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Research paper

Live–dead comparison of benthic foraminiferal faunas from the Rhône prodelta (Gulf of Lions, NW Mediterranean): Development of a proxy for palaeoenvironmental reconstructions

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ABSTRACT

Dead benthic foraminiferal faunas (>150 μm) from the Rhône prodelta (Gulf of Lions, NW Mediterranean) were analysed at 41 stations (15–100 m water depth) sampled in June 2005 and September 2006, and compared to the living faunas investigated during previous studies at the same stations. The comparison between dead and living assemblages enhances the understanding of taphonomic processes that may modify the composition of the dead faunas in this area. We observed a loss of individuals from living to dead assemblages of species characterised by a fairly fragile test and therefore more prone to fragmentation or dissolution (e.g., *Bolivina alata*, *Quinqueloculina tenuicollis*). Allochthonous dead and/or live specimens may be transported to some parts of the prodelta, particularly the shallowest sites where hydrodynamic processes (i.e., river flood, storm swells, longshore currents) are more intense. These specimens may originate from relict deltaic structures (e.g., *Elphidium* spp. from the lobe of Bras de Fer) or from surrounding areas (e.g., *Ammonia beccarii* forma *beccarii* from the river). Opportunistic species (e.g., *Bulimina marginata*, *Cassidulina carinata*) characterised by high reproductive rates have much higher relative abundances in the dead than in the living fauna. Cluster analyses based on dead foraminiferal assemblages divide our study area into four main thanatofacies directly related to distinct local environmental conditions prevailing in the prodelta. Close to the river mouth, *Ammonia beccarii* forma *beccarii* and *Ammonia tepida* are found in sediments subject to a high riverine influence (i.e., bottom currents, high organic and inorganic material input of continental origin). *Elphidium* species are abundant in the silty-sandy relict deltaic lobe west of the river mouth which is characterised by strong longshore currents that disturb the benthic environment. *Nonion fabum*, *Rectuvigerina phlegeri* and *Valvulineria bradyana* are found along the coast west of the Rhône River mouth, in the area defined as the "river plume" thanatofacies. In the more stable and deeper prodeltaic area, species known to feed on fresh phytodetritus (e.g., *Bulimina aculeata/marginata*, *C. carinata*, *Hyalinea balthica*) dominate the faunas. Since only minor variations in species relative abundances and spatial distributional patterns are observed between the living and the dead faunas, we consider that our thanatofacies have not been influenced by substantial transport of dead tests. This suggests that fossil benthic foraminifera can provide a reliable tool for investigating the development of the palaeo-Rhône prodelta.

1. Introduction

Because of their widespread distribution in various environmental settings (i.e., mud flats, shallow coastal areas, continental slope, deep-sea…) and their adaptability to various ecological conditions (i.e., substrate, oxygen and food availability), benthic foraminifera are very useful tools for environmental studies in modern habitats. The preservation in sediments of their calcareous and in some cases agglutinated tests after death makes them also a perfect proxy for palaeoenvironmental reconstructions (Gooday, 2003; Murray, 2006; Jorissen et al., 2007). However, the use of foraminiferal faunas in palaeoenvironmental studies requires a good knowledge of recent foraminiferal faunas (e.g., species composition, abundances), and of the bias which is introduced when these recent faunas are preserved in the sediment record. Indeed, important differences in faunal composition may be observed between living and dead faunas at the same site (Murray, 1991; Jorissen and Wittling, 1999). Therefore, the identification of these differences and the taphonomical and biological processes responsible for them is a key step in the investigation and

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interpretation of fossil benthic foraminiferal records. Transport of small-sized specimens by bottom currents, and dissolution or destruction of the most fragile species (e.g., some agglutinated species) may change the composition of dead faunas compared with the living ones (Murray, 1991; de Stigter et al., 1999; Jorissen and Wittling, 1999; Fontanier et al., 2008a). Moreover, some biological factors linked to population dynamics, such as interspecific differences in reproduction rates or seasonal variability in standing stocks, may result in considerable differences between the living fauna present at any one time and the fossil fauna preserved at the same site (de Stigter et al., 1999; Jorissen and Wittling, 1999). In fact, in environments subjected to important seasonal and/or interannual variations in organic matter fluxes and sediment/bottom water oxygenation (e.g., continental shelves), dead foraminiferal faunas reflect a time-averaged mixture of the assemblages succeeding each other in time, and provide an integrated picture of the population dynamics and of the functioning of the ecosystem as a whole (Murray, 1991; Jorissen and Wittling, 1999).

The Rhône River delta is a complex hydrological system located in the Gulf of Lions (NW Mediterranean). Previous ecological studies on benthic foraminifera from this area have concentrated on the spatial distribution of living faunas in relation to the Rhône prodeltaic environment (Kruit, 1955; Blanc-Vernet, 1969; Bizon and Bizon, 1984a; Mojtahid et al., 2009; Goineau et al., 2011, 2012). Studies by Mojtahid et al. (2009) and Goineau et al. (2011) both concluded that living foraminiferal faunal composition and spatial distribution in the prodelta are controlled not only by the quality (fresh or degraded), quantity and origin (continental or marine) of sedimentary organic matter but also by hydro-sedimentary processes and sediment grain size. Another major constrain is the intensity of aerobic (i.e., sediment oxygen penetration depth) and anaerobic degradation of the organic matter (nitrate/nitrite consumption), which directly depends on the quality and quantity of the organic material. These parameters may vary over the year according to the Rhône River discharge and the intensity of riverine and marine primary production. The wide range of environmental conditions that succeed each other during the course of the year in the Rhône prodelta is responsible for rapid changes in faunal characteristics, even at a single site (Goineau et al., 2012).

The aim of the present study is to investigate the present-day spatial distribution of dead foraminiferal faunas in order to develop a reliable proxy for future environmental reconstructions over the Holocene in the Rhône prodelta. To achieve this objective, we first characterise dead foraminiferal faunas sampled at 41 stations in the Rhône prodelta by describing the faunal diversity, composition, and by defining thanatofacies. Then, in order to explore potential taphonomical and biological processes, we identify differences between these dead faunas and the living ones described by Mojtahid et al. (2009, 2010) and Goineau et al. (2011) by comparing their composition and spatial distribution in the prodelta.

2. Material and methods

2.1. Study area

The Rhône River flows from the mountain chains of the Alps to the Gulf of Lions (Mediterranean Sea), and drains a catchment area of 97,800 km^2. It is characterised by heterogeneous substrates (calcareous and crystalline rocks from the Jura, Alps and Massif Central mountains) and three different climatic zones (alpine, oceanic and Mediterranean), resulting in strong seasonal and interannual variability of water discharge and terrigeneous input to the deltaic system. With an annual mean flow of 1700 $m^3 \cdot s^{-1}$ (Pont et al., 2002), the Rhône River is the main source of freshwater, organic–inorganic material and nutrients in the Gulf of Lions (Lochet and Leveau, 1990; Durrieu de Madron et al., 2000, 2003). The mixing between riverine (low salinity) and marine (high salinity) waters generates a typical microtidal saltwedge in the Rhône channel. The landward extension of this wedge is mainly controlled by the river discharge. During high-water discharge (>3000 $m^3 \cdot s^{-1}$), the salt wedge is pushed seaward to the river mouth. Beyond the river mouth, the freshwater forms a plume that flows on the surface of marine waters. This surficial layer of freshwater has no impact on bottom-water salinity, even in the immediate vicinity of the river mouth (Eisma, 1993). The offshore extension and shape of this turbid river plume depend on the Rhône outflow (low/high discharge), wind regime (Mistral and Tramontane; Naudin et al., 1997; Millot, 1999) and the intensity of the North Mediterranean Current (Béthoux and Prieur, 1983; Millot, 1990). Although 30% of the introduced particles are transferred to the slope and to the deeper basin (Got and Aloisi, 1990), a major part of the riverine terrigeneous input is deposited close to the river outlet, from 0 to 60 m water depth and from 0 to 6 km off the mouth, thus forming a delta front and a prodeltaic area (Rabineau et al., 2005). This zone is subject to very high deposition rates ranging from 30 to 50 $cm \cdot year^{-1}$ (Calmet and Fernandez, 1990; Radakovitch et al., 1999; Miralles et al., 2005). Because of these important riverine supplies, the Gulf of Lions is one of the most productive areas of the Mediterranean Sea (Diaz, 2000). Phytoplankton primary production is maximal from March to May with Chl-*a* concentrations in sea-surface waters of 1 mg Chl-$a \cdot m^{-3}$ (Bosc et al., 2004). The summer season is the most oligotrophic period with 0.1–0.2 mg Chl-$a \cdot m^{-3}$ in surface waters. Conditions in the Rhône prodelta remain fairly eutrophic over the year. However, an "oligotrophic" (i.e., less eutrophic) period occurs in late summer–early fall (i.e., from August to October), with Chl-*a* concentrations in sea-surface waters about 0.7 mg Chl-$a \cdot m^{-3}$ (Bosc et al., 2004). In the Rhône River, riverine phytoplankton blooms also occur during spring. This riverine production can be exported to the open sea in the surface waters of the river plume (Harmelin-Vivien et al., 2008).

The Rhône River has existed since the Messinian crisis (between −5.96 and −5.33 Ma), when the Mediterranean sea-level fell by about 1500 m (Clauzon, 1974). During the Holocene, both sea-level variations and enhanced human activities modulated sedimentary fluxes and erosional processes that control the morphology of the deltaic and prodeltaic systems (Berendsen and Stouthamer, 2000; Stouthamer, 2001). Since 4000 year BP (Before Present), the Rhône River has developed several successive arms and mouths such as the Grand Passon (13th century–1607 AD), the Bras de Fer (1585–1711 AD), the Piémanson (1711–1856 AD), the Pégoulier (1711–1892 years BP) and the Roustan channels (1711 AD–Today) (Colomb et al., 1975; Rossiaud, 1994; Vella et al., 2005). Their relict structures, which are still visible in the modern deltaic plain and on the continental shelf (Vella et al., 2005) (Fig. 1), are eroded and redistributed alongshore according to wave action (Sabatier and Suanez, 2003). For the last 200 years (i.e., since the 18th century), engineering works (bank revetment, groynes, hydraulic deflectors, dams) have stopped this natural evolution, leading to the fixation of the present Roustan mouth and channel (Sabatier et al., 2006).

2.2. Dead foraminiferal faunal sampling and analyses

Forty-one stations were sampled from the *R/V* Téthys II (INSU) in June 2005 and September 2006 during the MINERCOT 2 and the BEHEMOTH cruises, respectively. Sediment cores of 72 cm^2 surface area were collected using a Barnett multicorer (Barnett et al., 1984) at water depths ranging between 15 and 100 m (Fig. 1, Table 1). At each station, one core was sliced on board for benthic foraminiferal analyses into 0.5 cm levels from the surface down to 2 cm depth. Deeper layers were sliced into 1 cm levels down to 5 cm depth, except at stations M2, M5, M6, M8, M10, M12, M16, M18, M20, M23, M24 (MINERCOT 2 cruise) where 3 cm-thick slices were sampled (i.e., 2–5 cm sediment layer). Each sediment layer was then preserved in 95% ethanol with 1 $g \cdot l^{-1}$ Rose Bengal. Sediment samples were sieved in the laboratory using sieves of 63 and 150 μm mesh size. All living (Rose Bengal stained) specimens from the >150 μm size fraction were hand-picked in water