



Research paper

Stable isotope composition of deep-sea benthic foraminifera under contrasting trophic conditions in the western Mediterranean Sea

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ABSTRACT

We have evaluated the environmental and biological processes affecting the stable oxygen and carbon isotope composition of live (Rose Bengal stained) and dead (unstained) tests of different benthic foraminiferal species from the western Mediterranean Sea. Samples were retrieved from comparable water depths but contrasting trophic regimes, comprising the meso- to eutrophic Alboran Sea and the oligo- to mesotrophic Mallorca Channel. The recorded isotope signatures mirror the average microhabitat depth of each species and reflect the specific gradients in pore water $\delta^{13}\text{C}$ of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) and oxygen. Maximum $\delta^{13}\text{C}_{\text{DIC}}$ pore water gradients of up to -2.3‰ were estimated under the influence of meso- to eutrophic conditions in the Alboran Sea. The $\delta^{13}\text{C}$ signal of *Uvigerina mediterranea* reflects the opportunistic behavior of this species as its $\delta^{13}\text{C}$ is shifted to more negative values at higher organic matter fluxes. Accordingly, the $\delta^{13}\text{C}$ signal of *U. mediterranea* appears particularly suitable as a proxy for quantitative reconstructions of past trophic conditions. Previously reported ontogenetic increase of stable isotope values is confirmed for buliminid taxa (genera *Uvigerina* and *Globobulimina*), while it is largely absent in rotaliid taxa (genera *Cicidides*, *Cibicidoides*, and *Melonis*). Particularly strong metabolic fractionation is observed in small specimens of *Uvigerina peregrina* overprinting the pore-water $\delta^{13}\text{C}_{\text{DIC}}$ signal and resulting in steep ontogenetic $\delta^{13}\text{C}$ gradients. The $\delta^{18}\text{O}$ values of epifaunal taxa, which thrive under high dissolved oxygen concentrations, and the shallow to intermediate infaunal *Melonis barleanum*, are up to 1.2‰ lower relative to equilibrium calcite. In epifaunal taxa, this depletion can be attributed to enhanced fractionation at high concentrations of metabolically utilizable oxygen.

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1. Introduction

The stable oxygen and carbon isotope compositions of foraminifera are widely used as proxies for the reconstruction of past climate and ocean circulation changes. The $\delta^{18}\text{O}$ signal of deep-sea benthic foraminifera ($\delta^{18}\text{O}_{\text{For}}$) mainly contains the signal of global ice volume and is commonly applied to the reconstruction of global glaciation states, sea-level changes and for stratigraphic purposes (e.g., Shackleton and Opdyke, 1973; Zachos et al., 2001; Waelbroeck et al., 2002; Lisiecki and Raymo, 2005). The benthic foraminiferal $\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{For}}$) signal provides information on past ocean circulation changes and the marine carbon cycle (e.g., Curry and Lohmann, 1982; Zahn et al., 1986; Duplessy et al., 1988; Bickert and Mackensen, 2004; Mackensen, 2008). In a simplified view, the foraminiferal stable isotope signal mirrors the physical conditions and composition of ambient bottom and pore waters at the time of calcification, i.e. for oxygen the equilibrium calcite $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{EQ}}$) and for carbon the $\delta^{13}\text{C}$ of dissolved inorganic carbon

($\delta^{13}\text{C}_{\text{DIC}}$). However, the isotope signal is additionally influenced by various ecological and biological effects, which result in significant offsets relative to the ambient bottom water and equilibrium conditions (Rohling and Cooke, 1999; Ravelo and Hillaire-Marcel, 2007; Mackensen, 2008).

One important process is related to microbial remineralization of organic matter at the sea floor resulting in a decrease of pore water $\delta^{13}\text{C}_{\text{DIC}}$ with increasing sediment depth of up to -1.0‰ cm^{-1} (McCorkle et al., 1985; Stott et al., 2000; Holsten et al., 2004). Since different benthic foraminifera inhabit different microhabitats on or within the sediment (Corliss, 1985; Jorissen et al., 1995), the pore water effect accounts for significantly lower $\delta^{13}\text{C}_{\text{For}}$ values of infaunal species, with lowest values observed in deep infaunal taxa such as *Chilostomella* spp., *Globobulimina* spp. and *Pleurostomella* spp. (Grossman, 1984a; McCorkle et al., 1990, 1997; Schmiedl et al., 2004). At sites of rapid phytodetritus deposition, negative offsets of $\delta^{13}\text{C}_{\text{For}}$ from ambient bottom water DIC can even occur in the strictly epifaunal species *Cibicidoides wuellerstorfi* (Mackensen et al., 1993). On the other hand, most taxa seem to reflect the isotopic composition of the porewater $\delta^{13}\text{C}_{\text{DIC}}$ close to the upper part of their Average Living Depth (McCorkle et al., 1990; Loubere et al., 1995; Rathburn et al., 1996; Schmiedl et al., 2004; Mackensen and Licari, 2004) although

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specimens are able to shift their microhabitat responding to changes in oxygen and food availability and are often found alive over a relatively wide depth range (Linke and Lutze, 1993; Ohga and Kitazato, 1997). Accordingly, the $\delta^{13}\text{C}_{\text{For}}$ difference between epifaunal and preferentially shallow infaunal taxa reflects the intensity of organic matter remineralization and can thus be used for the estimation of organic matter flux rates (Zahn et al., 1986; McCorkle and Emerson, 1988; Vergnaud Grazzini and Pierre, 1991; Schilman et al., 2003). In addition, at depth in the sediment where oxygen approaches zero the $\delta^{13}\text{C}_{\text{DIC}}$ is directly proportional to the oxygen concentration of the bottom water mass (McCorkle and Emerson, 1988). Based on this observation, the difference between $\delta^{13}\text{C}_{\text{For}}$ of epifaunal and deep infaunal species was successfully applied to the quantification of changes in bottom water oxygenation during the Late Quaternary (Schmiedl and Mackensen, 2006; Hoogakker et al., 2015).

There is increasing evidence that the stable isotope signal of foraminifera is also influenced by the carbonate ion concentration of the ambient water, which is closely related to alkalinity and pH (Spero et al., 1997; Bemis et al., 1998; Zeebe et al., 1999; Mackensen, 2008). The magnitude of this effect in benthic foraminifera is not yet well constrained but both carbonate ion gradients in the pore water (Jahnke et al., 1994; Martin and Sayles, 1996) and within cysts during calcification (Diz et al., 2012) may play a relevant role.

Additional isotope fractionation in the form of species-specific 'vital effects' are caused by incorporation of metabolic CO_2 during precipitation of test calcite and during the processes of hydration and hydroxylation at variable metabolic rates (Erez, 1978; Grossman, 1984a, 1984b; McConnaughey, 1989a, 1989b; Mackensen, 2008). It is generally assumed that the metabolic rate decreases during ontogeny of planktonic foraminifera, explaining increasingly heavier stable isotope values with increasing test size (Spero and Lea, 1996; Spero et al., 1997). Comparable ontogenetic trends in benthic foraminifera reveal a more inconsistent picture, with species-dependent constant, increasing or decreasing $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values with increasing test sizes (Dunbar and Wefer, 1984; Grossman, 1984a, 1984b, 1987; Wefer and Berger, 1991; Corliss et al., 2002; Schmiedl et al., 2004; McCorkle et al., 2008; Schumacher et al., 2010; Diz et al., 2012). To date, only one study (Dunbar and Wefer, 1984) included a comprehensive multi-species approach.

Here, we evaluate the biological and environmental effects on the stable isotope signatures of live (Rose Bengal stained) and dead (unstained) benthic foraminifera from several middle bathyal sites of the western Mediterranean Sea. The major target of our study is to improve the applicability of deep-sea benthic foraminifera in quantitative paleoenvironmental reconstructions. The present western Mediterranean Sea is ideally suited for this study, because it is well ventilated and its intermediate and deep-water $\delta^{18}\text{O}_{\text{Water}}$ and $\delta^{13}\text{C}_{\text{DIC}}$ compositions are relatively homogenous (Pierre, 1999). The measured benthic foraminiferal tests have grown under contrasting trophic regimes, including the meso- to eutrophic Alboran Sea and the oligo- to mesotrophic Mallorca Channel, SW of Mallorca Island (Fig. 1). A total of nine different species, representing the full range of epifaunal to deep infaunal microhabitats and associated pore water signals, have been included in the analysis. For further characterization of metabolic processes and ontogenetic effects, the stable isotope signals of three common shallow to intermediate infaunal species (*Uvigerina peregrina*, *Uvigerina mediterranea* and *Melonis barleeanum*) were determined for various test size classes.

2. Study area

The semi-enclosed Mediterranean Sea exhibits strong gradients in temperature, salinity and surface water productivity, which are caused by the overall anti-estuarine circulation, high evaporation rates, inflow of nutrients through rivers and with Atlantic surface waters and loss of salt and nutrients through the Mediterranean outflow (Pinardi and Masetti, 2000; Tanhua et al., 2013; Rohling et al., 2015). Due to the

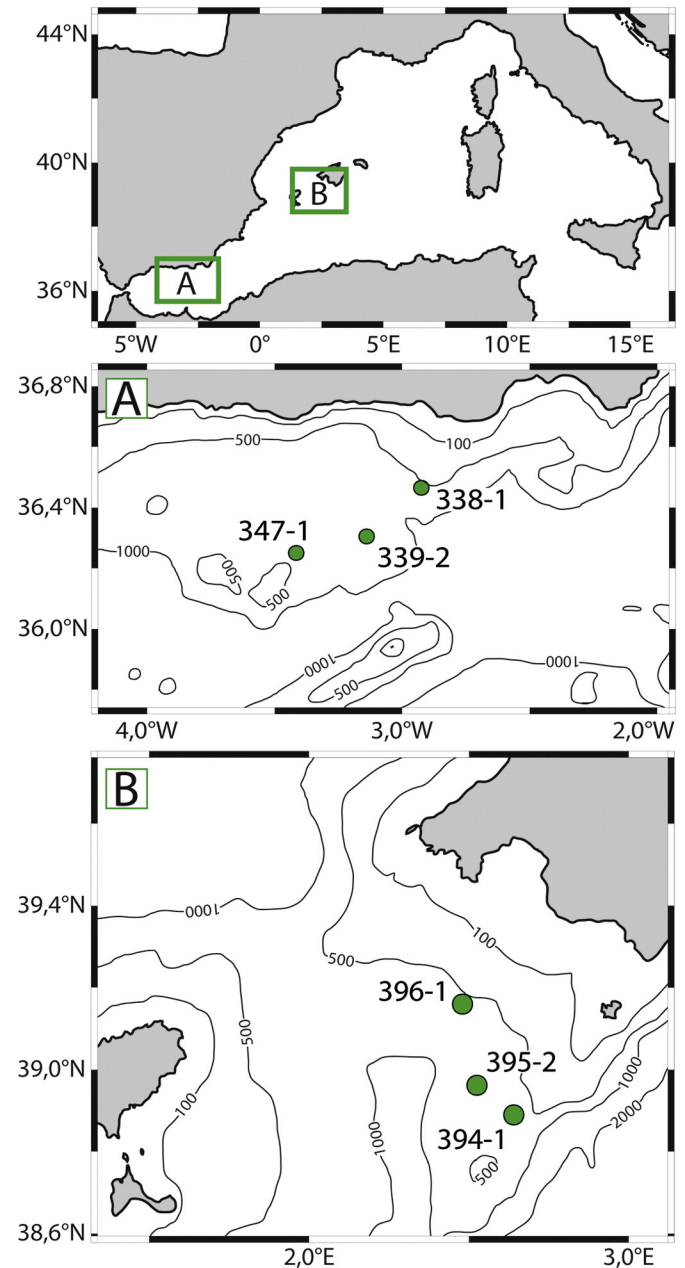


Fig. 1. Location of the study areas in the western Mediterranean Sea and regional bathymetric maps with location of sample sites in the (A) Alboran Sea and (B) the Mallorca Channel southwest of Mallorca Island.

anticlockwise surface circulation of the western Mediterranean Sea, the Alboran Sea is influenced by relatively fresh Atlantic surface waters, while the areas around Mallorca exhibit significantly higher salinities because surface waters are derived from Algerian Basin eddies in the south and the Liguro-Provençal-Catalan Current (LPCC) in the north (Millot, 1999; Millot and Taupier-Letage, 2005). The investigated sites are all located within a depth range of 500 to 1000 m, implying a bathing by the lower part of the Levantine Intermediate Water (LIW) and the upper part of the Tyrrhenian Deep Water (TDW) (Fig. 1, Table 1). The LIW originates in the eastern Mediterranean Sea and its salinity maximum is observed between 200 and 500 m water depth (e.g. Tanhua et al., 2013). The LIW is an important factor for western Mediterranean deep-water formation (Millot, 1999, 2005). The TDW emerges in the Tyrrhenian Sea probably as a mixture of LIW and western Mediterranean deep water (WMDW) (Rhein et al., 1999; Send et al., 1999) or as a result of deep-water formation east of the Bonifacio

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