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Cold-water coral growth in the Alboran Sea related to high productivity during the Late Pleistocene and Holocene

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ABSTRACT

Cold-water corals are common along the Moroccan continental margin off Melilla in the Alboran Sea (western Mediterranean Sea), where they colonise and largely cover mound and ridge structures. Radiocarbon ages of the reef-forming coral species *Lophelia pertusa* and *Madrepora oculata* sampled from those structures, reveal that they were prolific in this area during the last glacial–interglacial transition with pronounced growth periods covering the Bølling–Allerød interstadial (13.5–12.8 ka BP) and the Early Holocene (11.3–9.8 ka BP). Their proliferation during these periods is expressed in vertical accumulation rates for an individual coral ridge of 266–419 cm ka^{-1} that consists of coral fragments embedded in a hemipelagic sediment matrix. Following a period of coral absence, as noted in the records, cold-water corals re-colonised the area during the Mid-Holocene (5.4 ka BP) and underwater photographs indicate that corals currently thrive there. It appears that periods of sustained cold-water coral growth in the Melilla Coral Province were closely linked to phases of high marine productivity. The increased productivity was related to the deglacial formation of the most recent organic rich layer in the western Mediterranean Sea and to the development of modern circulation patterns in the Alboran Sea.

1. Introduction

Scleractinian cold-water corals form the habitat for unique and species-rich ecosystems along the world's continental margins (Roberts et al., 2006). Most of the scientific knowledge on cold-water coral ecosystems has been gained from sites in the Northeast Atlantic (Roberts et al., 2006), where they form living reefs of several kilometres length (Freiwald et al., 1997; Fosså et al., 2005) and massive mound structures of in excess of 300 m in height (Kenyon et al., 2003; Mienis et al., 2007; Wheeler et al., 2007). The most prominent reef-forming scleractinian cold-water coral species are *Lophelia pertusa* and *Madrepora oculata* (Freiwald et al., 2004). Some ecological thresholds in terms of water mass properties have been described for living occurrences of *L. pertusa*; it thrives in a temperature range of 4–14 °C (Roberts et al., 2006; Freiwald et al., 2009), in a salinity window of 31.7–38.8 ‰ (Freiwald et al., 2004; Davies et al., 2008) and at oxygen contents of 2.6–7.2 ml l^{-1} (Davies et al., 2008). Moreover, cold-water corals are sessile suspension feeders and thus depend on sufficient food supply (Duineveld et al., 2004). This environment is sustained by high marine productivity at the ocean's surface and by a highly energetic hydrodynamic regime, characterised by bottom currents or internal tides (Messing et al., 1990; Frederiksen et al., 1992; White, 2007) that deliver the food particles to the coral's tentacles (Duineveld et al., 2004).

Under optimal growth conditions cold-water corals can form large thickets of several decimetres in height. Coral framework thickets have the capability to baffle suspended matter, that, once deposited, (a) has a stabilising effect on the framework and (b) is protected against re-mobilisation (Dorschel et al., 2005, 2007; Huvenne et al., 2009). Over time this results in the formation of large and complex seabed structures (e.g. coral mounds) composed of coral fragments embedded in a matrix of hemipelagic sediments. In contrast, a shift to unfavourable environmental conditions induced by climatic changes (for example) may cause the demise of the corals, which results in a stagnation of mound accumulation or even erosion of such coral build-ups (Dorschel et al., 2005; Roberts et al., 2006; Kano et al., 2007). Hence, the development and accumulation pattern of coral mounds over millennial time scales is directly linked to the environmental setting, stimulating or inhibiting the prosperity of cold-water corals.

The Mediterranean Sea presently hosts thriving cold-water coral ecosystems, settling on steep cliffs in canyons and rocky outcrops (i.e. seamounts) as well as on (coral) mounds and elongated ridge structures (Taviani et al., 2005b; Comas et al., 2009; Freiwald et al., 2009; Hebbeln et al., 2009; Orejas et al., 2009). Fossil coral sites are also widespread, reaching back to the Latest Pliocene/Early Pleistocene when cold-water corals re-colonised the Mediterranean Sea after the Messinian Salinity Crisis (Taviani et al., 2005a). U-series and radiocarbon ages of

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cold-water corals sampled from various sites in the Mediterranean Sea revealed flourishing coral communities throughout most of the Late Pleistocene and Holocene though being most prolific around the Younger Dryas cold event (McCulloch et al., 2010). However, this compilation is solely based on surface coral samples and comprises solitary as well as reef-forming coral species. Continuous and well-dated sedimentary records covering extended coral growth sequences have only been reported from the eastern Mediterranean cold-water coral province off Santa Maria di Leuca (Ionian Sea), where Holocene cold-water coral proliferation appears to be linked to the degree of bottom water oxygenation (Fink et al., 2012).

This study aims to introduce and describe in a morphological sense some prominent coral ridges and mounds (Melilla Coral Province, MCP), which were recently discovered along the Moroccan margin in the western Mediterranean Sea (southern Alboran Sea). In addition, a set of 30 radiocarbon dates obtained on cold-water coral samples (derived from seabed surface samples and coral-bearing sediment cores) collected from these seabed structures was used to reveal the long-term development of the corals of the MCP since the Late Pleistocene, thereby identifying periods of sustained coral growth during the past ~14 ka. With respect to the complex depositional setting on such coral ridges/mounds (e.g. Dorschel et al., 2005) the structures themselves are exploited as coral archives only. By following a simple present/absent criterion, robust coral time series can be deduced from the resulting age clustering. In a second step the age cluster, here defined as coral growth periods, were put into a palaeoceanographic context by linking them to an undisturbed, palaeoceanographic record collected nearby, with the main objective of identifying the environmental forcing factors that control coral development in this westernmost part of the Mediterranean Sea.

2. Regional setting

2.1. Alboran Sea

The Alboran Sea is bounded by the Iberian Peninsula in the north and North Africa in the south (Fig. 1a). The narrow Strait of Gibraltar (~300 m water depth) in the west connects the Alboran Sea with the Atlantic Ocean; to the east it opens into the Algerian basin. Both the Iberian and the North African continental margins are smooth and gently dipping down to a water depth of ~1800 m in the Alboran Trough in the central Alboran Sea. The seafloor in the central Alboran Sea is marked by several topographic heights such as the Alboran Ridge and the Djibouti Bank (Fig. 1a).

Cold-water corals are widespread in the Alboran Sea, where they are associated with elevated seabed structures. They have been detected along the Iberian margin (Lo Iacono et al., 2008; Palomino et al., 2011; De Mol et al., 2012), on seamounts and ridges in the central Alboran Sea (Schröder-Ritzrau et al., 2005; Hebbeln et al., 2009), in the Strait of Gibraltar (Álvarez-Pérez et al., 2005) as well as on mud volcanoes along the Moroccan margin (Margreth et al., 2011).

2.2. Study area — Melilla Coral Province (MCP)

Along the Moroccan margin of the Alboran Sea, several conical mound and elongated ridge structures have been discovered (Comas and Pinheiro, 2007) which occur in water depths of between 250 and 450 m and appear in small clusters or as individual features. They are up to 3000 m in length, 100–250 m wide and reach heights of 20–100 m. All mounds and ridges are surrounded by erosional moats, most likely created by strong bottom currents (Comas et al., 2009),

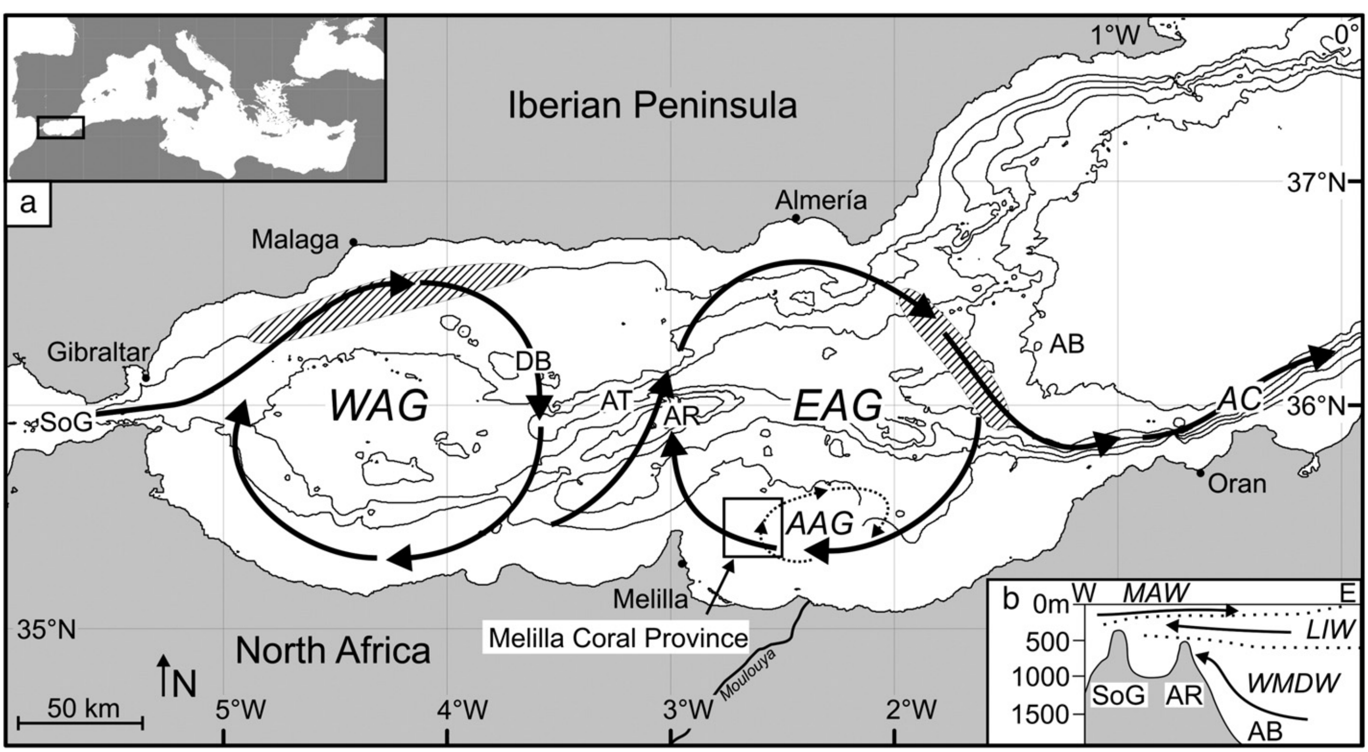

Fig. 1. (a) Bathymetric map of the Alboran Sea (contour interval 500 m) showing the location of the study area (Melilla Coral Province: 250–450 m water depth). Displayed are the major physiographic features (SoG: Strait of Gibraltar, ~300 m water depth; DB: Djibouti Bank, ~350 m water depth; AT: Alboran Trough, ~1800 m water depth; AR: Alboran Ridge, 100 m water depth; AB: Algerian Basin, >2500 m water depth), the main flow patterns of surface circulation (*WAG*: Western Alboran Gyre, *EAG*: Eastern Alboran Gyre, *AAG*: Atlantic Anticyclonic Gyre and *AC*: Algerian Current) and areas of today's high fertility zones (hatched), modified after Tintore et al. (1988), Prieur and Sournia (1994), L'Helguen et al. (2002) and Bárcena et al. (2001). (b) Schematic W–E cross section (along 36°N) showing the main water masses (*MAW*: Modified Atlantic Water, *LIW*: Levantine Intermediate Water, *WMDW*: Western Mediterranean Deep Water) modified after Jimenez-Espejo et al. (2008).