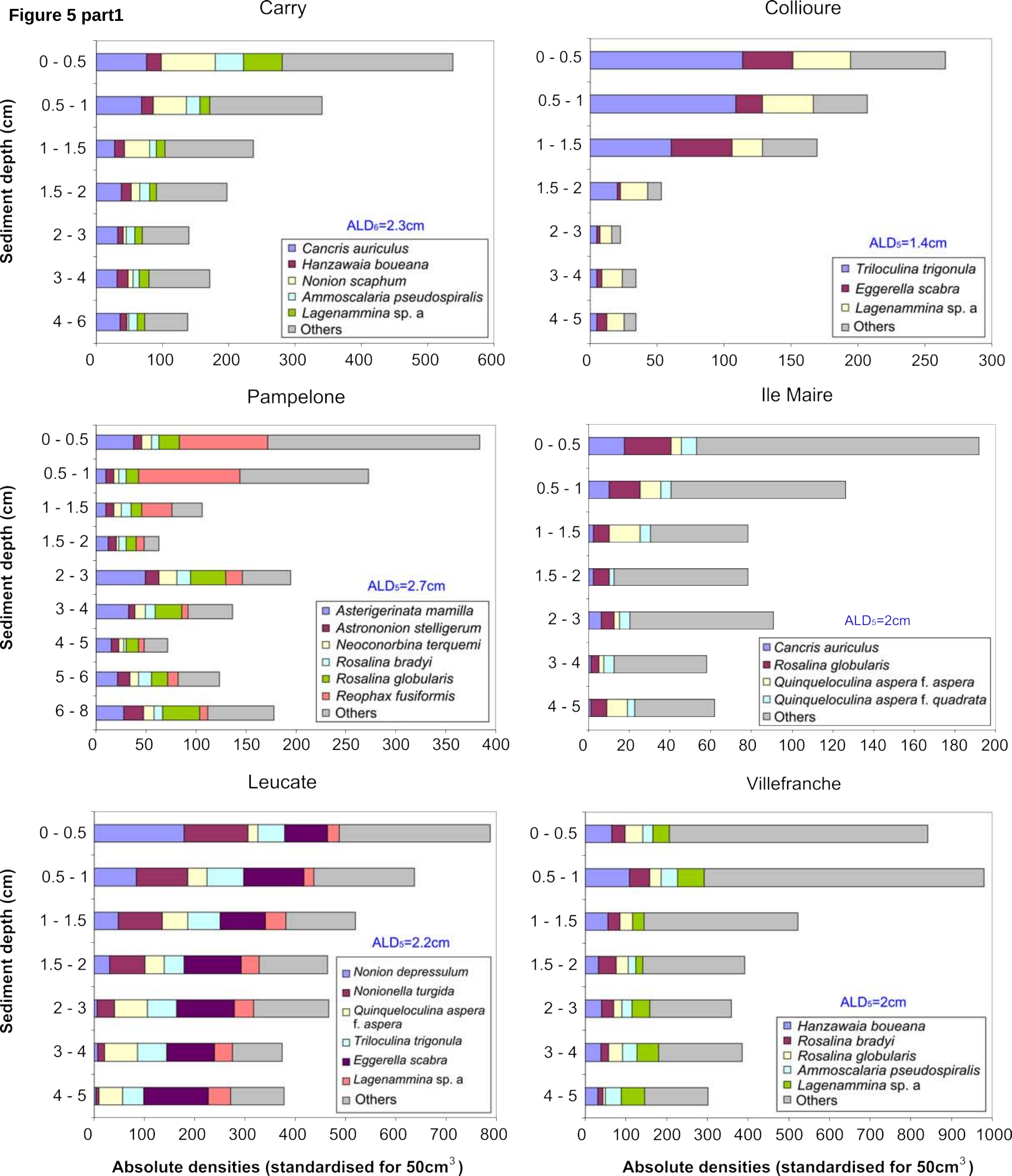


Figure 5 part2

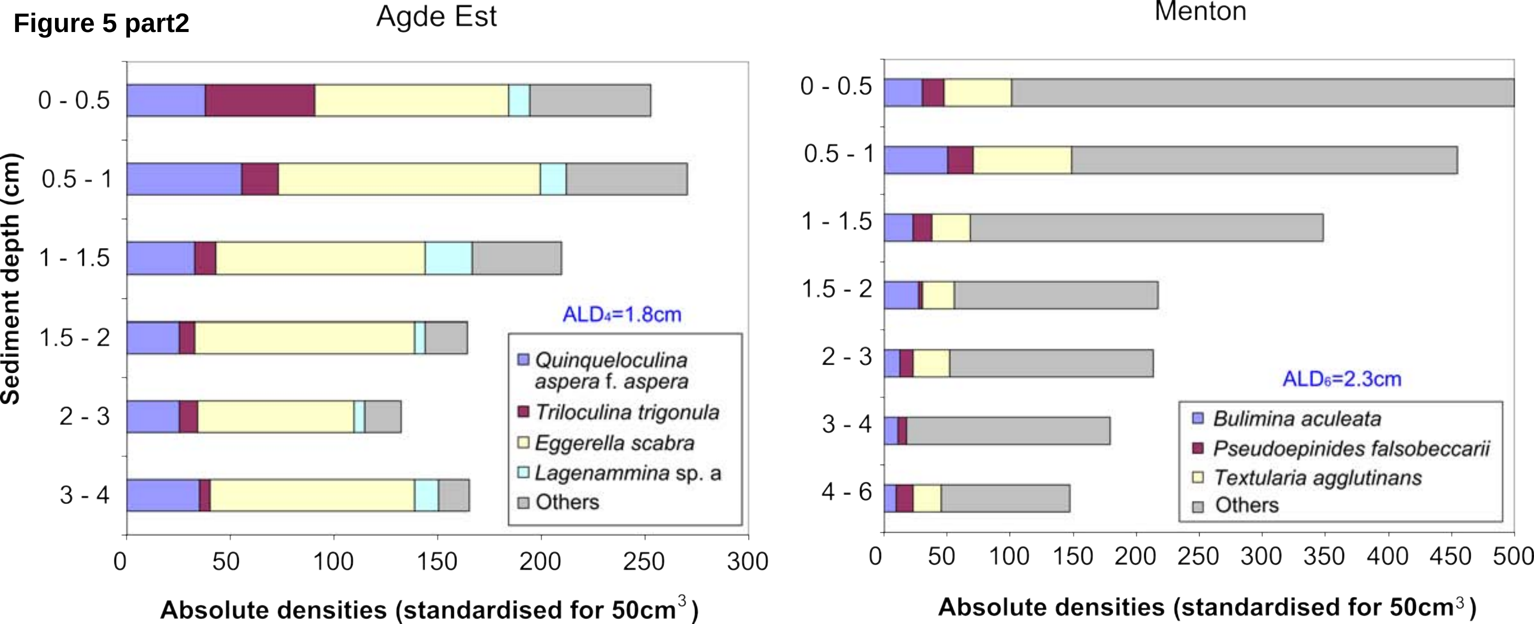


Figure 6 B&W

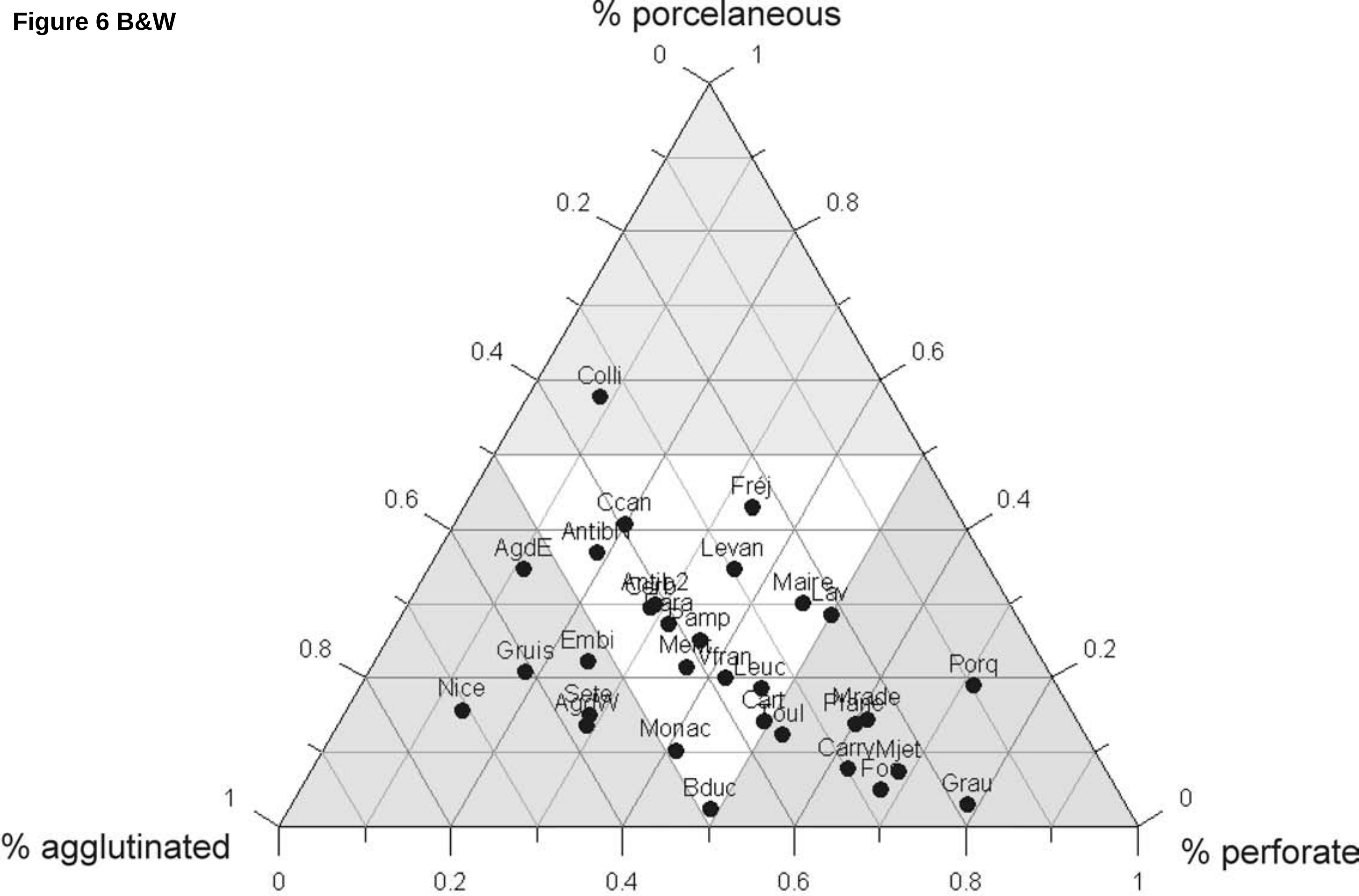

% porcelaneous
% agglutinated
% perforate
0
0.2
0.4
0.6
0.8
1
Colli
Fréj
Ccan
AntibN
AgdE
Levan
Antib2
Cerb
Maire
Lav
Para
Pamp
Embi
Ment
Gruis
Vfran
Leuc
Porq
Nice
Sete
AgdW
Cart
Mrade
Plane
Toul
Monac
CarryMjet
Fo
Grau
Bduc

Figure 6 color

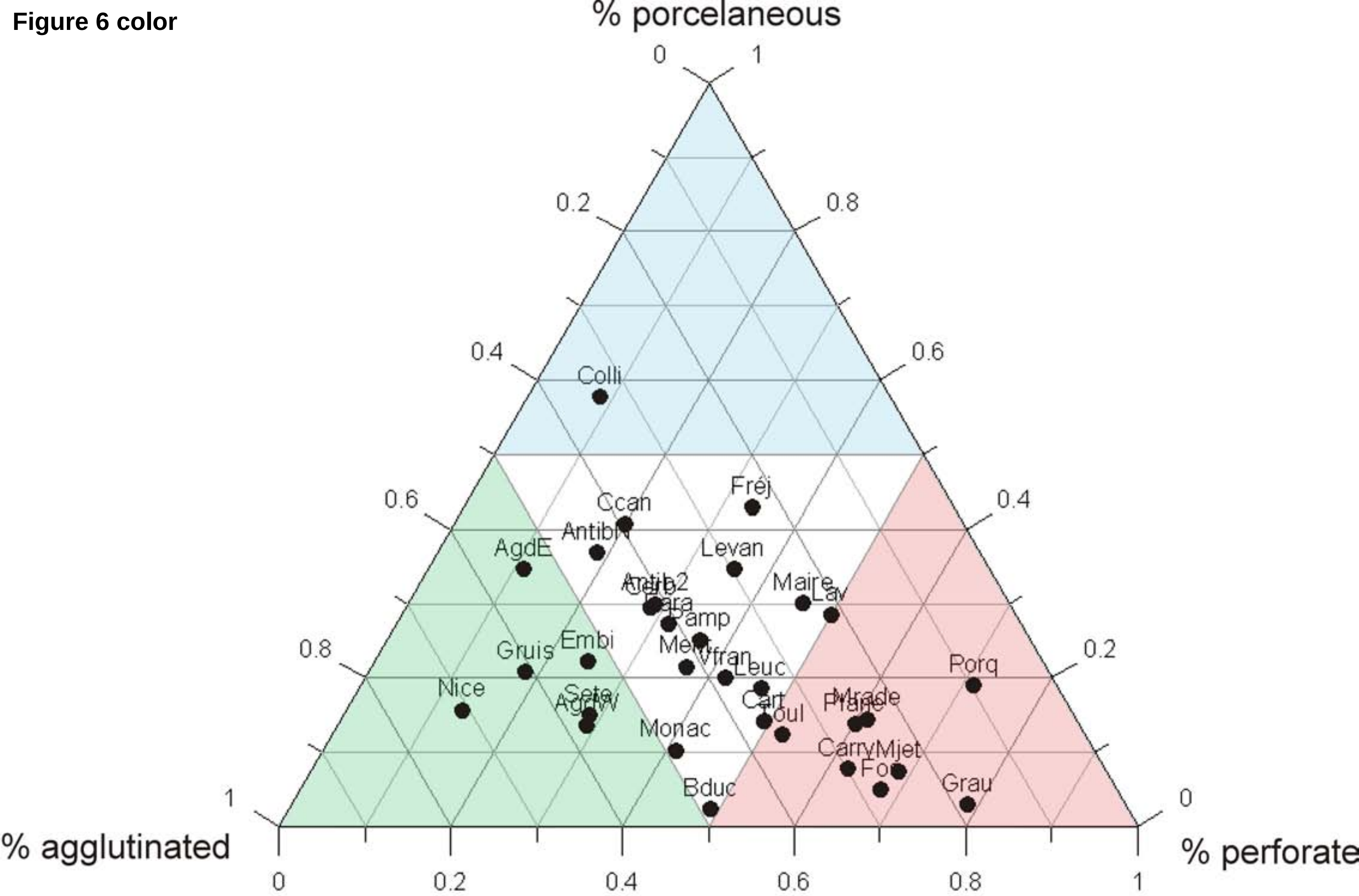


Figure 7

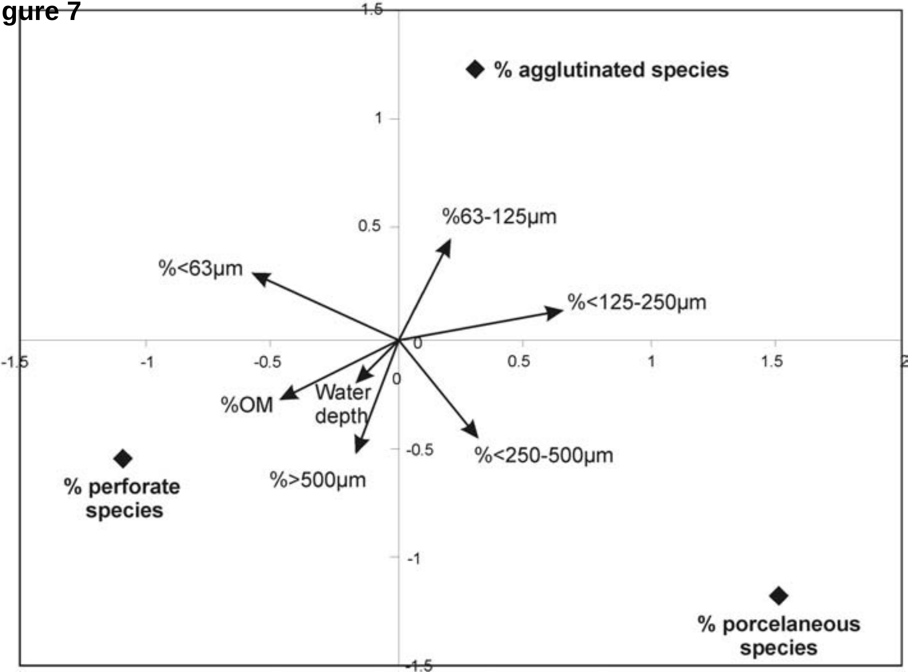
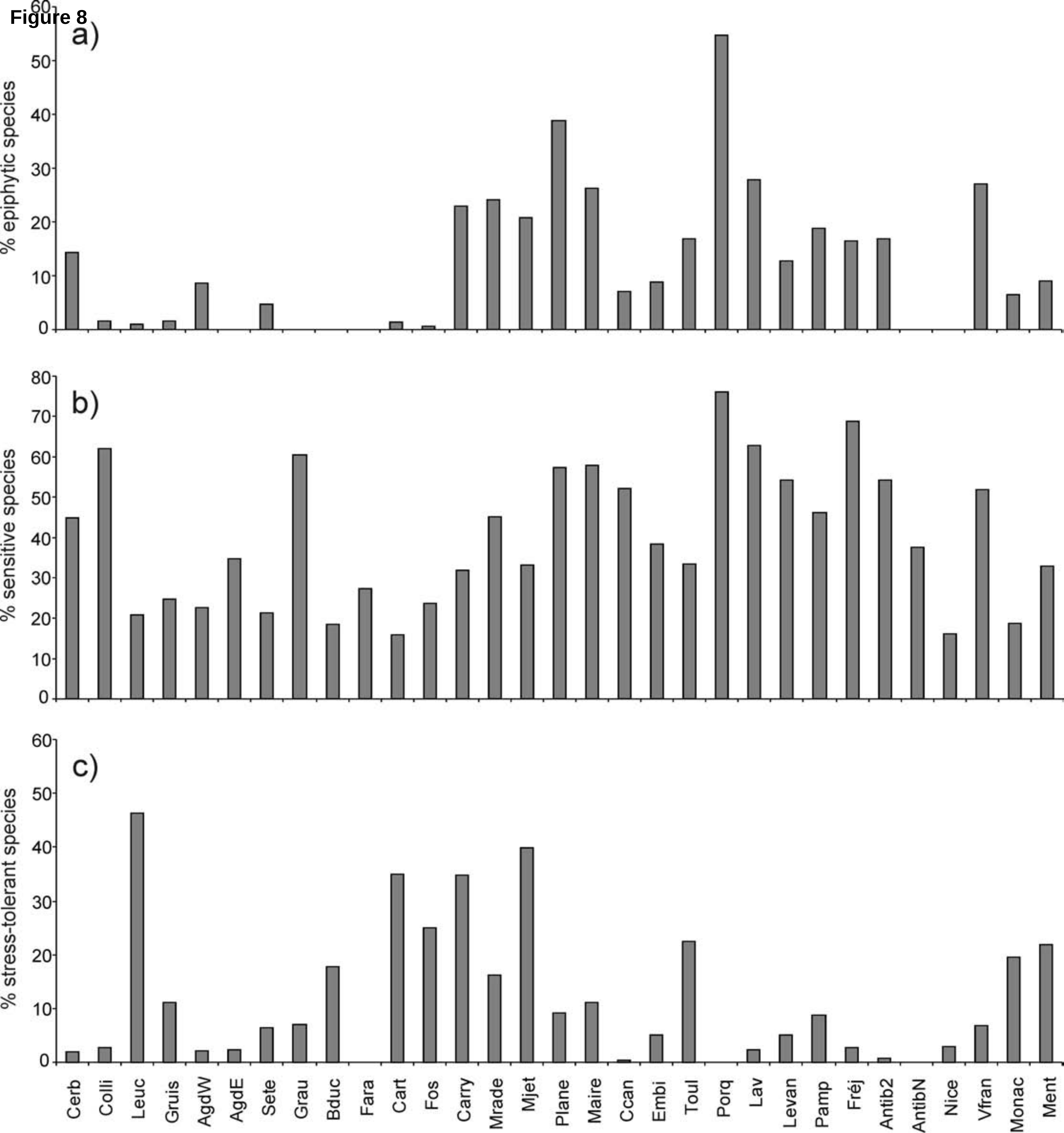

1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5
% agglutinated species
%63-125µm
%<63µm
%<125-250µm
%OM
Water depth
%>500µm
%<250-500µm
% perforate species
% porcelaneous species

Figure 8



a)
b)
c)
% epiphytic species
% sensitive species
% stress-tolerant species
0
10
20
30
40
50
60
70
80
Cerb
Colli
Leuc
Gruis
AgdW
AgdE
Sete
Grau
Bduc
Fara
Cart
Fos
Carry
Mrade
Mjet
Plane
Maire
Ccan
Embi
Toul
Porq
Lav
Levan
Pamp
Fréj
Antib2
AntibN
Nice
Vfran
Monac
Ment

Figure 9

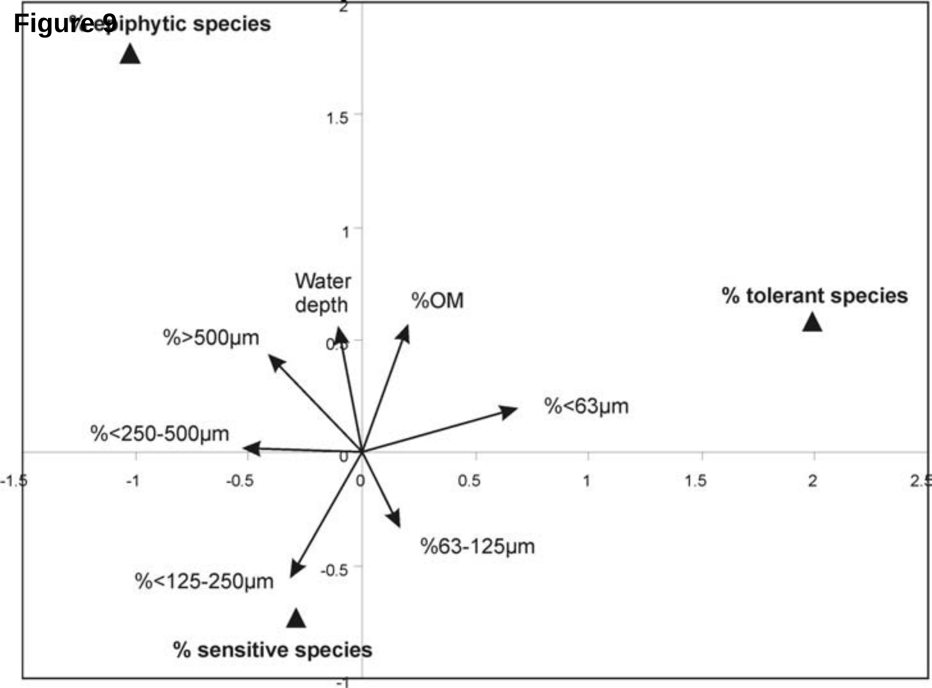
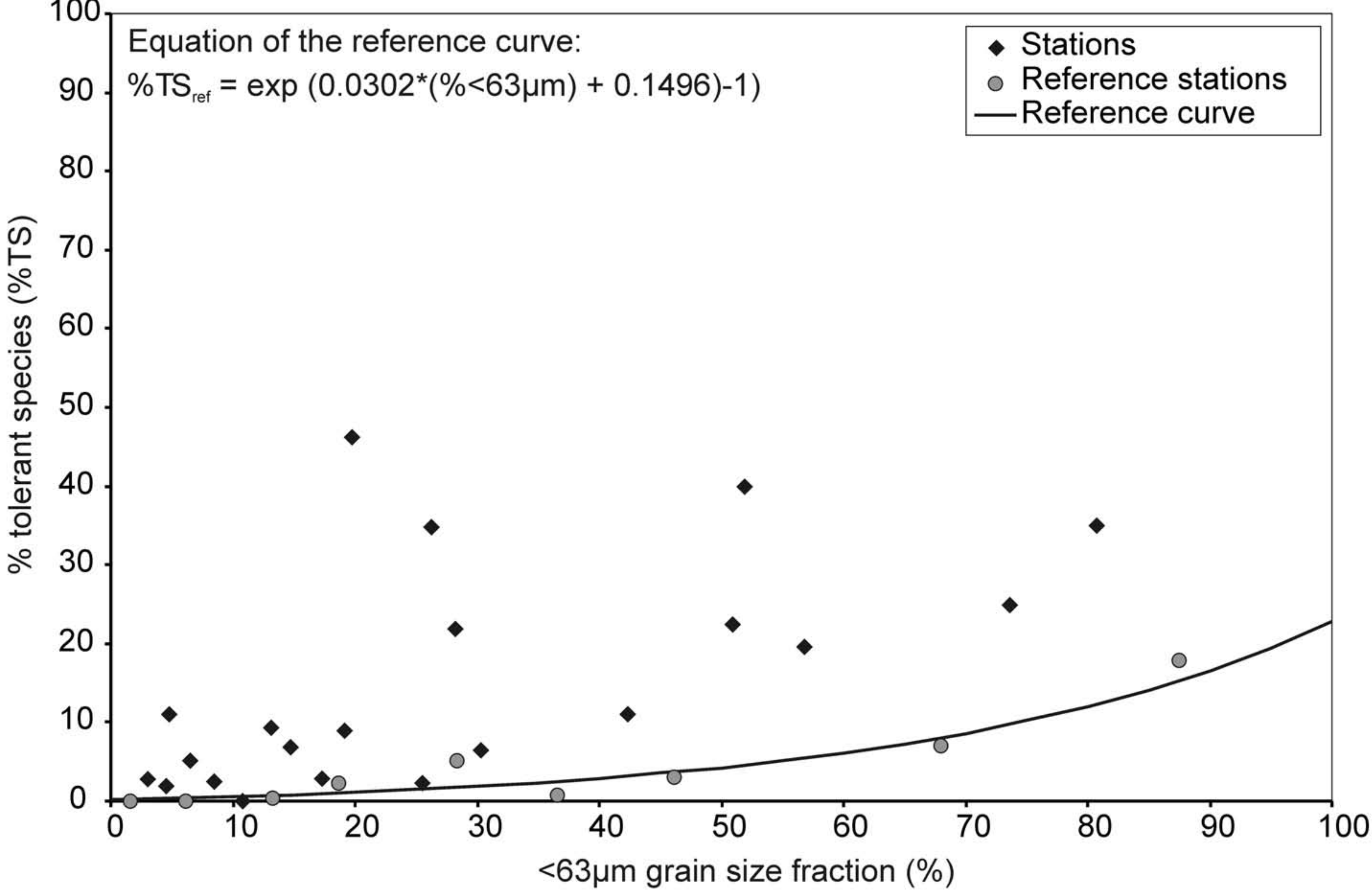

% epiphytic species
% tolerant species
% sensitive species
Water depth
%OM
%>500µm
%<63µm
%<250-500µm
%63-125µm
%<125-250µm
2
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

Figure 10


Equation of the reference curve:
$\%TS_{ref} = \exp(0.0302*(\%<63\mu m) + 0.1496)-1)$
Stations
Reference stations
Reference curve
% tolerant species (%TS)
<63µm grain size fraction (%)
0
10
20
30
40
50
60
70
80
90
100

Appendix A

Appendix A: Localisation (WGS84) and water depth of the stations. The sediment layers analysed for living foraminiferal faunas are indicated.

Station	Station abbr.	Longitude (°E)	Latitude (°N)	Water depth (m)	Sediment interval studied (cm), living fauna	Oxygen profiles
Cerbère	Cerb	3°10'21"	42°26'43"	26	0-1	
Collioure	Colli	3°05'22"	42°31'54"	23	0-5	
Leucate	Leuc	3°04'00"	42°51'09"	22	0-5	
Gruissan	Gruis	3°12'16"	43°09'12"	21.5	0-1	
Agde Ouest	AgdW	3°28'16"	43°14'21"	18	0-1	
Agde Est	AgdE	3°32'23"	43°16'17"	21	0-4	
Sète	Sete	3°42'41"	43°22'38"	20	0-1	
Grau du Roi	Grau	4°03'12"	43°31'34"	15	0-10	X
Beauduc	Bduc	4°30'08"	43°2484'"	14	0-5	
Faraman	Fara	4°43'13"	43°20'00"	10	0-1	
Carteau	Cart	4°53'44"	43°23'08"	10	0-10	X
Fos	Fos	4°55'46"	43°21'38"	20.8	0-1	X
Carry	Carry	5°09'38"	43°18'40"	48	0-6	
Marseille Grande Rade	Mrade	5°18'28"	43°16'10"	35	0-1	
Marseille Jetée	Mjet	5°19'41"	43°20'15"	41	0-6	X
Marseille-Ile Plane	Plane	5°23'02"	43°11'41"	40	0-1	
Ile Maire	Maire	5°20'50"	43°12'16"	40	0-5	
Cap Canaille	Ccan	5°33'11"	43°11'07"	43	0-1	
Ile Embiez	Embi	5°46'47"	43°06'08"	32	0-1	
Toulon Gde Rade	Toul	5°57'54"	43°05'34"	43	0-3	
Porquerolles	Porq	6°16'28"	43°01'08"	40	0-1	
Lavandou	Lav	6°23'13"	43°06'08"	40	0-1	
Ile Levant	Levan	6°25'60"	43°00'13"	47	0-1	
Pampelone	Pamp	6°41'44"	43°13'44"	42	0-8	
Fréjus	Fréj	6°52'07"	43°25'20"	33	0-1	X
Antibes 2	Antib2	7°08'29"	43°33'34"	25	0-1	X
Antibes Nord	AntibN	7°08'07"	43°36'47"	19	0-1	
Nice Ville	Nice	7°14'08"	43°40'51"	30	0-10	X
Villefranche	Vfran	7°18'40"	43°41'35"	42	0-5	
Monaco 2	Monac	7°25'47"	43°43'43"	69	0-1	X
Menton	Ment	7°59'41"	43°45'21"	51	0-6	

Appendix B

Appendix B: Environmental parameters and faunal parameters (considering foraminiferal faunas from the >150µm size fraction and 0-1cm sediment interval) calculated for the 31 stations analysed in this study (presented from West to East).

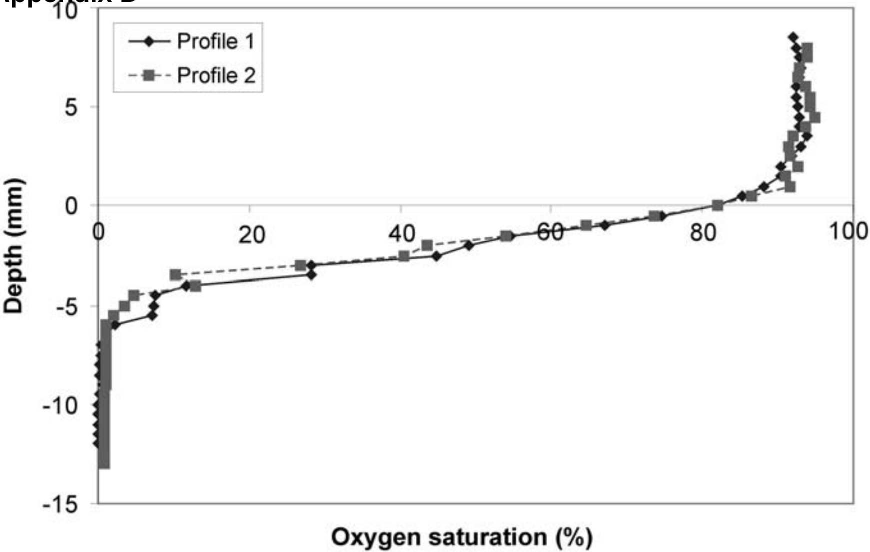
Station	**Environmental parameters**							**Foraminiferal parameters**										
			Grain size fraction of the sediment															
	Water depth (m)	% organic matter	%<63µm	%63-125µm	%125-250µm	%250-500µm	%>500µm	%tolerant species	%sensitive species	%epiphytic species	%perforate species	%porcelaneous species	%agglutinated species	Absolute densities	Specific richness	Shannon index	Equitability index	ES50
Cerb	26	2.20	4.56	0.47	26.30	55.53	13.14	1.90	44.76	14.29	28.57	29.52	41.90	132	32	3.02	0.87	21.37
Colli	23	1.37	2.89	13.86	39.90	33.74	9.62	2.67	62.03	1.60	8.56	57.75	33.69	237	26	1.96	0.60	12.29
Leuc	22	1.72	19.73	53.10	24.61	2.41	0.14	46.28	20.92	0.89	46.81	18.62	34.57	709	36	2.71	0.76	16.52
Gruis	21.5	2.30	42.36	35.64	20.34	1.18	0.49	11.11	24.84	1.63	18.30	20.92	60.78	301	24	2.26	0.71	13.33
AgdW	18	1.36	18.70	39.71	40.63	0.97	0.00	2.21	22.55	8.58	28.92	13.73	57.35	516	32	2.56	0.74	15.92
AgdE	21	1.57	8.45	27.56	56.99	6.99	0.00	2.42	34.78	0.00	11.11	34.78	54.11	260	20	1.95	0.65	11.00
Sete	20	2.30	30.35	31.39	30.66	5.67	1.93	6.54	21.25	4.63	28.61	14.99	56.40	461	37	2.59	0.72	16.88
Grau	15	3.28	67.92	25.86	6.21	0.00	0.00	7.07	60.51	0.06	78.74	3.02	18.24	2091	33	1.86	0.53	11.55
Bduc	14	1.68	87.52	10.75	1.73	0.00	0.00	17.79	18.40	0.00	49.08	2.45	48.47	209	21	2.62	0.86	15.29
Fara	10	1.08	6.16	52.35	40.01	1.49	0.00	0.00	27.27	0.00	31.82	27.27	40.91	22	5	1.34	0.83	n.d.
Cart	10	5.91	80.80	13.07	6.14	0.00	0.00	35.06	16.02	1.30	49.35	14.29	36.36	287	28	2.51	0.75	14.28
Fos	20.8	3.10	73.57	12.42	8.91	4.49	0.61	24.93	23.84	0.55	67.67	4.93	27.40	459	39	2.83	0.77	17.98
Carry	48	3.54	26.28	14.25	17.57	17.72	24.18	34.77	31.90	22.99	62.36	7.76	29.89	439	46	3.07	0.80	20.67
Mrade	35	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	16.13	45.16	24.19	61.29	14.52	24.19	81	23	3.01	0.96	20.65
Mjet	41	5.41	51.91	19.80	19.78	7.61	0.90	39.84	33.13	20.73	68.50	7.52	23.98	620	49	3.14	0.81	21.58
Plane	40	3.34	13.18	11.24	23.55	26.40	25.63	9.26	57.41	38.89	60.19	13.89	25.93	137	32	3.13	0.90	21.82
Maire	40	3.31	4.82	4.26	11.22	23.28	56.42	11.11	57.94	26.19	46.03	30.16	23.81	159	39	3.27	0.89	24.30
Ccan	43	n.d.	13.25	39.96	35.56	7.25	3.97	0.36	52.14	7.14	20.00	40.71	39.29	354	38	3.02	0.83	19.66
Embi	32	1.87	28.30	50.41	16.44	1.98	2.87	5.10	38.22	8.92	24.84	22.29	52.87	199	32	2.93	0.84	19.38
Toul	43	7.52	50.90	11.59	4.84	2.82	29.85	22.47	33.33	16.85	52.43	12.36	35.21	337	48	3.46	0.89	26.05
Porq	40	2.84	10.83	3.24	4.78	13.83	67.31	0.00	76.19	54.76	71.43	19.05	9.52	51	19	2.48	0.84	18.75
Lav	40	3.78	25.56	13.16	19.98	25.89	15.41	2.33	62.79	27.91	50.00	28.57	21.43	43	26	3.10	0.95	n.d.
Levan	47	2.83	6.47	6.09	13.60	37.84	35.99	5.08	54.24	12.71	35.59	34.75	29.66	149	34	2.97	0.84	21.81
Pamp	42	2.78	19.10	6.06	11.39	23.95	39.49	8.85	46.15	18.85	36.43	25.19	38.37	331	39	2.85	0.78	19.52
Fréj	33	4.04	17.35	22.82	33.57	20.25	6.02	2.82	68.75	16.53	33.67	42.94	23.39	627	62	3.52	0.85	25.72
Antib2	25	4.13	36.56	26.20	16.04	12.91	8.29	0.78	54.09	16.93	28.79	29.96	41.25	648	56	3.21	0.80	22.88
AntibN	19	1.04	1.62	22.75	59.25	16.37	0.00	0.00	37.39	0.00	18.49	36.97	44.54	302	26	2.45	0.75	15.22
Nice	30	2.21	46.12	28.47	17.79	6.80	0.81	3.00	16.10	0.00	13.48	15.73	70.79	338	32	2.22	0.64	14.74
Vfran	42	3.99	14.66	12.25	18.11	22.75	32.22	6.93	51.80	26.98	41.99	20.06	37.95	874	52	3.41	0.86	24.19
Monac	69	3.72	56.83	20.53	11.39	4.92	6.33	19.51	18.76	6.57	41.09	10.32	48.59	664	73	3.71	0.87	27.98
Ment	51	1.73	28.26	37.50	32.75	1.49	0.00	21.96	32.80	8.99	36.62	21.56	41.82	486	61	3.48	0.85	25.59

Appendix C

Appendix C: Linear correlations between environmental and faunal parameters (upper right triangle shows p values and lower left triangle shows r values) considering foraminiferal faunas from the >150µm size fraction and 0-1cm sediment interval.

	Environmental parameters							**Foraminiferal parameters**											
	Water depth	%OM	%<63µm	%63-125µm	%125-250µm	%250-500µm	%>500µm	%tolerant sp.	%sensitive sp.	%epiphytic sp.	%perforate sp.	%porcelaneous sp.	%agglutinated sp.	Absolute densities	Specific richness	Shannon index	Equitability index	ES50	%Etstd
Environmental parameters																			
Water depth		0.07	0.42	0.08	0.15	0.16	0.01	0.45	0.22	0.00	0.27	0.80	0.22	0.72	0.00	0.00	0.00	0.00	0.21
%OM	0.34		0.02	0.02	0.00	0.83	0.18	0.03	0.59	0.07	0.01	0.11	0.03	0.39	0.01	0.00	0.10	0.01	0.05
%<63µm	-0.16	**0.42**		0.87	0.00	0.00	0.04	0.01	0.01	0.07	0.02	0.00	0.66	0.06	0.39	0.80	0.47	0.51	0.17
%63-125µm	-0.33	**-0.42**	-0.03		0.03	0.00	0.00	0.75	0.02	0.01	0.08	0.85	0.01	0.36	0.61	0.07	0.15	0.22	0.60
%125-250µm	-0.27	**-0.56**	**-0.60**	**0.41**		0.61	0.03	0.07	0.84	0.11	0.00	0.00	0.09	0.40	0.28	0.08	0.18	0.17	0.28
%250-500µm	0.27	-0.04	**-0.59**	**-0.62**	0.10		0.01	0.06	0.00	0.03	0.46	0.00	0.10	0.11	0.98	0.22	0.16	0.22	0.21
%>500µm	**0.50**	0.25	**-0.39**	**-0.63**	**-0.39**	**0.46**		0.39	0.00	0.00	0.10	0.54	0.00	0.16	0.93	0.11	0.03	0.04	0.67
Foraminiferal parameters																			
%tolerant sp.	0.15	**0.40**	**0.48**	0.06	-0.34	-0.35	-0.17		0.01	0.55	0.01	0.00	0.37	0.40	0.10	0.14	0.68	0.55	0.00
%sensitive sp.	0.23	0.10	**-0.49**	**-0.44**	-0.04	**0.59**	**0.60**	**-0.48**		0.00	0.33	0.01	0.00	0.78	0.92	0.44	0.39	0.28	0.03
%epiphytic sp.	**0.53**	0.34	-0.34	**-0.50**	-0.30	**0.40**	**0.80**	-0.12	**0.65**		0.01	0.95	0.00	0.24	0.48	0.01	0.00	0.01	0.92
%perforate sp.	0.21	**0.50**	**0.42**	-0.33	**-0.63**	-0.14	0.32	**0.48**	0.19	**0.46**		0.00	0.00	0.06	0.44	0.19	0.19	0.25	0.03
%porcelaneous sp.	-0.05	-0.30	**-0.71**	-0.04	**0.57**	**0.55**	0.12	**-0.52**	**0.50**	-0.01	**-0.65**		0.88	0.06	0.51	0.54	0.79	0.89	0.04
%agglutinated sp.	-0.24	**-0.40**	0.09	**0.47**	0.32	-0.31	**-0.52**	-0.17	**-0.69**	**-0.60**	**-0.74**	-0.03		0.43	0.67	0.25	0.13	0.16	0.30
Absolute densities	-0.07	0.17	0.36	0.18	-0.16	-0.30	-0.27	0.16	0.05	-0.22	0.35	-0.35	-0.15		0.04	0.95	0.01	0.63	0.61
Specific richness	**0.66**	**0.46**	0.17	-0.10	-0.21	0.01	0.02	0.31	0.02	0.14	0.15	-0.13	-0.08	**0.38**		0.00	0.16	0.00	0.07
Shannon index	**0.74**	**0.52**	0.05	-0.34	-0.33	0.23	0.30	0.28	0.15	**0.45**	0.25	-0.12	-0.22	-0.01	**0.82**		0.00	0.00	0.09
Equitability index	**0.52**	0.31	-0.14	-0.28	-0.26	0.27	**0.42**	0.08	0.17	**0.57**	0.25	-0.05	-0.29	**-0.48**	0.27	**0.69**		0.00	0.52
ES50	**0.79**	**0.47**	-0.13	-0.24	-0.27	0.24	**0.39**	0.12	0.21	**0.51**	0.23	-0.03	-0.28	-0.10	**0.81**	**0.97**	**0.82**		0.33
%Etstd	0.24	0.36	0.26	0.10	-0.21	-0.24	-0.08	**0.97**	**-0.40**	-0.02	**0.41**	**-0.38**	-0.20	0.10	0.34	0.32	0.12	0.193	

Appendix D



Profile 1
Profile 2
Depth (mm)
10
5
0
-5
-10
-15
0
20
40
60
80
100
Oxygen saturation (%)

Appendix E

Appendix E: Wilcoxon tests (Z) results and their corresponding probabilities (p) in order to test similarities of major species (>5%) between intervals 0-1 and 0-4cm.

Stations	**n**	**Z**	**p**
Grau du Roi	18	0.54	0.59
Carteau	18	0.28	0.78
Agde Est	16	0.78	0.44
Pampelone	24	0.06	0.95
Nice	14	0.60	0.55
Ile Maire	21	0.26	0.79
Villefranche	28	0.18	0.86
Menton	29	0.18	0.85
Collioure	17	1.35	0.18
Beauduc	17	0.69	0.49
Toulon Grande Rade	28	0.87	0.39
Carry	30	0.63	0.53
Leucate	24	0.14	0.89
Marseille Jetée	30	0.63	0.53

Appendix F

Appendix F: Linear correlation (r) between the relative densities of the major species (see Table 2 for the meaning of species abbreviations) and the environmental parameters available for this study. The statistically significant correlations ($p<0.05$) are indicated in bold.

	Water depth	**% organic matter**	**Grain size fraction (%)**				
			<63μm	**63-125μm**	**125-250μm**	**250-500μm**	**>500μm**
Abecc	**-0.52**	-0.10	**0.54**	0.05	-0.11	**-0.38**	**-0.40**
Amami	0.31	0.16	-0.24	**-0.41**	-0.28	0.24	**0.69**
Astel	**0.41**	0.32	-0.21	**-0.48**	-0.35	0.29	**0.74**
Bgran	**-0.38**	**-0.39**	-0.26	**0.41**	**0.39**	-0.19	-0.15
Bacul	**0.40**	-0.13	0.24	0.26	-0.02	-0.30	-0.28
Cauri	**0.53**	**0.56**	0.04	-0.29	-0.28	0.08	0.34
Cloba	**0.46**	0.28	-0.31	**-0.38**	-0.16	**0.52**	**0.46**
Ecris	-0.23	0.05	0.30	0.04	-0.20	-0.17	-0.15
Egran	-0.30	-0.22	**0.48**	0.06	-0.28	-0.30	-0.25
Epoey	-0.18	0.01	**0.50**	-0.12	-0.25	-0.21	-0.22
Hboue	**0.49**	**0.51**	-0.08	-0.30	-0.18	0.19	0.35
Nterq	0.28	0.16	-0.20	-0.36	-0.24	0.15	**0.65**
Ndepres	-0.20	-0.21	-0.08	**0.44**	0.07	-0.15	-0.19
Nscap	-0.18	0.14	**0.61**	-0.18	-0.34	-0.27	-0.21
Nturg	-0.25	-0.18	0.06	**0.40**	0.00	-0.24	-0.22
Pmedit	0.35	0.18	-0.21	-0.15	0.04	0.27	0.17
Rphle	0.24	**0.59**	0.31	-0.16	-0.23	-0.12	-0.01
Rglob	0.35	0.23	-0.34	**-0.48**	-0.29	**0.40**	**0.77**
Spiril	0.23	0.21	-0.26	-0.24	-0.11	**0.37**	0.36
Vbrad	-0.06	**0.47**	**0.50**	-0.11	-0.27	-0.28	-0.16
Along	-0.04	0.26	0.15	-0.24	-0.21	0.19	0.02
Birreg	0.12	-0.15	-0.26	-0.07	0.21	0.27	0.04
Qasp	-0.35	**-0.45**	**-0.48**	**0.44**	**0.64**	0.02	-0.24
Qbosc	-0.13	-0.18	-0.26	-0.05	**0.43**	0.14	-0.06
Qcost	**0.46**	0.06	-0.38	**-0.43**	-0.17	**0.54**	**0.58**
Qsemi	0.19	0.05	-0.08	-0.10	-0.03	0.13	0.11
Sgrata	0.20	0.13	-0.17	-0.20	-0.11	0.22	0.30
Ttrigo	-0.19	-0.29	-0.30	0.01	**0.40**	0.26	-0.13
Apseudo	0.15	**0.52**	**0.44**	-0.22	-0.32	-0.17	-0.03
Escab	**-0.58**	**-0.53**	-0.16	**0.54**	**0.60**	-0.26	**-0.51**
LagenamA	-0.03	-0.08	-0.03	0.06	0.04	0.16	-0.16
LagenamB	-0.14	-0.11	0.01	0.23	-0.02	-0.10	-0.10
Pfusc	-0.28	-0.36	0.29	0.28	-0.02	**-0.38**	-0.32
Rfusif	0.18	0.01	-0.11	-0.29	-0.18	0.25	0.33
Rmica	0.28	0.16	0.12	-0.05	-0.19	-0.10	0.12
Rscorp	0.31	0.37	0.07	-0.12	-0.17	-0.04	0.16
Rsubfus	0.19	0.31	0.18	-0.13	-0.27	-0.03	0.10
Rscot	-0.12	-0.15	-0.09	**0.41**	0.04	-0.14	-0.13
Taggl	0.32	-0.13	-0.08	0.21	0.14	-0.07	-0.11
Tsagit	**0.62**	0.37	-0.03	-0.26	-0.23	0.10	0.36

Appendix G: Evidence from the literature that support our choice to attribute species to stress-tolerant and sensitive (including epiphytic species) groups.

Tolerant species group

Bulimina* species** (e.g. *B. marginata, B. aculeata, B. denudata*) are typical of environments with high food input (De Rijk et al., 2000; Morigi et al., 2001; Donnici and Serandrei-Barbero, 2002; Mendes et al., 2004; Eberwein and Mackensen, 2006). For example, *B. marginata* responds to seasonal fluxes of phytodetritus in the Bay of Biscay by increasing its density (Langezaal et al., 2006). *Bulimina* spp. have also been considered as good markers of oxygen-poor conditions (Sen Gupta and Machain-Castillo, 1993; Ohga and Kitazato, 1997; Bernhard and Sen Gupta, 1999; van der Zwaan et al., 1999). ***Cancris auriculus and ***Rectuvigerina phlegeri*** are often found in the same assemblages. These species are indicative of eutrophic conditions and stress due to hypoxia (Corliss, 1985; Sen Gupta and Machain-Castillo, 1993; Schmiedl et al., 2000; Milker et al., 2009). More precisely, Diz et al. (2006) described *R. phlegeri* as an opportunistic species rapidly developing after labile organic matter inputs. ***Nonion scaphum*** and ***Nonion depressulum*** are species living in fine sediment with high organic matter inputs (Venec-Peyré, 1984; Mathieu, 1986; Murray, 1991; Debenay et Redois, 1997; Fontanier et al., 2002; Mojtahid et al., 2006). ***Nonionella turgida, N. stella*** and ***Pseudoeponides falsobeccarii*** are all characteristic of fine-grained sediments with high organic matter contents and would be tolerant or even slightly favoured by stressed conditions such as hypoxia (Venec-Peyré, 1984; Jorissen, 1987; Bernhard and Reimers, 1991; Van der Zwaan and Jorissen, 1991; Barmawidjaja et al., 1992; Bernhard et al., 1997; Duijnstee et al., 2003; Diz et al., 2006). ***Valvulineria bradyana*** is considered as an excellent indicator of sediment enriched in organic matter where environmental stress conditions, such as hypoxia, occur periodically (Jorissen, 1987, 1988 ; Fontanier et al., 2002). Finally, ***Leptohalysis scottii*** is considered as a strongly opportunistic species because it responds quickly to labile organic matter inputs in the first centimetre of sediment (Scott et al., 2005; Diz et al., 2008; Sabbatini et al., 2012). It can support highly turbid waters (Scott et al., 2005; Mojtahid et al., 2009; Goineau et al., 2011) but would only be weakly tolerant to severe hypoxia (Moodley et al., 1997; Ernst et al., 2002; Duijnstee et al., 2003).

Sensitive species group:

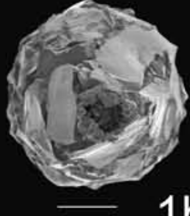
According to the literature, **porcelaneous foraminifera** live preferentially in sandy, well oxygenated sediments with relatively low organic matter content (Bizon and Bizon, 1984;

Jorissen, 1988; Donnici and Serandrei-Barbero, 2002; Schmiedl et al., 2003). Most of the porcellaneous species will therefore be absent from the assemblage in case of a muddy sediment enriched in organic matter (naturally or anthropogenetically).

The group of **epiphytic species** as described in the main text is sensitive to low oxygen conditions. High percentages suggests the presence of seagrass or macroalgae meadow in the vicinity (Pujos, 1976; Spindler, 1980; Bizon and Bizon, 1984; Jorissen, 1987; Murray, 1991; Langer, 1993; Coppa and Di Tuoro, 1995; Guimerans and Currado, 1999; Van der Zwaan *et al*., 1999; Villanueva Guimerans and Cervera Currado, 1999; Mendes et al., 2004; Panieri et al., 2005; Mojtahid et al., 2006; Schönfeld, 2002; Martins et al., 2007; Milker et al., 2009). In addition to the sessile and temporarily motile species from morphotypes A and B (Langer et al., 1993) considered in our "epiphytic group", we added some species from the motile epiphytic morphotypes C and D in the sensitive species. This concerns *Reussela spinulosa*, *Spirillina* and *Elphidium* species. According to a study in the Adriatic Sea, *Reussela spinulosa* would show a certain preference for a sandy substratum with a low input of clay (Jorissen, 1987). *Elphidium crispum* shows no specific preference to a particular type of sediment. In the study of Jorissen (1987), this species is found at sites where the organic matter content is slightly elevated but it is very rare in stations under the direct influence of the Po river output. This species is also considered as a motile epiphytic suspension feeder (Langer, 1993). Therefore, this species would not support severe stress conditions. In our material, *Elphidium granosum* and *E. poeyanum* are mainly represented by the *lidoense* and *decipiens* morphotypes, respectively. These two morphotypes, which have been considered as sensitive by Jorissen (1987), are mainly found in silty to sandy areas with a relatively low organic matter content, probably with well oxygenated bottom waters.

Supplementary Material 1 Plate 1


1a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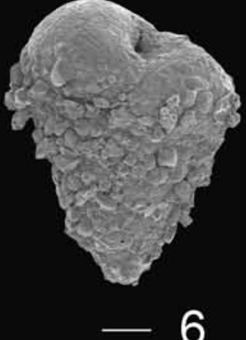
2


3


4


5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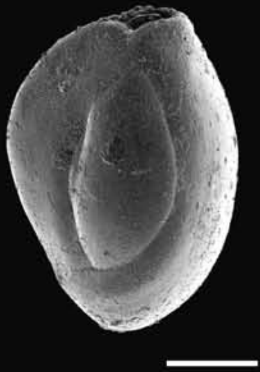
7


8


9


10a


10b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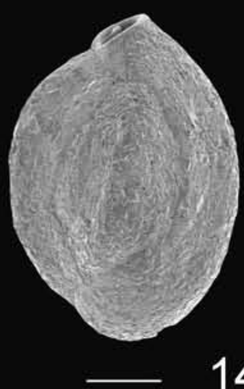
12


13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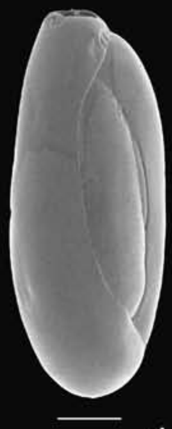
14b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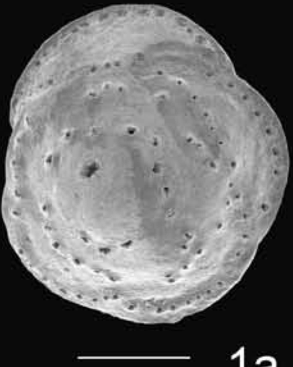
16

Supplementary Material 1 Plate 2

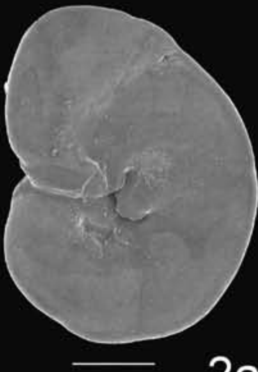
Supplementary Material 1 Plate 3



1a

1b

1c



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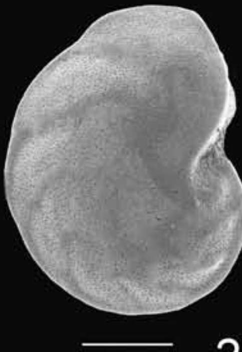


2b

3

4a

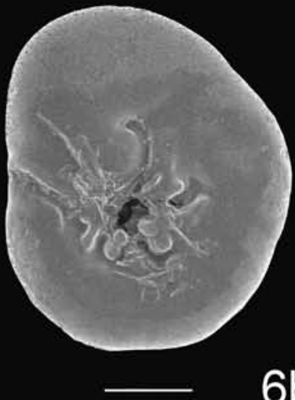
4b

4c

5a

5b

6a



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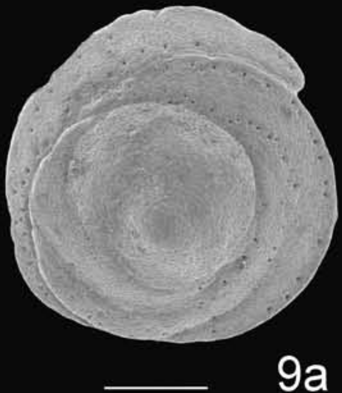

9a

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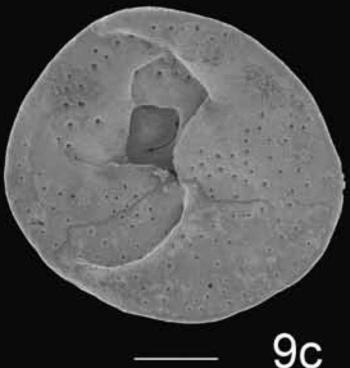

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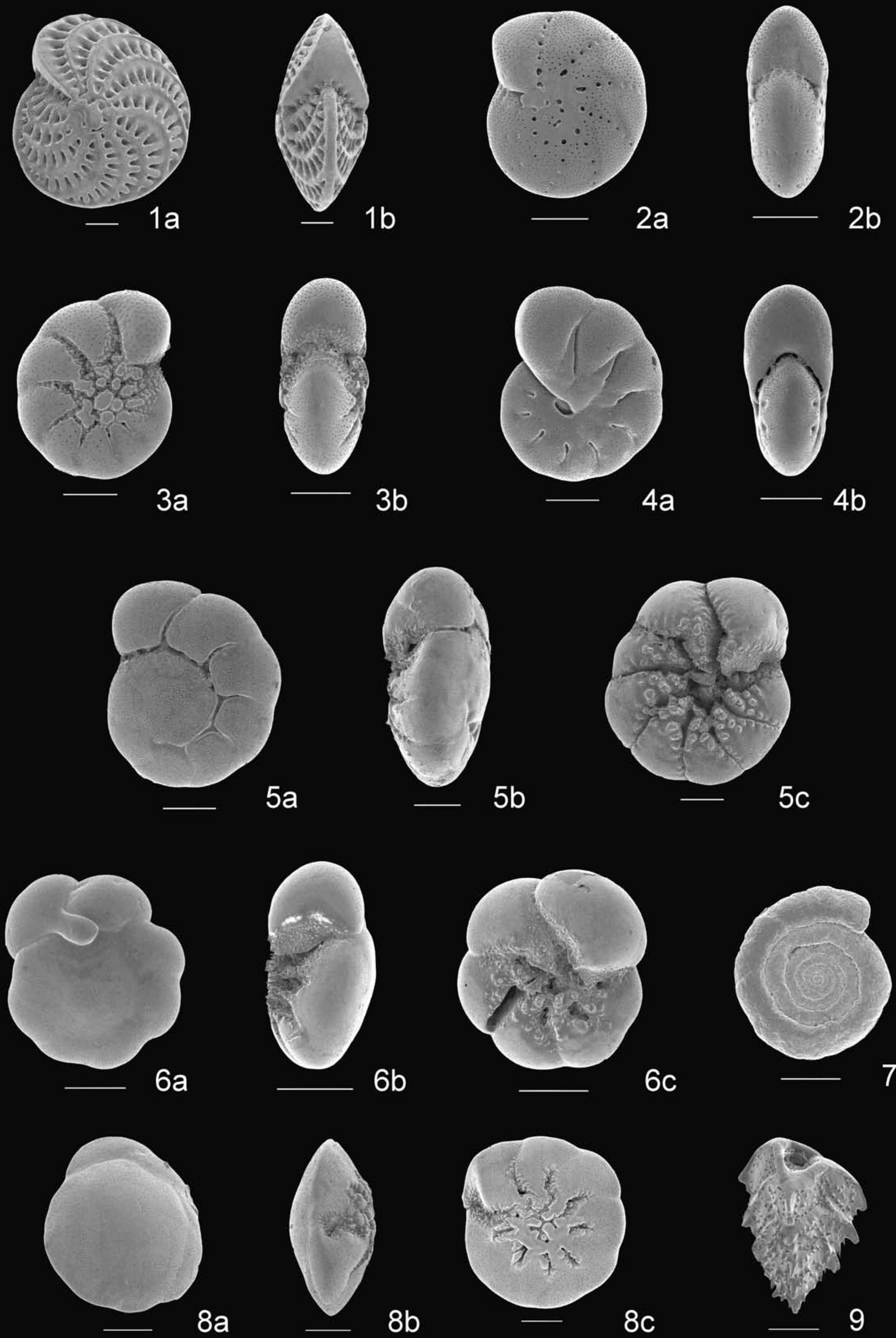
Supplementary Material 1 Plate 4



Supplementary Material 2

Supplementary material 2: Number of living (Rose Bengal stained) benthic foraminifera (>150µm) in the first centimetre of sediment standardised for 50cm².

	Cerb	Colli	Leuc	Gruis	AgdW	AgdE	Sete	Grau	Bduc	Fara	Cart	Fos	Carry	Mrade	Mjet	Plane	Maire	Ccan	Embi	Toul	Porq	Lav	Levan	Pamp	Fréj	Antib2	AntibN	Nice	Vfran	Monac	Ment
Perforate																															
Ammonia beccarii f. beccarii			24	8	14	4	53	237	18		21	86	1	4	1	5	1	3	5					1	8	11	25	8	3	1	6
Ammonia beccarii f. inflata							1	27			5	1						5						1	1				3	1	1
Ammonia parkinsoniana f. parkinsoniana									3			4					1					1					4				
Ammonia parkinsoniana f. tepida		1	1				5	11	3			6													1		4				
Ammonia perlucida								1			1																			1	
Amphicoryna intercellularis												1																			
Amphicoryna scalaris													1																	3	
Astacolus crepidulus																														1	
Astacolus sp.							1																								1
Asterigerinata mamilla	3				9		1						6	4	18	3		1	1	10	10	4	5	24	21	8			25		1
Astrononion stelligerum											1		5	3	6		1			10	4	3	6	8	8	1			18		
Bolivina dilatata																															1
Bolivina spathulata								4			1																				
Buccella granulata			5	3	58	14	9		9	8		4		3		1	3	20	1	4	1	3	5	6	1	5	16	11	4		
Buccella sp.																											3				
Bulimina aculeata	1		13	14			15	16	3		1	1														3		10	1	61	44
Bulimina costata																														4	
Bulimina marginata								1																							
Buliminella elegantissima								1																							
Cancris auriculus							3				3	8	72	8	110	9	14	1	8	43		1	6	25	6				28	15	13
Cassidulina carinata																														1	
Cassidulina oblonga																				1										9	3
Cibicides lobatulus	8				8		6						24	3	30	14	9	5	8	9	1	3	5	3	10	9			20	8	4
Coryphostoma sp.											1	1																			
Dentalina bradyensis																				1											
Dentalina sp.																												1			
Elphidium advenum		1	1	3	16	5	1			1													1	3		4					
Elphidium complanatum	4																														
Elphidium crispum	1	3	1	1			1	1142			1	15			4					1			1		13	3	1				
Elphidium granosum		4	8	3	1		5	49	20			4			3			3	8	3											3
Elphidium macellum																					1										
Elphidium maioricense																										1					
Elphidium poeyanum f. decipiens			1	1			1	6	10			64			15			1	3						8	1				4	
Fissurina sp.													5		10			1		4			1	1	6					1	
Fursenkoina acuta											1	1							1						3	3					1
Fursenkoina complanata																														3	
Gavelinopsis phlegeri		1	6	6	5		10					3	3		1		5	1						1	1	3			4	5	5
Glabratella patelliformis																												1			
Glandulina laevigata																				1					1						1
Glandulina ovula	1																														
Glandulina sp.	1																														
Globobulimina affinis													1							4									1	21	
Globocassidulina subglobosa																													1		1
Globulina gibba		1																				1									
Globulina sp.																	3														
Hanzawaia boueana													20	5	28	6	3			15		1	1	3	4	5			87	8	5
Lagena striata			1		3												1											3	1	1	3
Lagena sp.			1									3			1													1			
Lenticulina sp.																				1											
Melonis barleeanus													1							3										25	
Neoconorbina terquemi		1											8		13	13	1	6	1	9	8	1		8	1				4		
Neolenticulina variabilis																														1	
Nodosaria lamnulifera											1																				
Nodosaria sp.																															1
Nonion depressulum	1	4	131	11	6	1	4	34																		1					
Nonion scaphum			16	8	4	1	8	57	29		21	67	66	4	48	1															

Supplementary material 3: Taxonomical list of the major species identified in this study.

Species	**References**
Adelosina longirostra (d'Orbigny), 1846	Jorissen (1987), pl. 2, fig. 14
Ammonia beccarii (Linnaeus), 1758	Jorissen (1988), pl. 5, figs. 1-4
Ammoscalaria pseudospiralis (Williamson), 1958	Jones (1994), pl. 33, figs. 1-4
Asterigerinata mamilla (Williamson), 1858	Jorissen (1987), pl. 3, fig. 1
Astrononion stelligerum (d'Orbigny), 1839	Jones (1994), pl. 109, figs. 3-4
Biloculinella irregularis (d'Orbigny), 1839	d'Orbigny (1839), pl. 8, figs. 20-21
Buccella granulata (Di Napoli Alliata), 1952	Jorissen (1987), pl. 3, fig. 5
Bulimina aculeata (d'Orbigny), 1826	Jones (1994), pl.51, figs. 7-9
Cancris auriculus (Fichtel & Moll), 1942	Jones (1994), pl. 106, fig. 4
Cibicides lobatulus Walker & Jacob, 1798	Jones (1994), pl. 93, fig. 1
Eggerella scabra (Williamson), 1858	Jones (1994), pl. 47, figs. 15-17
Elphidium crispum (Linnaeus), 1758	Jorissen (1987), pl. 3, fig. 8
Elphidium granosum (d'orbigny) f. *lidoense* Cushman, 1936	Jorissen (1988), pl. 17, figs. 1-4
Elphidium poeyanum f. *decipiens* (Costa), 1856	Jorissen (1988), pl. 20, figs. 2-3
Hanzawaia boueana (d'Orbigny), 1846	Jorissen (1987), pl. 3, fig. 10
Leptohyalis scotti (Chaster), 1892	Sgarrella *et al.* (1993), pl. 2, fig. 5
Neoconorbina terquemi (Rzehak), 1888	Jorissen (1987), pl. 3, figs. 3-4
Nonion depressulum (Walker and Jacob), 1798	Jorissen (1987), pl. 2, fig. 7
Nonion scaphum (Fichtel & Moll), 1798	Jones (1994), pl. 109, fig. 12
Nonionella turgida (Williamson), 1858	Jones (1994), pl. 109, figs. 17-19
Planorbulina mediterranensis d'Orbigny, 1826	Jones (1994), pl. 92, fig. 1
Psammosphaera fusca Schulze, 1875	Jones (1994), pl. 18, figs. 1-8
Quinqueloculina aspera (d'Orbigny), 1826	Jorissen (1987), pl. 3, fig. 2; in this species, we lumped different morphotypes (f. *aspera* , f. *rugosa* , f. *berthelotiana* , f. *quadrata*)
Quinqueloculina bosciana d'Orbigny, 1839	Sgarrella *et al.* (1993), pl. 6, figs. 8-9
Quinqueloculina costata (d'Orbigny), 1826	Milker and Schmiedl (2012), pl. 15, figs. 17-19; in this species, we lumped different morphotypes (f. *costata* , f. *limbata* , f. *disparilis* , f. *lucida*)
Quinqueloculina seminula (Linné), 1758	Jones (1994), pl. 5, fig. 6
Rectuvigerina phlegeri Le Calvez, 1959	Schiebel (1992), pl. 3, figs. 10a-d
Reophax fusiformis (Williamson), 1858	Jones (1994), pl. 30, figs. 7-10
Reophax micaceus Earland, 1934	Timm (1992), pl. 2, fig. 6
Reophax scorpiurus Montfort, 1808	Loeblich and Tappan (1988), pl. 44, figs. 1-3
Reophax subfusiformis Earland, 1933	Timm (1992), pl. 2, fig. 1
Rosalina globularis d'Orbigny, 1826	Milker and Schmiedl (2012), pl. 22, figs. 17-18
Sigmoilina grata (Terqem), 1878	Sgarrella et al. (1993), pl. 9, fig. 9
Textularia agglutinans d'Orbigny, 1839	Cimerman and Langer (1991), pl. 10, figs. 1-2
Textularia sagittula Defrance, 1824	Jorissen (1987), pl. 3, fig. 12
Triloculina trigonula (Lamarck), 1804	Jorissen (1987), pl. 2, fig. 13
Valvulineria bradyana (Fornasini), 1900	Jorissen (1987), pl. 4, fig 1-2

Supplementary material 4: Loadings on the species on the 2 first axis of the PCA performed on the relative densities of the major species (>5%) of the 31 stations (see Table 2 for the meaning of species abbreviations). The percentage of variance explained by the axes is indicated in parenthesis.

	PCA1 (35.4%)	**PCA2 (13.8%)**
Abecc	0.02	-0.24
Amami	-0.09	0.10
Astel	-0.05	0.05
Bgran	0.17	0.05
Bacul	0.01	-0.01
Cauri	-0.16	0.10
Cloba	-0.06	0.07
Ecris	**-0.08**	**-0.91**
Egran	0.00	-0.04
Epoey	-0.02	-0.04
Hboue	-0.07	0.04
Nterq	-0.06	0.06
Ndepres	0.02	-0.03
Nscap	-0.07	-0.07
Nturg	0.02	-0.03
Pmedit	-0.02	0.03
Rphle	-0.07	0.02
Rglob	-0.11	0.12
Spiril	-0.03	0.03
Vbrad	-0.04	-0.01
Along	-0.04	0.04
Birreg	0.00	0.01
Qasp	0.22	0.09
Qbosc	0.02	0.00
Qcost	-0.05	0.06
Qsemi	0.01	0.02
Sgrata	-0.03	0.03
Ttrigo	0.12	0.06
Apseudo	-0.09	0.02
Escab	**0.89**	**-0.04**
LagenamA	0.03	0.08
LagenamB	0.01	0.04
Pfusc	0.05	0.00
Rfusif	-0.12	0.15
Rmica	0.02	0.01
Rscorp	-0.02	0.01
Rsubfus	-0.04	-0.11
Rscot	0.00	0.00
Taggl	-0.02	0.02
Tsagit	-0.03	0.02

Supplementary Material 5

Supplementary material 5: Cluster analysis (R-mode) based on the relative densities of major species (>5%) in the 31 stations using paired group algorithm and correlation similarity measures (see Table 2 for the meaning of species abbreviations).