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Paleobathymetric history of the Western Mediterranean Sea shelf during the latest glacial period and the Holocene: Quantitative reconstructions based on foraminiferal transfer functions

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ABSTRACT

We present results of the palaeobathymetric evolution in cool-water shelf carbonate environments of the Western Mediterranean Sea during the latest glacial period and the Holocene. For this quantitative approach, we used the Weighted Averaging-Partial Least Squares (WA-PLS) regression method for the development of benthic foraminifera-based transfer functions, and the Modern Analog Technique (MAT) to test the robustness of the models. Transfer functions were created on the basis of recent benthic foraminiferal assemblages in surface samples (modern data sets), and were then applied to fossil samples in sediment cores from the Alboran Platform, the Oran Bight and the Mallorca Shelf. The performance of the WA-PLS transfer functions suggests a close relationship between the observed and estimated water depths in the modern data sets with a precision of ~11 m (Root Mean Squared error of Prediction (RMSEP)) within water depths ranging from 38 to 160 m. The estimated relative sea-level histories of the Alboran Platform and the Mallorca Shelf show a total relative sea-level rise of ~50 m with sample-specific errors of approximately ±7 m and generally match the global and regional Mediterranean Sea records. Inconsistencies in the paleobathymetric estimates are strongly attributed to redeposition processes, dating problems and to minor effects of an under-representation of modern samples from shallower water depths.

1. Introduction

Relative sea-level changes are mainly related to eustatic (changes in global ocean volume) and isostatic (land level movements) factors, and are further influenced by tectonic processes (e.g., Peltier, 1987; Lambeck, 2001). They have a strong impact on sedimentation processes at continental margins and in epicontinental seas. Accurate sea-level estimates are relevant for a wide range of scientific questions, such as documentation of the ice sheet history, modeling of global circulation patterns, and reconstruction of spatial and temporal variations of crustal movements. Global sea-level was approximately 120 m lower than today at the time of maximum continental glaciation during the Last Glacial Maximum at around 20 kyr BP (Thornalley et al., 2011). The deglaciation occurred between approximately 21 and 5 kyr BP and was associated with a dramatic sea-level rise, comprising two major melt-water pulses around 14 and 11 kyr BP and a slowing-down of sea-level rise during the Younger Dryas period and in the middle Holocene (Bard et al., 1996, 2010).

In the Mediterranean Sea, sea-level changes generally follow the global development, but are also influenced by hydro-isostatic effects and neotectonic movements (Lambeck and Bard, 2000; Morhange and Pirazolli, 2005; Stocchi and Spada, 2007). In contrast to northern European shelf areas and coastlines, glacio-isostatic effects can be neglected for the Mediterranean Sea during the Holocene (Pirazolli, 2005). Various aspects and regional expressions of Mediterranean sea-level change are documented by geomorphologic, geophysical and archeological observations (Kayan, 1988; Morhange et al., 2001; Sivan et al., 2001; Goy et al., 2003; Vouvalidis et al., 2005; Berne et al., 2007), overgrowth rates of speleothems (e.g., Alessio et al., 1994; Antonioli et al., 1999, 2001, 2002), and are simulated by numerical models (Lambeck and Bard, 2000; Lambeck et al., 2004; Pirazolli, 2005; Stocchi and Spada, 2007).

1.1. Quantitative paleobathymetric reconstructions based on foraminifera

Foraminifera proved particularly useful for accurate paleowater depth reconstructions over a wide bathymetric range and on different time scales. Quantitative methods were developed, e.g., based on the ratio between planktic and benthic foraminifera (P/B ratio) or the distribution patterns of certain benthic indicator taxa. Paleo-water depth reconstructions based on modified P/B ratios transfer functions have been tested and applied by several authors, e.g., in the Mediterranean Sea (van der Zwaan et al., 1990; De Rijk et al., 1999;

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Wilson, 2003; van Hinsbergen et al., 2005). Although these studies delivered reasonable results, the confidence level of this method is limited by the availability of regional calibration curves and the interference of benthic foraminiferal abundance with oxygen and food levels at the sea floor (van Hinsbergen et al., 2005; Milker, 2010).

Other authors used alternative methods that are based on the presence/absence data of selected benthic foraminiferal taxa. Hohenegger (2005) developed transfer equations, using weighted arithmetic and geometric means of the depth ranges of benthic foraminifera and applied these equations for paleo-water depth estimates along a middle Miocene transect in the Styrian Basin in Austria. Spezzaferri and Tamburini (2007) applied these transfer equations to paleo-bathymetric reconstructions on Neogene sediments from the Eratosthenes Seamount (Eastern Mediterranean Sea). In a similar way, Morigi et al. (2005) calculated weighted mean water depths (MWDs) based on percentages of recent benthic foraminifera in relation to their known water depth intervals in the Adriatic Sea, and applied these MWDs to fossil foraminifera for paleowater depth reconstructions of late glacial and Holocene successions. Hayward (2004) used the Modern Analog Technique (MAT) approach in order to generate consistent paleobathymetric estimates for Miocene benthic foraminiferal assemblages from offshore Taranaki, New Zealand.

In modern studies, more advanced and accurate regression methods, such as Weighted Averaging (WA), Partial Least Squares (PLS) or Weighted Averaging-Partial Least Squares (WA-PLS), were applied to marsh benthic foraminifera from the North Sea and the US-Pacific coast for quantitative paleowater depth estimates resulting in precise transfer functions (Horton et al., 1999; Horton and Murray, 2006) and Holocene relative sea-level reconstructions (Sabean, 2004; Boomer and Horton, 2006; Horton and Edwards, 2006; Nelson et al., 2008; Hawkes et al., 2010). Similar applications provided precise sea-level transfer functions for intertidal environments of the Atlantic coast of Maine and the Bay of Biscay for the latest Holocene (Gehrels, 2000; Leorri et al., 2008) and of the Australian great barrier reef shelf (Horton et al., 2007; Woodroffe, 2009). Rossi and Horton (2009) used WA-PLS for the development of a shelf benthic foraminifera-based transfer function for paleo-water depth reconstructions in the northern Adriatic Sea during the Holocene, resulting in a root mean squared error of prediction (RMSEP) of ± 5 m within water depths ranging from 8 to 100 m.

Here, we present quantitative paleowater depth estimates for the latest glacial period and the Holocene, based on recent and fossil benthic foraminiferal assemblages of carbonate shelf environments from three regions with different environmental settings in the Western Mediterranean Sea (Alboran Platform, Oran Bight and Mallorca Shelf). For the development of the transfer functions, the WA-PLS regression method was applied. The MAT was used to find out "close" and "no close" analogs for the fossil samples in the modern data sets. Further, we have compared our estimates with the global deglacial sea-level history, and with several regional relative sea-level reconstructions from the Mediterranean Sea. Major target of this study is to test the potential, applicability, and limitation of the WA-PLS method for paleowater depth estimates in shelf environments of the Mediterranean Sea. In contrast to the most previous applications of regression methods on intertidal environments, we intend to cover a much higher water depth range.

2. Study area

2.1. Tectonic setting and sedimentation processes

The study area is located in the westernmost part of the Mediterranean Sea (Fig. 1A), which consists of the Alboran, Provencal and Algerian sub basins that were formed mainly during the Oligocene and Miocene by late orogenic extension as a result of the collision of Eurasian and African plates (Comas et al., 1999) (Fig. 1B). Recent seismicity and tectonic movements in the Western Mediterranean Sea are concentrated in the Western Alboran Basin and in the North Algerian coastal region, where earthquakes are relatively frequent (Piromallo and Morelli, 2003; Giresse et al., 2009). The Oran region is characterized by relatively high seismicity and the occurrence of earthquakes (Bouhadad, 2001), while the more offshore areas are nearly aseismic with exception of the Yusuf Fault (Domzig et al., 2006). The estimated uplift rates in the Oran Bight amount to 0.186 ($\pm$0.023) mm/yr (Bouhadad, 2001). Along the Alboran Ridge, recent uplifting co-occurs with active subsidence (Comas et al., 1999; Martinez-Garcia et al., 2010). Present seismic activity in the Mallorca region is low (Silva et al., 2001). Earthquakes with a magnitude higher than 4 and epicenters shallower than 30 km were not observed since 1973 (Tinti et al., 2005). No distinct vertical movements since the Miocene are documented for the southern part of the Mallorca Island (Pomar, 1991).

The specific tectonic, morphological and oceanographic settings influence the recent sedimentation processes in the different areas. The Alboran Ridge forms a steep-flanked and rugged plateau around the small Alboran Island (Fig. 1B). The southern shelf of Mallorca, as part of the low energy and temperate Balearic carbonate platform, as well as the Algerian shelf off Oran are distally-steepened ramps (Fornos and Ahr, 2006; Betzler et al., 2011). The shallow subtidal zones (uppermost 40 m water depth) of the Western Mediterranean Sea are dominated by *Posidonia* meadows with bioclastic sand patches, whereas red algae and coarse-grained carbonate particles (rhodoliths, gastropods, bivalves and various other biogenic components) prevail between around 40 to 90 m water depths. Outer ramp sediments – deeper than approximately 90 m – consist of muddy sands with mixed biotic content (Betzler et al., 2011). Siliciclastic components are rare in all of these cool-water carbonate environments, with exception of a quartz sand nearshore prism at the Algerian coast.

2.2. Oceanographic settings

The surface water mass of the Western Mediterranean Sea mainly consists of inflowing Atlantic Water (AW). Subsurface water masses include the Levantine Intermediate Water, formed in the eastern part of the Mediterranean Sea, and the Western Mediterranean Deep Water (Robinson et al., 2001; Masque et al., 2003; Rixen et al., 2005). The AW enters the Alboran Basin as the westernmost part of the Mediterranean Sea and forms two anticyclonic gyres, the Western Alboran Gyre (WAG) and the Eastern Alboran Gyre (EAG), separated by the Alboran Ridge (Fig. 1C). These gyres and the Almeria-Oran-Front that corresponds to the eastern edge of the EAG are zones of high primary production (Arnone, 1994; Helguen L' et al., 2002; Masque et al., 2003; Velez-Belchi et al., 2005). The Alboran Platform is directly influenced by the up to 100 km wide, and up to 200 m deep and seasonally variable WAG (Gascard and Riches, 1985; Preller, 1986; Cantos-Figuerola et al., 1991). The WAG surface water velocities measured in October 1996 ranged from 124 to 140 cm/s (Velez-Belchi et al., 2005). Geostrophic currents with velocities of ~20 cm/s at water depths of 0 to 200 m are postulated for the shelf south-west of Mallorca by model results of Werner et al. (1993). The Oran Bight is influenced by the variable Algerian Current flowing along the Algerian coast. This current supplies the coastal regions with elevated nutrient loads and is characterized by higher chlorophyll a values when compared to the more oligotrophic Algerian Basin (Millot et al., 1990; Arnone, 1994). As a consequence of this oceanographic setting, the Alboran Basin and the Oran Bight have higher annual primary production rates when compared to the more oligotrophic Balearic region (Antoine et al., 1995).