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Oxygen control on Holocene cold-water coral development in the eastern Mediterranean Sea

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ABSTRACT

Continuous sedimentary records from an eastern Mediterranean cold-water coral ecosystem thriving in intermediate water depths ($\sim$600 m) reveal a temporary extinction of cold-water corals during the Early to Mid Holocene from 11.4–5.9 cal kyr BP. Benthic foraminiferal assemblage analysis shows low-oxygen conditions of 2 ml l^{-1} during the same period, compared to bottom-water oxygen values of 4–5 ml l^{-1} before and after the coral-free interval. The timing of the corals' demise coincides with the sapropel S1 event, during which the deep eastern Mediterranean basin turned anoxic. Our results show that during the sapropel S1 event low oxygen conditions extended to the rather shallow depths of our study site in the Ionian Sea and caused the cold-water corals temporary extinction. This first evidence for the sensitivity of cold-water corals to low oceanic oxygen contents suggests that the projected expansion of tropical oxygen minimum zones resulting from global change will threaten cold-water coral ecosystems in low latitudes in the same way that ocean acidification will do in the higher latitudes.

1. Introduction

Over the past 15 years cold-water corals and their associated faunas have been identified as the most species-rich bathyal ecosystems in the world's oceans (e.g. Roberts et al., 2006), forming living reefs several kilometers long (Freiwald et al., 1997) and geological mound structures with elevations of $>$300 m (van Weering et al., 2003). Cold-water corals require specific environmental conditions for a sustained development (Roberts et al., 2006). In this context environmental thresholds have been identified for *Lophelia pertusa*, the most prominent reef-forming, scleractinian cold-water coral species thriving presently along the world's continental margins (Freiwald et al., 2004; Davies et al., 2008). Based on their present-day distribution these thresholds comprise a bottom-water temperature range of 4–13.8 °C (Taviani et al., 2005b; Roberts et al., 2006) and a salinity range of 31.7–38.8‰ (Freiwald et al., 2004; Davies et al., 2008). Dissolved oxygen levels at *Lophelia* sites in the Northeast Atlantic range from 2.6 to 7.2 ml l^{-1} (Davies et al., 2008). In addition, Late Pleistocene cold-water coral records revealed that surface water productivity and vigorous bottom currents, which strongly influence the food supply to the sessile suspension feeders, have been the main environmental factors controlling the onset and cessation of coral growth along the NE Atlantic margin (Dorschel et al., 2005; Wienberg et al., 2010; Eisele et al., 2011).

In the Mediterranean Sea fossil cold-water coral sites date back to the Latest Pliocene/Early Pleistocene, when corals entered the Mediterranean Sea (see review by Taviani et al., 2005a). Although less diverse than their Pleistocene ancestors and Atlantic counterparts, thriving cold-water coral sites are presently widespread in the Mediterranean Sea. Flourishing cold-water coral ecosystems have been observed 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; Freiwald et al., 2009 and references therein; Hebbeln et al., 2009; Orejas et al., 2009). Based on surface coral samples from various sites in the Mediterranean Sea, a recent compilation has revealed that cold-water corals were also abundant during the Late Pleistocene and Holocene though being most prolific during the Younger Dryas (McCulloch et al., 2010). However, well-dated sedimentary records, covering extended coral growth sequences, so far have only been reported from the Melilla coral province located in the Alboran Sea, the westernmost Mediterranean Sea basin, where periods of intense cold-water coral growth were linked to phases of enhanced marine productivity in the Early and Late Holocene (Fink et al., unpublished data).

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This study presents continuous and well-dated down-core sedimentary records that contain fragments of cold-water corals. They were obtained from the eastern Mediterranean cold-water coral province off Santa Maria di Leuca (SML) located on the Apulian margin in the Ionian Sea. These records allow us to trace environmental factors controlling the proliferation and demise of cold-water corals in this region.

2. Regional setting

The cold-water coral province off Santa Maria di Leuca (SML) is one of the largest known and best documented occurrences of living cold-water corals in the Mediterranean Sea (Fig. 1; Taviani et al., 2005b; Freiwald et al., 2009; Corselli, 2010). The SML province presently hosts thriving colonies of *Lophelia pertusa* and *Madrepora oculata*, which occur as small, patchily distributed reefs or isolated colonies (Freiwald et al., 2009; Mastrototaro et al., 2010; Rosso et al., 2010; Vertino et al., 2010). In water depths of 500–900 m, the corals are associated with elongated mound-like structures, 50–300 m wide and up to 25 m high, that are widespread along the Apulian margin and are most likely formed as a result of Pleistocene mass wasting events (Taviani et al., 2005b; Savini and Corselli, 2010). Corals predominantly grow on the exposed summits and flanks of these structures, thereby facing the main incoming current from the northeast (Freiwald et al., 2009).

The hydrography along the Apulian shelf is mainly influenced by water-masses formed in the Adriatic Sea, which is one of the major deep-water formation sites in the Mediterranean Sea. During winter, cold, oxygen-enriched dense water is formed in the shallow northern Adriatic (Fig. 1). It flows southward and mixes in the southern Adriatic with the South Adriatic Dense Water and Levantine Intermediate Water (LIW) to become Adriatic Deep Water (AdDW; Fig. 1; Manca et al., 2006). This dense water-mass flows through the Strait of Otranto, passes the Apulian shelf and becomes Eastern Mediterranean Dense Water (EMDW). The core of the AdDW forms the bottom waters at sites with the most active coral growth (500–1000 m water depth; Budillon et al., 2010). Recent measurements report water temperatures of 12.9–13.8 °C, salinities from 38.65 to 38.88‰ and dissolved oxygen concentrations of 3.98–4.45 ml l^{-1} (Taviani et al., 2005b; Freiwald et al., 2009; Budillon et al., 2010).

3. Material and methods

3.1. Sampling material

Two sediment cores, collected with a gravity corer during R/V *Meteor* cruise *M70-1*, were analyzed for this study. They were obtained from the top (GeoB 11185-1) and the north-eastern flank (GeoB 11186-1) of a N–S elongated mound structure within the SML coral province (see Table 1). The upper sections of both cores contain two distinct cold-water coral bearing intervals (Table 1), which are

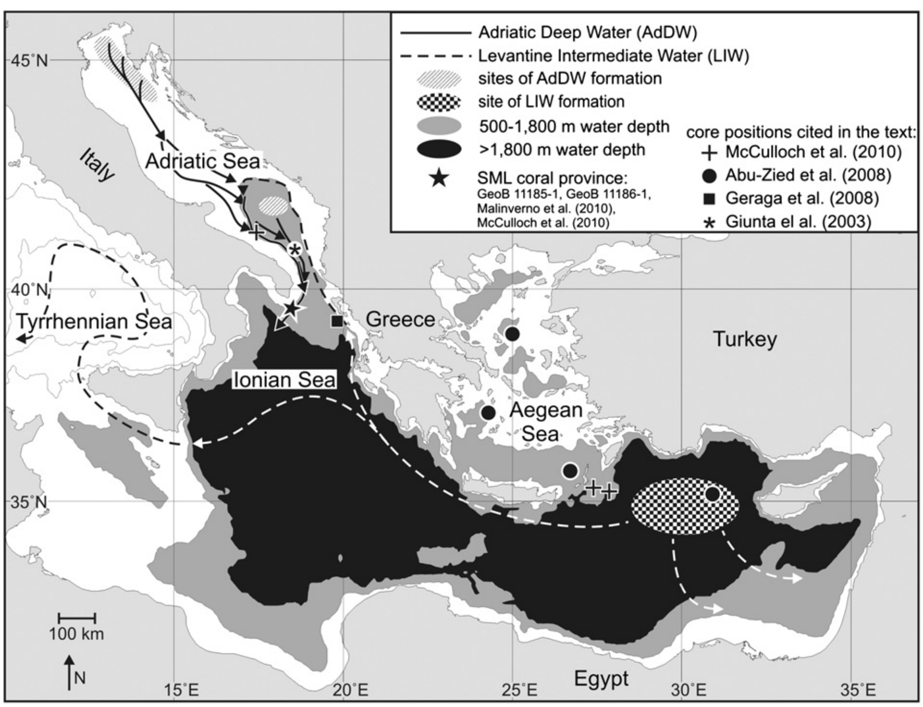

Fig. 1. Map of the eastern Mediterranean Sea showing the location of the Santa Maria di Leuca (SML) cold-water coral province in the Ionian Sea. The figure shows the modern sites of deep-water formation in the Adriatic Sea, pathways of the Adriatic Deep Water (AdDW) and the Levantine Intermediate Water (LIW; modified after Trincardi et al., 2007). The water-depth contours at 1800 m and 500 m are highlighted, indicating the extent of anoxic (> 1800 m) and dysoxic conditions (~500–1800 m) in the eastern Mediterranean Sea during sapropel S1 event. SML Province, the location of cores GeoB 11185-1 and GeoB 11186-1 and sites referred to in the text are shown.

Table 1
Metadata of sediment cores retrieved from the Santa Maria di Leuca (SML) cold-water coral province (Ionian Sea) during R/V *Meteor* cruise *M70-1*.

Core	Latitude	Longitude	Water depth (m)	Core recovery (cm)	Coral containing sequences (cm core depth)
GeoB 11185-1	39°33.314′N	18°27.339′E	612	266	0–43; 63–101
GeoB 11186-1	39°33.434′N	18°27.357′E	628	310	0–71; 76–143