Mediterranean cold-water corals – an important regional carbonate factory?

JÜRGEN TITSCHACK*†, HISKE G. FINK*, DANIEL BAUM†‡, CLAUDIA WIENBERG*, DIERK HEBBELN* and ANDRÉ FREIWALD†

*MARUM – Center for Marine Environmental Sciences, Leobener Strasse, D-28359 Bremen, Germany (Email: jtitschack@marum.de)
†Senckenberg am Meer, Abteilung Meeresforschung, Südstrand 40, D-26382 Wilhelmshaven, Germany
‡ZIB – Zuse Institute Berlin, Takustraße 7, D-14195 Berlin-Dahlem, Germany

ABSTRACT

This study presents aggradation rates supplemented for the first time by carbonate accumulation rates from Mediterranean cold-water coral sites considering three different regional and geomorphological settings: (i) a cold-water coral ridge (eastern Melilla coral province, Alboran Sea), (ii) a cold-water coral rubble talus deposit at the base of a submarine cliff (Urania Bank, Strait of Sicily) and (iii) a cold-water coral deposit rooted on a predefined topographic high overgrown by cold-water corals (Santa Maria di Leuca coral province, Ionian Sea). The mean aggradation rates of the respective cold-water coral deposits vary between 10 and 530 cm kyr⁻¹ and the mean carbonate accumulation rates range between 8 and 396 g cm⁻² kyr⁻¹ with a maximum of 503 g cm⁻² kyr⁻¹ reached in the eastern Melilla coral province. Compared to other deep-water depositional environments the Mediterranean cold-water coral sites reveal significantly higher carbonate accumulation rates that were even in the range of the highest productive shallow-water Mediterranean carbonate factories (e.g. Cladocora caespitosa coral reefs). Focusing exclusively on cold-water coral occurrences, the carbonate accumulation rates of the Mediterranean cold-water coral sites are in the lower range of those obtained for the prolific Norwegian coral occurrences, but exhibit much higher rates than the cold-water coral mounds off Ireland. This study clearly indicates that cold-water corals have the potential to act as important carbonate factories and regional carbonate sinks within the Mediterranean Sea. Moreover, the data highlight the potential of cold-water corals to store carbonate with rates in the range of tropical shallow-water reefs. In order to evaluate the contribution of the cold-water coral carbonate factory to the regional or global carbonate/carbon cycle, an improved understanding of the temporal and spatial variability in aggradation and carbonate accumulation rates and areal estimates of the respective regions is needed.

INTRODUCTION

Framework-forming scleractinian cold-water corals (CWC) are a common faunal element in deep-marine communities of all world oceans (Freiwald et al., 2004 and references therein; Roberts et al., 2009). Where the environmental conditions are especially favourable for CWCs, they form extensive frameworks and function as ecosystem engineers (Van Oevelen et al., 2009). Over time, these frameworks can result in the formation of three-dimensional seabed structures, called CWC mounds, which reach several kilometres in length and hundreds of metres in height (Mienis et al., 2007; Wheeler et al., 2007). The highest worldwide abundance of known CWC habitats and CWC mounds occurs in the NE Atlantic (Davies et al., 2008).

Intense research within the last three decades has provided comprehensive insight into this fascinating ecosystem and sedimentary system, such as its spatial distribution, environmental controls, diversity and
temporal development (Freiwald et al., 2004; Roberts et al., 2006; Wienberg & Titschack, in press). However, little is known about the importance of CWCs as carbonate factories and their role in the global carbonate/carbon cycle (Lindberg & Mienert, 2005; Dorschel et al., 2007; Titschack et al., 2009, 2015). Initial studies from the Norwegian Sea and the Irish continental margin suggested that CWC deposits exhibit carbonate accumulation rates (CAR) of up to 25 g cm\(^{-2}\) kyr\(^{-1}\) (Lindberg & Mienert, 2005; Dorschel et al., 2007; Titschack et al., 2009). These rates were enhanced compared to the adjacent sea floor by a factor of 4 to 11 but were still at least an order of magnitude lower than rates of tropical shallow-water reefs (Milliman, 1993; Schneider et al., 2000; Smith & Mackenzie, 2016). However, new results from CWC deposits off Norway with mean CARs of about 100 g cm\(^{-2}\) kyr\(^{-1}\) (max. of up to 2100 g cm\(^{-2}\) kyr\(^{-1}\)) suggest that CWC systems have the potential to reach CARs that are in the range of tropical shallow-water reefs (Titschack et al., 2015).

The aim of this study is to evaluate the Mediterranean CWC occurrences as carbonate factories (sensu Schlager, 2003), and to compare the results obtained with shallow-water Mediterranean carbonate factories, such as Cladocora caespitosa reefs, seagrass meadows, coralligenous, maerl and rhodolith beds, as well as with depositional environments, such as Mediterranean shelf and deeper water environments (Canals & Ballesteros, 1997; Medernach et al., 2000; Cocito & Ferdeghini, 2001; Peirano et al., 2001; Cocito et al., 2004; El Haikali et al., 2004; Ballesteros, 2006; Betzler et al., 2011; Savini et al., 2012). As a measure of carbonate factory prosperity, the carbonate production and/or CARs of carbonate factories were evaluated. In this context, it is important to keep in mind that carbonate production refers exclusively to the amount of biomineralized carbonate produced during the organism’s life while CARs refer to the finally buried carbonate irrespective of where the carbonate was produced, including also laterally imported and/or vertically imported carbonate. Further included within CARs are all carbonate destroying processes (bioerosion, chemical dissolution), which take place after production and before burial, together with potential dissolution during early diagenesis. In order to gain insight into the variability of CARs within Mediterranean CWC deposits, four gravity cores from CWC occurrences in three different geomorphological settings were selected comprising (i) an elongated CWC ridge (Brittlestar ridge I of the eastern Melilla coral province, Moroccan margin) in the Alboran Sea; (ii) a CWC rubble talus deposit at the base of a submarine cliff (Urania Bank) in the Strait of Sicily; and (iii) a CWC deposit rooted on a pre-existing topographic feature (Santa Maria di Leuca coral province, Apulian margin) in the Ionian Sea. The comparison between CARs/carbonate production of the CWC carbonate factory and various shallow-water Mediterranean carbonate factories with CARs originating in other depositional environments allows them to be evaluated as potential local/regional carbonate sinks within the Mediterranean Sea.

**FRAMEWORK-BUILDING COLD-WATER CORALS IN THE MEDITERRANEAN SEA**

First records of potentially living framework-building CWCs from the Mediterranean Sea date back to the 19th century (Duncan, 1873; Marenzeller, 1893; Lacaze-Duthiers, 1897). Slightly earlier, researchers documented CWC-bearing deposits along uplifted coasts, such as the flanks of the Strait of Messina and SE Rhodes (Jüsson, 1890; Seguenza, 1864; see also reviews by Taviani et al., 2000; Smith & Mackenzie, 2007). These early records and subsequent observations have provided important insights into the potential role of CWCs as framework-building agents in the Mediterranean Sea close to their ecological limit with respect to temperature and oxygen (Freiwald et al., 2009).

**STUDY AREAS**

**Eastern Melilla coral province (Alboran Sea)**

The Alboran Sea constitutes the westernmost part of the Mediterranean Sea and is bounded by the Iberian Peninsula in the north and Morocco in the south. It is connected with the NE Atlantic through the narrow Strait of Gibraltar in the west. To the east it opens to the south Balearic Basin. Living and fossil CWC occurrences are known from its northern (Lo Iacono et al., 2008, 2012; Coiras et al., 2011), western (associated with mud volcanos; Margreth et al., 2011), and southern margins (Fink et al., 2013; Lo Iacono et al., 2014) and from several seamounts (Palomino et al., 2011; De Mol et al., 2012). In 2006, several conical mounds and elongated ridge structures were discovered in 200 to 400 m water depth east of the Ionian Sea. The comparison between CARs/carbonate production of the CWC carbonate factory and various shallow-water Mediterranean carbonate factories with CARs originating in other depositional environments allows them to be evaluated as potential local/regional carbonate sinks within the Mediterranean Sea.
of Trape Tres Forcas on the Moroccan margin of the Alboran Sea – the eastern Melilla coral province (Comas & Pinheiro, 2007). The largest structures within this province are up to 100 to 250 m wide, 2 to 6 km long and 20 to 60 m high. The elongated ridges are connected to the shallow (ca 200 m deep) Banc de Provençaux, which is formed by a submarine volcanic plateau (Ammar et al., 2007). Remotely operated vehicle (ROV) video observations along the Brittlestar ridge I (Fig. 1B) revealed a predominance of dead coral framework and coral rubble. Living colonies of *Lophelia pertusa* and *Madrepora oculata* were small (15 to 20 cm), patchily distributed, and restricted to the crest of the ridge (Figs 2A, B; Comas et al., 2009; Hebbeln et al., 2009). During the last 13.5 kyr, the formation of Brittlestar ridge I occurred during distinct phases of enhanced primary productivity (Fink et al., 2013).

**Urania Bank (Strait of Sicily)**

The Strait of Sicily, which separates the eastern from the western Mediterranean Sea, is subdivided by a central longitudinal ridge into two channels with very different cross-sections. The northern channel is very narrow and has a maximum water depth of 430 m while the southern channel is shallower but wider with a sill depth of 360 m (Astraldi et al., 1999). Within the Strait of Sicily, CWCs are reported from the Urania Bank.
The Mediterranean cold-water coral carbonate factory

Bank (Zibrowius & Taviani, 2005; Freiwald et al., 2006), the Nameless Bank (Zibrowius & Taviani, 2005), the southern Maltesian slope (Schembri et al., 2007; Angeletti & Taviani, 2011) and south off Pantelleria Island (Martorelli et al., 2011). Urania Bank is positioned on the northern slope of the northern channel.

Table 1. Metadata of sediment cores retrieved from three different Mediterranean cold-water coral sites during R/V Meteor cruise M70/1 and R/V Poseidon cruise POS385

| Station        | Region          | Latitude       | Longitude      | Depth [m] | Recovery [cm] | CWC-bearing intervals [cm core depth] |
|----------------|-----------------|----------------|----------------|-----------|---------------|---------------------------------------|
| GeoB13729-1    | Alboran Sea     | 35°26.07‘N     | 2°30.83‘E      | 442       | 447           | 0–447                                 |
| GeoB11135-2    | Urania Bank     | 36°50.35‘N     | 13°09.32‘E     | 634       | 578           | 0–501, 535–578                        |
| GeoB11185-1    | Santa Maria di Leuca | 39°33.31‘N     | 18°27.34‘E     | 612       | 266           | 0–43, 63–101                          |
| GeoB11186-1    | Santa Maria di Leuca | 39°33.43‘N     | 18°27.36‘E     | 628       | 310           | 0–73, 89–140                          |

Fig. 2. (A, B) Remotely operated vehicle (ROV) still images of Brittlestar ridge I, Alboran Sea, western Mediterranean showing the summit region (A) where small, living, cold-water coral colonies occur only rarely and the slope (B), which is covered by coral rubble. (C, D) ROV images from Urania Bank showing a large colony of Madrepora oculata that is attached to the submarine cliff surface (C) and a cold-water coral rubble talus deposit at the foot of a cliff (D). (E, F) ROV images of the predefined high within the Santa Maria coral province showing the living cold-water coral colonies in the summit region (E) and coral rubble that dominates the slopes of the seabed structure (F). ROV images A and B were taken during R/V POSEIDON cruise POS385 with the MARUM ROV Cherokee (Dive GeoB13727-1), ROV images C to F were taken during R/V METEOR cruise M70/1 with the MARUM ROV Quest (C, D: dive GeoB11132; E, F: dive GeoB11183).
of the Strait of Sicily (Fig. 1; Freiwald et al., 2009). Living CWCs on the flanks of Urania Bank were first discovered during R/V URANIA cruise CS-96 (Zibrowius & Taviani, 2005) and revisited during R/V METEOR cruise M70/1 (Freiwald et al., 2006). The ROV video observations revealed a stepped cliff morphology with huge CWC colony fragments deposited on the horizontal areas (Freiwald et al., 2006). Large fan-shaped Madrepora oculata colonies appeared predominantly at the edges of overhangs and downward-growing colonies occur directly attached to the steep cliff walls (Fig. 2C). At the base of the cliff, thick talus deposits occur covered by coral rubble containing predominantly Madrepora oculata fragments and subordinately Corallium rubrum, Lophelia pertusa and Desmophyllum dianthus (Fig. 2D). The degree of colony fragmentation on the talus deposits varied significantly. Fink et al. (2015) provided the first coral ages suggesting a Middle to Late Holocene accumulation of the talus deposit.

**Santa Maria di Leuca coral province (Ionian Sea)**

The Santa Maria di Leuca (SML) coral province is positioned off SE Italy on the upper Apulian continental slope in the northern Ionian Sea (Fig. 1; eastern Mediterranean Sea; Savini et al., 2014; Taviani et al., 2005b). It occurs in water depths of ca 300 to 1100 m on the Apulian Ridge, which separates the Adriatic from the Ionian Basin (Taviani et al., 2005b; Fusi et al., 2006; Savini & Corselli, 2010). The SML coral province has a rough sea floor topography with up to 500 m wide and up to 25 m high mound-like and ridge-like structures (Vertino et al., 2010) that were interpreted as mass-wasting related deposits (Savini & Corselli, 2010). The ROV video observations revealed the highest densities of CWCs and upright growing coral colonies on the summits (Figs 1D and 2E), while the flanks are characterized by a reduced CWC coverage of predominantly coral rubble (Figs 1D and 2F; Freiwald et al., 2006, 2009). In contrast, Vertino et al. (2010) observed on a similar structure within the SML coral province a preference for living CWCs along its current-exposed north-eastern flank, while the top was predominantly covered by coral rubble. Stratigraphic studies point to a sudden onset of CWC colonization in this region at ca 13.15 kyr BP (Malinverno et al., 2010; McCulloch et al., 2010; Fink et al., 2012). A distinct temporary extinction during the Early to Mid-Holocene (11.4 to 5.9 kyr BP) was related to dysoxic conditions in intermediate water depths coinciding with the sapropel S1 formation in the eastern Mediterranean Sea (Fink et al., 2012).

**MATERIAL AND METHODS**

Four CWC-bearing gravity cores from three different regions were selected for this study. The cores were collected during R/V METEOR cruise M70/1 and R/V POSEIDON cruise POS385 (Fig. 1; Table 1; Freiwald et al., 2006; Hebbeln et al., 2009).

In the eastern Melilla coral province (southern Alboran Sea), gravity core GeoB13729-1 was retrieved from the coral rubble-covered slope of Brittlestar ridge I (Fig. 1B). The core has a recovery of 447 cm and contains CWC fragments throughout. In the Strait of Sicily, gravity core GeoB11135-2 was retrieved from the base of a submarine cliff that partly forms the slope of Urania Bank (Fig. 1C). The gravity core, taken from a talus deposit, has a recovery of 578 cm and contains CWC fragments throughout the entire core except for a layer between 501 and 535 cm, where no, or only very minor amounts of, CWCs occur. Within the SML coral province (Apulian Margin, Ionian Sea) both investigated gravity cores were retrieved from one pre-existing high and are only 222 m apart (Freiwald et al., 2006). GeoB11185-1 is located near the summit while GeoB11186-1 is positioned close to its toe (Fig. 1D). Core recoveries were 266 and 360 cm, respectively. The performed analyses focused exclusively on the upper CWC-bearing part of both cores (GeoB11185-1: 0 to 100 cm, GeoB11186-1: 0 to 140 cm). Within the upper CWC-bearing core sequences, layers depleted in CWC fragments occur (GeoB11185-1: 43 to 63 cm; GeoB11186-1: 73 to 89 cm).

Overall, all cores are composed of CWCs (mainly Lophelia pertusa and Madrepora oculata) and other shell fragments embedded in hemipelagic sediments (for further details on the core material see Fink et al., 2012, 2013, 2015). Age models of cores GeoB11185-1, GeoB11186-1 and GeoB13729-1 are discussed by Fink et al. (2012, 2013), and are based on AMS radiocarbon ($^{14}$C) dating performed on fragments of L. pertusa, M. oculata and, in case of core GeoB11185-1, on planktonic foraminiferal assemblages. Two additional AMS $^{14}$C dates of CWCs (L. pertusa and M. oculata) from core GeoB11135-2 are published in Fink et al. (2015).

**Radiometric dating**

In addition to the existing CWC and mixed planktonic foraminifera ages (see Fink et al., 2012, 2013, 2015), one fragment of the solitary CWC Desmophyllum dianthus from the top of core GeoB11135-2 and two mixed planktonic foraminifera samples from cores GeoB11185-1 and GeoB1186-1 were used for AMS $^{14}$C dating (Table 2). Prior to dating, the D. dianthus fragment was mechanically cleaned to remove contaminants (e.g. bioerosion,
coatings) from the skeleton surface. The coral sample was dated at the Australian Nuclear Science and Technology Organisation ANTARES-STAR AMS Facility. Two mixed planktonic foraminifera samples of ca 8 mg were picked for AMS 14C dating performed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) in Woods Hole, USA. Analogous to Fink et al. (2012), all ages were corrected for 13C and converted to calendar years [cal yr BP(1950)] using the CALIB 6.0 software (Stuiver & Reimer, 1993) with the Marine09 calibration curve (Reimer et al., 2009) assuming a reservoir effect of 400 yr (Siani et al., 2001) (Table 2). Finally, the newly obtained AMS 14C dates, together with the ages previously published by Fink et al. (2012, 2013, 2015), were used to estimate aggradation rates for each of the analysed cores (age to age calculation).

**Computed tomography**

All archive halves of the CWC-bearing core sections were scanned by a Toshiba Aquilion 64 computer tomograph (CT) at the hospital Klinikum Bremen-Mitte (sum of scanned core metres: 14.59 m) with an x-ray source voltage of 120 kV and a current of 600 mA. The CT image stacks have a resolution of 0.35 mm in x-direction and y-direction and 0.5 mm resolution in z-direction (0.3 mm reconstruction unit). Images were reconstructed using Toshiba’s patented helical cone beam reconstruction technique (TCOT) and are provided in DICOM-format.

The analysis of the CT scans follows Titschack et al. (2015). The data were processed with the ZIB edition of the Amira software (version 2013.47) (Stalling et al., 2005; http://amira.zib.de). Within Amira, the CT scans of the core sections were merged and the core liners, including about 2 mm of the core rims, were deleted from the data set. The results were saved as AmiraMesh files. Sediment constituents with diameters >ca 1 mm, dominated by CWCs (in the following referred to as CWC clasts due to the observation that the clasts >2 cm are absolutely dominated by CWCs and that this size fraction provides between 50 vol.% (GeoB11185-1) and >80 vol.% (GeoB13729-1) of all segmented constituents), were visualized with the IsoSurface module (isovalue: 1400). All CWC clasts >ca 1 mm were quantified in each reconstruction slice with the Segmentation Editor (threshold segmentation; threshold value: 1400) and the MaterialStatistics module. The clasts were further evaluated by performing a 3-dimensional segmentation of these clasts with the ContourTreeSegmentation module (threshold value: 1400; persistence value: 1150; for further details see Titschack et al., 2015). Subsequently, every clast was analysed with the ShapeAnalysis module for its parameterization. For the visual evaluation of the segmentation results, clasts with a maximal length of >2 cm were selected and visualized with the SurfaceGen and SurfaceView module. Each identified clast was displayed with a different colour to allow a fast evaluation of the clast separation by the ContourTreeSegmentation module. The determined clast length was further used for a clast size and orientation analysis. Therefore, every clast within an interval of 167 CT-slices (corresponds to a ca 5 cm core interval) was considered and the obtained result was written to the central slice position. The analysing interval was moved slice by slice. The final results (unit: volume-% of all segmented CWC clasts) were exported in a spreadsheet. In addition, the z-orientation (horizontal = 0°; vertical = 90°) of the maximal clast length was analysed in the same manner.

**Matrix sediment phase quantification by X-ray powder diffraction (XRD)**

Samples for X-ray diffraction (XRD) analysis were collected from the matrix sediment (each sample: ca 3 g; avoiding CWC clasts) of all gravity cores. Altogether, 152 XRD samples were analysed (equal to a 10 cm resolution). Prior to the XRD measurement, the samples were ground in ethanol emulsion for 10 min with a planetary ball mill (Retsch S1000, Speed: 50). Particle sizes were randomly checked to be <2 μm. Sample powder was transferred into the sample container with a back-loading technique. The XRD analyses were performed with a Philips X’Pert Pro multipurpose diffractometer (hosted at the Crystallography laboratory, Department of Geoscience, University Bremen). The diffractometer was equipped with a Cu-tube (kα,α) 1.541 A, 45 kV, 40 mA), a fixed divergence slit of ¼°, a secondary nickel filter and the X’Celerator detector system. The XRD scans

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**Table 2. AMS 14C dates obtained from mixed planktonic foraminiferal assemblages (pFo) and Desmophyllum dianthus (Dd)**

| Core-ID      | Core depth [cm] | Type | Lab code | 14C age [yr BP] | Error | Calibrated 14C age [yr BP] |
|--------------|-----------------|------|----------|----------------|-------|---------------------------|
| GeoB 11135-2 | 1.5             | Dd   | OZI972   | 1 560          | 45    | 997                       |
| GeoB 11185-1 | 101–103         | pFo  | OS-67288 | 13 000         | 60    | 14 791                    |
| GeoB 11186-1 | 143–145         | pFo  | OS-67289 | 12 050         | 45    | 13 385                    |

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comprise 20 angles ranging from 3 to 120° with a step size of 0.01671°.

Phase quantification was performed with the Rietveld refinement software TOPAS 4.2 (Bruker AXS) with a fundamental parameter approach (Cheary & Coelho, 1992; Cheary et al., 2004). For details on the method including the reliability of the phase quantification see Titschack et al. (2009). High magnesium calcite (HMC) quantification and Mg-content determination within calcites is based on the methodology of Titschack et al. (2011). Gypsum, halite and celestine are interpreted to have most probably originated from the evaporation of enclosed marine pore water during sample preparation and/or diagenesis, and were therefore removed from the phase quantification.

**Density measurements**

The matrix sediment density was determined on 32 samples (GeoB13729-1: n = 9, range: 1.1 to 1.2 g cm⁻³; GeoB11135-2: n = 11, range: 0.9 to 1.1 g cm⁻³; GeoB11185-1: n = 6, range: 1.1 to 1.6 g cm⁻³; GeoB11186-1: n = 6, range: 1.0 to 1.7 g cm⁻³). Matrix sediment samples (again avoiding CWC clasts) were placed into glass beakers, weighed and subsequently dried in the oven at 105 °C for 24 h. After cooling to room temperature in a desiccator, dry sample volume was analysed with a Pentapyc 5200e gas pycnometer (Quantachrome instruments) at the Geotechnics laboratory at MARUM. The dry matrix sediment density (DBD) was determined following the method of IODP Expedition 311 Scientists (2011).

**Calculation of accumulation rates**

The calculation of CARs is based on well-constrained age models (see Fink et al., 2012, 2013, 2015), carbonate content and matrix sediment density measurements, and a CWC density of 2.66 g cm⁻³ that is assumed to be representative for their skeleton (Dorschel et al., 2007). The sediment heterogeneity of the CWC-bearing cores with high amounts of CWCs in fine matrix sediment required a combined methodological approach to determine the carbonate content avoiding large sample volumes. Therefore, the methodological approach follows Titschack et al. (2015) and combines the CWC content, determined from CT image data (every 0.3 mm), with XRD analysis of the matrix sediment (see also Titschack et al., 2009). This approach allowed a further differentiation of the carbonate sources – CWC-carbonate factory-derived (subsequently abbreviated as CWC-fac.-derived) versus background-sediment-derived (subsequently abbreviated as backgr.-sed.-derived) carbonate. In this context, the CWC-fac.-derived carbonate comprises the carbonate content of the CWCs and the aragonite, HMC and dolomite content of the matrix sediment. The three above-mentioned carbonate mineral phases are assigned to the CWC-fac.-derived source due to the dominance of the first two phases in benthic carbonate-producing organisms (aragonite: corals, molluscs; HMC: molluscs, bryozoans, echinoderms) and due to the likely origination of dolomite from an early diagenetic transformation of HMC to low-magnesium calcite (LMC) and dolomite (see Lohmann & Meyers, 1977; Munnecke et al., 1997). The backgr.-sed.-derived carbonate is determined by the carbonate provided by the LMC content of the matrix sediment based on the observation that the dominant carbonate-producing organisms in non-CWC-fac.-related hemipelagic sediments, such as most foraminifers and coccolithophores, precipitate LMC.

The results obtained from the Mediterranean CWC sites were compared with records of other Mediterranean carbonate factories (such as coralligene, maerl and Clado-cora reefs) and other depositional environments (Fig. 1; Table S1).

**RESULTS**

**Melilla coral province, Alboran Sea (Core GeoB13729-1)**

**Chronostratigraphy and aggradation rates**

The chronostratigraphy of core GeoB13729-1 is based on five AMS ¹⁴C dates obtained from CWC fragments published by Fink et al. (2013). The ages comprise a period from 11.2 to 9.8 kyr BP. The calculated aggradation rates range between 125 and 530 cm kyr⁻¹ (Fig. 3; Table 3). Based on the calculated aggradation rates in conjunction with distinct lithological attributes (CWC size and orientation patterns obtained from the CT analysis, see below), four units were differentiated for this core (Fig. 3). Unit A (0 to 140 cm) reveals aggradation rates between 125 and 241 cm kyr⁻¹. Unit B (140 to 315 cm) shows an enhanced aggradation rate of 530 cm kyr⁻¹ while Unit C (315 to 375 cm) shows an aggradation rate of 189 cm kyr⁻¹ (Fig. 3; Table 3). The lack of dates for Unit D (375 to 447 cm) prohibited the calculation of aggradation rates for this interval.

**Cold-water coral clast size and orientation**

The CWC clasts within core GeoB13729-1 range in size between −7.0 and 1.5 Φ. Unit A has mean clast sizes between −5.7 and −4.2 Φ (unit mean: −5.0 Φ) with a slight fining-upward trend. The clast orientation within this unit has moderately defined to well-defined maxima with orientations between 10 and 80° (Fig. 3). Unit B shows mean clast sizes between −5.8 and −4.3 Φ (unit...
mean: $-5.2 \Phi$) with well-defined clast orientation maxima, which vary between 20 and 90$^\circ$. Unit C is characterized by clast sizes between $-5.5$ and $-3.8 \Phi$ (unit mean: $-4.7 \Phi$) and shows an upwards fining trend from its base at 375 cm to 335 cm core depth. Above this level the clast sizes increase upwards (Fig. 3). Clast orientation within Unit C has moderately defined to well-defined maxima between 0 and 70$^\circ$. Unit D reveals a fining-upward trend with mean clast sizes ranging between $-5.3$ and $-4.5 \Phi$ (unit mean: $-4.9 \Phi$) and a sharp boundary at 375 cm. The clast orientation has moderately-defined maxima with orientations between 20 and 90$^\circ$ in the histogram plot (Fig. 3).

### Sediment composition and carbonate accumulation rates

The CWC content within core GeoB13729-1 varies between 1 and 42 vol.%. The content is slightly higher in Units A and D with mean values of $>20$ vol.% compared to Units B and C with contents of $<14$ vol.% (Fig. 3). Highest values occur in Unit D with up to 42 vol.% (Fig. 3). A similar distribution pattern is exhibited by the total carbonate content with slightly increased mean values of $>67$ wt.% in Units A and D, and reduced mean values of $<55$ wt.% in Units B and C (Fig. 3; Table 3). On average, CWC-fac.-derived carbonate contributes between 34 and 58 wt.% and backgr.-sed.-derived carbonate between 13 and 19 wt.% carbonate to the total sediment composition. The conspicuous matrix sediment composition at 83 cm core depth with an almost complete absence of silicilastic minerals (Fig. 3) represents the only sample in which the exotic mineral celestine is present (with about 9 wt.% in the matrix sediment XRD analysis prior to the exclusion of diagenetic phases from the quantification), suggesting intensive diagenesis and accompanying alteration of the primary matrix sediment composition within this interval.

The highest mean CAR occurs in Unit B with 396 g cm$^{-2}$ kyr$^{-1}$ (maximum: 503 g cm$^{-2}$ kyr$^{-1}$; Fig. 3; Table 3) of which 268 g cm$^{-2}$ kyr$^{-1}$ are CWC-fac.-derived and 127 g cm$^{-2}$ kyr$^{-1}$ backgr.-sed.-derived. The other units show slightly reduced mean CARs that vary between 130 and 189 g cm$^{-2}$ kyr$^{-1}$. Within these units, the CWC-fac.-derived and the backgr.-sed.-derived CARs range between 84 and 134 g cm$^{-2}$ kyr$^{-1}$ and between 45 and 56 g cm$^{-2}$ kyr$^{-1}$, respectively (Table 3).

### Cold-water coral clast size and orientation

Within the core, CWC clast sizes range between $-6.7$ and 1.5 $\Phi$. Within Unit A, the mean clast sizes vary between $-5.4$ and $-3.5 \Phi$ (unit mean: $-4.7 \Phi$; Fig. 4). Clast orientation has moderately defined maxima and varies between 0 and 80$^\circ$ (Fig. 4). Unit B has almost no CWCs mirrored by highly reduced clast sizes, which vary between $-5.0$ and $-1.9 \Phi$ (unit mean: $-3.4 \Phi$; Fig. 4). The clast orientation exhibits weakly defined maxima between 0 and 60$^\circ$. Within Unit C, the CWC content is higher and clast sizes are larger. Mean clast sizes vary between $-4.7$ and $-3.5 \Phi$ (unit mean: $-4.1 \Phi$). The clast orientation is comparable to the overlying unit, showing only weakly defined maxima between 0 and 70$^\circ$.

### Sediment composition and carbonate accumulation rates

Within core GeoB11135-2, the CWC content varies between 0 and 51 vol.% (Fig. 4). The highest mean value occurs in Unit A with 28 vol.%. Unit C has only a slightly lower value of 24 vol.%, while Unit B contains almost no CWCs with a mean value of 2 vol.%. Hence, also the total carbonate content of the CWC-bearing Units A and C is enhanced with mean values of 74 and 70 wt.%, respectively, while Unit B has only a mean total carbonate content of 41 wt.% (Fig. 4; Table 3). In contrast, the mean backgr.-sed.-derived carbonate content is slightly enhanced in Unit B with a mean value of 17 wt.% (9 wt.% in both CWC-bearing units; note that the presence of CWC-fac.-derived carbonate within the CWC-barren units is most probably related to bioturbation).

CARs reach maximum values of nearly 200 g cm$^{-2}$ kyr$^{-1}$ in Unit A (Unit A mean: 124 g cm$^{-2}$ kyr$^{-1}$; Fig. 3; Table 3). Due to the lack of dates in Units B and C, no CARs were calculated for these units.

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**Table 3**

| Unit | CWC Content | CAR | Mean CAR |
|------|-------------|-----|----------|
| A    | 28 vol.%    |     |          |
| B    | 24 vol.%    |     |          |
| C    | 41 wt.%     |     |          |
| D    | 74 wt.%     |     |          |

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The Mediterranean cold-water coral carbonate factory

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GeoB13729-1

Core Depth [cm]  CT orthosilicate  Cold-water corals  CWGs [2-2 cm]  CT CWC content [vol.%]  Matrix Sed. Comp. [wt.%]  Total Sed. Comp. [wt.%]  Age [kyr BP]  CAR [g cm\(^{-2}\) kyr\(^{-1}\)]

Unit A

Unit B

Unit C

Unit D

0 50 100 150 200 250 300 350 400 450

0 vol. % 15

Aragonite  Quartz  Feldspar  LMC  Hornblende  Dolomite  Clay

Aggradation rate [cm kyr\(^{-1}\)]
Santa Maria di Leuca coral province, Ionian Sea (Cores GeoB11185-1, GeoB11186-1)

GeoB11185-1

Chronostratigraphy and aggradation rates

The chronostratigraphy of core GeoB11185-1 is well-constrained by eight AMS 14C dates, five obtained from CWC fragments and three derived from planktonic foraminiferal assemblages of the matrix sediment. Seven dates have already been published (Fink et al., 2012), and one additional date is provided (Table 2). The upper 102 cm of the core encompasses >14.8 kyr BP until today, and calculated aggradation rates vary between 6 and 89 cm kyr⁻¹ (Table 3). Based on the lithologies and aggradation rates, four distinct units have been defined. Units A (0 to 43 cm) and C (63 to 101 cm), both containing high amounts of CWCs, have mean aggradation rates of 10 and 89 cm kyr⁻¹, respectively, while Units B (43 to 63 cm) and D (below 101 cm core depth, not studied in detail), which were depleted in CWC fragments, show highly reduced aggradation rates of <6 cm kyr⁻¹ (Fig. 5, Table 3). The maximum aggradation rate of 110 cm kyr⁻¹ is reached within Unit C.

Cold-water coral clast size and orientation

The CWC clast sizes range between ~6.6 and 1.5 m. Unit A shows large clast sizes at the base with a mean of about ~5.6 m that fine upwards to a mean clast size of about ~3.5 m at 22 cm core depth. Above 22 cm the CWC clast size coarsens upward to a mean clast size of ~5.4 m at the top of the core (unit mean: ~4.5 m). Well-defined clast orientation maxima are restricted to the coarse parts of this unit and exhibit angles between 10 and 80°. The CWC-depleted Unit B has significantly smaller clast sizes with a unit mean of about ~3.3 m (Fig. 5). The unit shows a coarsening-upward trend from ~4.9 to ~2.2 m. Its clast orientation revealed weakly defined maxima with angles predominantly <45°. The lower CWC-bearing Unit C shows a coarsening-upward trend with mean clast sizes increasing from about ~2.9 to ~5.2 m (unit mean: ~4.1 m; Fig. 5). Well-defined maxima of the CWC clast orientation are only developed in the upper part of the unit where they vary between 30 and 80° (Fig. 5).

Sediment composition and carbonate accumulation rates

The CWC content in the CWC-bearing Units A and C varies between 3 and 44 vol.% (unit mean: 15 vol.%) and between 1 and 25 vol.% (unit mean: 13 vol.%), respectively. The CWC-depleted Unit B has a maximum CWC content of 5 vol.% (unit mean: 1 vol.%). In combination with the XRD analysis of the matrix sediment, a mean total carbonate content of 59 and 52 wt.% was calculated for Units A and C, respectively. Unit B shows a reduced mean total carbonate content of 42 wt.%, as is the case for Unit D with a mean total carbonate content of 28 wt.% (Table 3). While the mean backgr.-sed.-derived carbonate content varies only slightly between 15 and 22 wt.% between all units, the mean CWC-fac.-derived carbonate content is enhanced by a factor of ca 2.8 in the CWC-bearing Units A and C with values of 44 and 37 wt.%, compared to 20 and 9 wt.% in the CWC-depleted Units B and D.

The upper CWC-bearing Unit A has low CARs with a mean value of 8 g cm⁻² kyr⁻¹ to which the CWC-fac.-derived carbonate contributes 6 g cm⁻² kyr⁻¹ and the backgr.-sed.-derived carbonate 2 g cm⁻² kyr⁻¹. The CARs reach a maximum of up to 95 g cm⁻² kyr⁻¹ in the lower CWC-bearing Unit C. This unit also shows the highest mean value with 62 g cm⁻² kyr⁻¹ to which the CWC-fac.-derived carbonate contributes 44 g cm⁻² kyr⁻¹ and the backgr.-sed.-derived carbonate 18 g cm⁻² kyr⁻¹. The CARs were reduced within the CWC-depleted Units B with mean CARs of only 3 g cm⁻² kyr⁻¹ (Table 3).

GeoB11186-1

Chronostratigraphy and aggradation rates

The chronostratigraphy of core GeoB11186-1 is based on seven CWC and one mixed planktonic foraminifera AMS 14C dates. All CWC dates were previously published by Fink et al. (2012). For the mixed planktonic...
### Table 3. Carbonate content, aggradation rates and carbonate accumulation rates from Mediterranean CWC deposits. In brackets the CWC-fac.-derived and backgr.-sed.-derived fraction is listed.

| Core          | Core unit [cm] | Unit age [kyr] | Carbonate content [wt.%] | Aggradation rate [cm kyr\(^{-1}\)] | Carbonate accumulation rate [g cm\(^{-2}\) kyr\(^{-1}\)] |
|---------------|----------------|----------------|----------------------------|-----------------------------------|--------------------------------------------------------|
| **Alboran Sea** |                |                |                            |                                   |                                                       |
| GeoB13729-1   | A: 0–140       | 9.81–10.56     | 66.6 (47.6, 19.0)          | 125.3–240.7                      | 105.0 (74.7, 26.2) – 330.2 (185.4, 193.9)              |
| B: 140–315    | 10.56–10.98    | 55.4 (37.4, 18.1) | 305.0 (158.2, 108.3)       | 189.3                            | 502.6 (382.0, 146.9) – 395.7 (268.2, 127.5)           |
| C: 315–375    | 10.89–11.21    | 52.7 (34.2, 18.6) | 107.9 (58.3, 40.4)         |                                  | 153.0 (112.6, 49.6) – 129.6 (84.2, 45.4)             |
| D: 375–447    |                | 70.5 (58.0, 12.5) |                            |                                   |                                                       |
| **Urania Bank** |              |                |                            |                                   |                                                       |
| Geob11135-2   | A: 0–501       | 1.10–6.00      | 73.5 (64.6, 8.9)           | 70.3–139.7                       | 43.8 (31.3, 6.1) – 195.3 (185.5, 24.2)               |
| B: 501–535    | 40.6 (23.4, 17.2) |                |                            |                                   | 123.9 (109.7, 14.2)                                  |
| C: 535–578    | 70.4 (61.0, 9.4) |                |                            |                                   |                                                       |
| **Santa Maria di Leuca** | |                |                            |                                   |                                                       |
| GeoB11185-1   | A: 0–43        | 0–5.65         | 59.0 (43.7, 15.3)          | 5.5–13.6                         | 3.7 (2.6, 1.2) – 11.7 (8.8, 3.4)                      |
| B: 43–63      | 5.65–9.54      | 42.0 (19.9, 22.1) | 5.1                        |                                  | 3.3 (1.9, 1.5) – 2.8 (1.4, 1.5)                      |
| C: 63–101     | 9.54–14.69     | 52.4 (37.0, 15.4) | 4.7 (3.2, 1.5)             |                                  | 94.6 (69.5, 26.1) – 61.9 (44.3, 17.6)               |
| D: >101       | 14.69–28.0     | 28.0 (9.1, 18.8) | 6.7                        |                                  | 3.3 (1.6, 1.7)                                      |
| GeoB11186-1   | A: 0–73        | 1.53–6.46      | 48.4 (30.8, 17.6)          | 7.5–97.8                         | 4.2 (2.8, 1.4) – 64.6 (45.2, 24.5)                    |
| B: 73–89      | 6.46–9.82      | 46.9 (26.0, 20.8) | 5.7                        |                                  | 3.6 (2.2, 1.5) – 3.3 (1.8, 1.5)                      |
| C: 89–140     | 9.82–12.80     | 52.2 (36.3, 15.9) | 5.0 (3.8, 1.2)             |                                  | 64.8 (48.5, 18.1) – 43.1 (29.3, 13.8)               |
| D: >140       | 12.80–27.5     | 27.5 (8.0, 19.5) |                            | 6.0                               |                                                       |
Fig. 4. Log of the core GeoB11135-2 collected from cold-water coral deposits forming a talus deposit at the base of Urania Bank (core position is indicated in Fig. 1). For description and figure legend see Fig. 3 caption.
foraminifera AMS$^{14}$C date see Table 2. The upper part of the core studied here (0 to 150 cm core depth) covers a time interval from 13.4 to ca 2.0 kyr BP. Four units are differentiated based on the lithology and aggradation rates. High aggradation rates occur within both CWC-bearing Units A (0 to 73 cm) and C (89 to 140 cm) with up to 98 cm kyr$^{-1}$, while the CWC-depleted Units B (73 to 89 cm) and D (>140 cm) have strongly reduced rates of <6 cm kyr$^{-1}$ (Table 3, Fig. 6).

**Cold-water coral clast size and orientation**

Within the core, CWC clast sizes range between −7.0 and 1.5 Φ. The CWC-bearing Unit A has mean clast sizes between −5.8 and −3.3 Φ (unit mean: −4.7 Φ) that are organized in three sub-units, each revealing a fining-upward trend with a sharp top boundary at 7, 35 and 55 cm core depth. The CWC clast orientation shows well-defined maxima in the coarse parts of the unit with...
angles between 20 and nearly 90° and upward decreasing angles. Also, the CWC-bearing Unit C shows large mean clast sizes that vary between −5.8 and −3.7 φ (unit mean: −4.8 φ). The mean CWC clast size shows a coarsening-upward trend until 125 cm. Above, the clasts gradually become smaller towards the top of the unit. In the lower part of Unit C, clast orientations with distinct maxima between 10 and 80° occur, which vanish upwards in concert with the decreasing mean clast sizes. The CWC-depleted Unit B has highly reduced mean clast sizes.

Fig. 6. Log of the core GeoB11186-1 from Santa Maria di Leuca cold-water coral deposits (core position is indicated in Fig. 1). For description and figure legend, see Fig. 3 caption.
with a unit mean value of $-3.1\,^\circ$ and weakly defined clast orientation maxima with angles $<45^\circ$ (Table 3, Fig. 6). With respect to clast size and orientation, Unit D was not studied in detail.

**Sediment composition and carbonate accumulation rates**

The CWC content varies within the core between $<1$ and $35\text{ vol.}\%$ with mean values of 8 and $13\text{ vol.}\%$ in the CWC-bearing Units A and C, respectively. Units B and D have reduced quantities of CWCs with a mean value of 5 and $<1\text{ vol.}\%$ (Fig. 6). The carbonate content is enhanced in both CWC-bearing Units A and C with mean total carbonate contents of 48 and $52\text{ wt.}\%$, respectively. Mean carbonate contents of the CWC-depleted Units B and D are 47 and $28\text{ wt.}\%$ (Table 3). While the **backgr.-sed.-derived** carbonate shows only minor variation with mean values between 18 and $21\text{ wt.}\%$ in all units, the **CWC-fac.-derived** carbonate is enhanced in the CWC-bearing Units A and C with mean values of 31 and $37\text{ wt.}\%$ compared to the CWC-depleted units with mean values of 26 and $8\text{ wt.}\%$, respectively.

The CARs are strongly enhanced in both CWC-bearing Units A and C with mean values of 33 and $43\text{ g cm}^{-2}\text{ kyr}^{-1}$. The **CWC-fac.-derived** CARs within Units A and C show mean values of 20 and $29\text{ g cm}^{-2}\text{ kyr}^{-1}$ and are about twice as high as the **backgr.-sed.-derived** CARs with mean values of 13 and $14\text{ g cm}^{-2}\text{ kyr}^{-1}$. The CWC-depleted Units B and D have one magnitude lower CARs of 3 and $2\text{ g cm}^{-2}\text{ kyr}^{-1}$ to which the **backgr.-sed.-derived** CARs contribute $2\text{ g cm}^{-2}\text{ kyr}^{-1}$ and the **CWC-fac.-derived** CARs between 1 and $2\text{ g cm}^{-2}\text{ kyr}^{-1}$ (Table 3).

**DISCUSSION**

**Aggradation rates of Mediterranean cold-water coral occurrences**

Overall, CWC-bearing deposits at the three studied Mediterranean CWC sites cover more or less two time intervals spanning (i) from the Bellinger-Allerød warm interval until the Early Holocene as displayed in the records of the eastern Melilla (see also Fink et al., 2013; Stalder et al., 2015) and SML coral provinces (Fink et al., 2012), and (ii) from the late Middle Holocene until today as displayed in records of the Urania Bank and SML coral province (Table 3). Within the eastern Melilla coral province this last phase is only documented by dated CWC samples collected from the sediment surface in the summit area (Fink et al., 2013).

In order to reconstruct the formation of CWC deposits through time it is necessary to understand the sedimentological processes involved in their formation. In principal, three kinds of CWC deposits can be differentiated: (i) autochthonous deposits that have formed exactly where the CWC were formerly growing and in which the corals are preserved in life position; (ii) par-autochthonous deposits in which the CWCs are not preserved in life position but which were transported only over very short vertical and/or horizontal distances, hence they collapsed more or less in place; and (iii) allochthonous deposits that were transported laterally before final deposition, in case of CWC deposits mostly by mass-wasting events. Fortunately, these deposits vary considerably in their preservation patterns. Autochthonous deposits should show CWCs with a very low degree of fragmentation, a more or less upright position of coral fragments (note that the fragmentation in this case is more or less exclusively caused by the coring process), a relatively low degree of bioerosion, and high aggradation rates and an absence of age reversals of dated corals (see also Titschack et al., 2015). Par-autochthonous deposits should be characterized by CWCs exhibiting a low to moderate degree of fragmentation, a variable orientation of coral fragments depending on the degree of collapse of coral colonies before burial, a variable degree of bioerosion, moderate aggradation rates and an absence of age reversals of dated corals. Within allochthonous deposits CWCs should exhibit a moderate to high degree of fragmentation (depending on the transport distance), a sub-horizontal orientation of coral fragments and a variable degree of bioerosion. In addition, age reversals of dated corals might be a common feature revealing a chaotic depositional process (Eisele et al., 2014). Identification of these various preservation patterns is limited in visual core descriptions due to the restricted observation imposed by the 2-dimensional cutting surface. In contrast, CT analyses allow not only examination in three dimensions but also the volumetric quantification and parameterization (clast size and orientation) of the CWC-dominated macrofossil content within the cores, facilitating identification of any preservation patterns (see also Titschack et al., 2015). Hence, the CT analyses are an important tool to optimize the sampling strategy for dating by identifying depositional units, allowing the samples to be placed close to the unit boundaries. Furthermore, dating within units with a homogenous preservation pattern can be reduced or even avoided as significant changes, for example, in aggradation rates within these units are rather unlikely. While dates of CWCs can only be used for the reconstruction of periods of CWC occurrence and growth (Malinverno et al., 2010; McCulloch et al., 2010; Fink et al., 2012, 2013, 2015; Stalder et al., 2015), their use in
combination with the reconstructed preservation patterns and deviated aggradation rates allow further insights into the formation processes of the CWC deposits and their development through time (Wienberg & Titschack, in press). In this regard, it is important to keep in mind that the calculation of aggradation rates is only applicable to autochthonous and para-autochthonous CWC deposits (Wienberg & Titschack, in press).

Within the Mediterranean CWC deposits studied here, the CT analyses allowed the differentiation of three distinct preservation patterns that are generally comparable to the interpretations of Titschack et al. (2015) from Norwegian CWC sites. The first pattern is characterized by CWC clasts with predominantly large clast sizes (mean: \(-5.0 \Phi\)) and clast orientations of up to 90° (vertical) with well-defined clast orientation maxima that are associated with aggradation rates exceeding ca 300 cm kyr\(^{-1}\). This pattern is interpreted as CWC frameworks preserved in life position and was identified within the core from the western slope of Brittlestar ridge I within the eastern Melilla coral province (Unit B of core GeoB13729-1; Table 3, Fig. 3) and in one core from the SML coral province (lower part of Unit A of core GeoB11186-1; Fig. 6). The second pattern is characterized by deposits containing moderate CWC clast sizes (between \(-4.0\) and \(-5.0 \Phi\)) and clast orientations that vary between 0 and 70°, again with well-defined clast orientation maxima. The pattern is predominantly related to aggradation rates of 90 to 300 cm kyr\(^{-1}\). It is interpreted as deposits composed of CWC frameworks that experienced minor breakdown or compaction and was observed within the Brittlestar ridge I core (Units A, C and D in core GeoB13729-1) and the cores from SML coral province (upper part of Units A and C in core GeoB11185-1; lower part of Unit C in core GeoB11186-1; Figs 3, 5 and 6). The third pattern exhibits rather small clast sizes (mean: \(> -4 \Phi\)) and clast orientations of predominantly <60° with weakly defined clast orientation maxima. It occurs in intervals with aggradation rates of <90 cm kyr\(^{-1}\). These deposits are interpreted to represent CWC rubble deposits with various degrees of reworking and are most common in the cores from the SML coral province (lower part of Unit C in core GeoB11185-1; uppermost part of Units A and C in core GeoB11186-1; Figs 5 and 6). Similar preservation patterns were observed in the CWC-depleted Units B in both cores collected from the SML coral province in which minor amounts of small clasts were incorporated into the predominant hemipelagic sediments, most probably by sedimentological and/or bioturbation processes. The latter aspect clearly emphasizes that the total sediment composition needs to be considered when interpreting CT-based CWC clast size and orientation patterns.

A special case is revealed by the CWC deposits from Urania Bank (Fig. 1C). In contrast to the afore mentioned CWC deposits that have formed (par-)autochthonously, CWC deposits at Urania Bank are located at the foot of a submarine cliff and are therefore allochthonous. The deposits are interpreted to have been accumulated by the gravitational, most-probably fall-like, down-cliff transport of CWC clasts and hemipelagic sediments, both forming a talus deposit. This process of formation is also reflected in a significantly different preservation pattern compared to all other deposits presented here and known from Norwegian CWC sites (Titschack et al., 2015). The CWC-bearing units of the core from Urania Bank (Units A and C in core GeoB11135-2; Fig. 4) are characterized by mean CWC contents exceeding 24 vol.% and by containing rather large and homogeneous CWC clast sizes (mean: \(-4.7 \Phi\)) with only weakly defined clast orientation maxima (Fig. 4). This pattern is interpreted as CWC rubble deposits. The large clast sizes suggest fast downslope transport and a quick burial of the CWC fragments by hemipelagic sediment that limited further fragmentation by reworking and/or bioerosion. This interpretation is supported by ROV observations that revealed the preferential occurrence of living CWCs on the exposed submarine cliff surfaces and CWC rubble deposits at the foot of the cliffs (Fig. 2C and D; Freiwald et al., 2006, 2009). The observed aggradation rates of 70 to 140 cm kyr\(^{-1}\) are in the range of CWC frameworks that experienced minor breakdown or compaction (see above). However, within such talus deposits, aggradation rates should be highly variable and rapidly decrease with increasing distance from the cliff which makes the calculation of budgets problematic for such sites. Similar depositional settings are described so far exclusively from outcrops from Carboneras (Spain; Krautworst & Brachert, 2003; Montenat et al., 2000), Calabria (Italy; Montenat et al., 1991) and Rhodes (Greece; Titschack et al., 2005; Titschack & Freiwald, 2005).

Different CWC preservation patterns, varying from CWC frameworks that are preserved in life position to redeposited CWC rubble deposits, can be identified within the studied Mediterranean CWC deposits that are linked to distinct ranges in aggradation rate. The upscaling of the obtained data from one core to an entire CWC deposit must be treated with care and might be accompanied by huge uncertainties since the results of extrapolation are uncertain. A comparison of the CT signatures of both cores from the SML coral province located only 222 m apart show opposing preservation patterns in both CWC-bearing units. For example, within the lower CWC-bearing Units C of both cores the CT-signature in core GeoB11185-1 suggests the preservation of coral rubble in the lower part succeeded by CWC framework that
experienced minor breakdown or compaction, while in core GeoB11186-1 the preservation pattern is directly opposing with a CWC framework that experienced minor breakdown or compaction in the lower part that is succeeded by coral rubble deposits (this interpretation is consistent with the reconstructed aggradation rates). Also the present-day predominance of coral rubble on the slopes of Brittlestar ridge I, which might be interpreted as being allochthonous in origin, contrasts with the sub-sea floor preservation patterns which indicate in situ CWC frameworks during several periods. These observations highlight (i) the spatiotemporal facies heterogeneity within CWC occurrences (Roberts et al., 2008; Heindel et al., 2010), (ii) the importance of a detailed knowledge about the actual position of cores collected from CWC deposits for their further interpretation (Eisele et al., 2014), and (iii) the need for an improved understanding how this spatiotemporal heterogeneity affects areal estimates, preservation patterns within CWC deposits and deviated CARs and their extrapolations to regional or global scales.

### Carbonate accumulation rates of Mediterranean cold-water coral deposits

The CARs of the Mediterranean CWC deposits are largely consistent with the CWC preservation patterns and aggradation rates described above. Overall, the highest total CARs were obtained from the eastern Melilla coral province (Fig. 3) with maximum values of 305 to 502 g cm\(^{-2}\) kyr\(^{-1}\) (mean: 396 g cm\(^{-2}\) kyr\(^{-1}\); Table 3) occurring during the Early Holocene and encompassing a rather short time period between 10.6 to 10.9 kyr BP. Prior to and following this 300 year interval, CARs were lower with mean values between 130 and 189 g cm\(^{-2}\) kyr\(^{-1}\). As about two-thirds of the accumulated total carbonate derived from the CWC carbonate factory (Table 3), the 300 year interval in the eastern Melilla coral province might represent one of the most prolific time intervals for CWC growth and accumulation of CWC deposits in the entire Mediterranean Sea. The CARs from the study sites in the eastern Mediterranean Sea had comparatively low rates. From the Bolling-Allerod to the lower Early Holocene (ca 14.7 to ca 9.5 kyr BP), CARs exhibited mean values of up to 62 g cm\(^{-2}\) kyr\(^{-1}\) (maximum value: 95 g cm\(^{-2}\) kyr\(^{-1}\)) within the SML coral province. During the time interval lasting from the late Mid-Holocene (ca 6.5 kyr BP) until today, CARs reached mean values of 124 (maximum value: 195 g cm\(^{-2}\) kyr\(^{-1}\)) and 33 g cm\(^{-2}\) kyr\(^{-1}\) (maximum value: 65 g cm\(^{-2}\) kyr\(^{-1}\)) at Urania Bank and SML, respectively. Hence, CWC aggradation rates and CARs in the western Mediterranean are higher than in the eastern Mediterranean. This difference might reflect environmental differences between the sites or even between Mediterranean sub-basins. Fink et al. (2012, 2013, 2015) highlighted the importance of primary production and oxygen conditions as significant factors. The present-day two to three times higher primary production in the western compared to the eastern Mediterranean (Turley et al., 2000) might indicate a link between CWC growth/accumulation of CWC deposits and primary production assuming that this difference in primary production occurred also in the past. However, the key environmental parameters controlling CWC growth and the accumulation of CWC deposits at the various sites within the Mediterranean must still be better constrained in order to identify qualitatively and to validate quantitatively potential supra-regional controls (see also Stalder et al., 2015).

Comparing the CARs of the CWC deposits with other Mediterranean depositional environments in intermediate to deep waters (ca 650 to 2900 m; CARs mainly below 20 g cm\(^{-2}\) kyr\(^{-1}\); for references see Table S1) shows an enhanced CAR of about an order of magnitude within the Mediterranean CWC carbonate factory (Fig. 7; Table S1; Masqué et al., 2003; Thomson, 1982; Weldeab et al., 2003). Compared to other carbonate factories in the Mediterranean Sea, the CARs of the CWC deposits studied here are in the range of the most productive Mediterranean shallow-water carbonate factories. In general, shallow-water carbonate factories in the Mediterranean Sea exhibit a wide range of CARs between 0.2 and 504 g cm\(^{-2}\) kyr\(^{-1}\). However, the majority, including coralligene, maerl and rhodolith deposits, exhibit rates below 100 g cm\(^{-2}\) kyr\(^{-1}\) (Fig. 7; for references see Table S1). Only the Coralina elongata (red algal) communities (El Haikali et al., 2004), Cladocora caespitosa coral reefs (Peirano et al., 2001), Pentapora fascialis (bryozoan) facies (Cocito & Ferdeghini, 2001) and bryozoan-serpulid constructions (Cocito et al., 2004) have maximum carbonate production rates exceeding 100 g cm\(^{-2}\) kyr\(^{-1}\) (Fig. 7; Table S1). This comparison clearly reveals that CARs of the Mediterranean CWC carbonate factory are among the highest rates of all Mediterranean carbonate factories and that their importance should not be ignored for the evaluation of a Mediterranean carbonate budget.

Comparing the Mediterranean CWC carbonate factory with CWC sites in the NE Atlantic reveals that CARs from the eastern Melilla coral province and Urania Bank are at least a factor of four higher than rates from CWC mounds along the Irish margin (<25 g cm\(^{-2}\) kyr\(^{-1}\); Fig. 7; Table S1; Dorschel et al., 2007; Titschack et al., 2009) while the rates obtained for the SML coral province are in the same range. The CARs of the Mediterranean CWC sites are in the lower range of the prolific...
Fig. 7. Compilation of aggradation/sedimentation rates, carbonate accumulation rates (CAR) and/or carbonate production (CP) from selected cold-water coral deposits within the Mediterranean Sea, compared to cold-water coral deposits from NE Atlantic sites, and other depositional environments/carbonate factories of the Mediterranean Sea. Note that carbonate production refers exclusively to the amount of biomineralized carbonate during the organism’s life while CARs refer to the finally buried carbonate that might include laterally imported and/or vertically imported carbonate, post-depositional carbonate destructing processes (bioerosion, chemical dissolution) and potential dissolution during early diagenesis. HMP: Hovland Mound Province; LMP: Logachev Mound Province; MMP: Magellan Mound Province; BMP: Belgica Mound Province; MMS: Mallorca-Menorca shelf. Data and references are provided in supplemental material (Table S1).
Norwegian CWC occurrences (12 to 2114 g cm$^{-2}$ kyr$^{-1}$; Titschack et al., 2015). For example, the maximal CAR of up to 502 g cm$^{-2}$ kyr$^{-1}$ identified for the eastern Melilla coral province is two to four times smaller than the maximal CARs known from Norwegian CWC reefs. However, they still belong to the highest CARs known from CWC carbonate factories studied so far and are close to the rates of tropical carbonate environments (Milliman, 1993; Schneider et al., 2000; Smith & Mackenzie, 2016).

In order to finally evaluate the importance of CWCs as a Mediterranean carbonate factory, areal estimates are needed, not only for the CWC carbonate factory but also for all other Mediterranean carbonate factories and depositional environments. In addition, an improved understanding of the local to regional variability of aggradation and carbonate accumulation of the carbonate factories is required. The same accounts for a carbonate budget estimation on a global scale and its contribution to the global carbonate and carbon cycles. Besides the lack of a global areal estimate (also lacking for more or less all none-tropical carbonate factories), further studies on CARs of the CWC carbonate factory are needed. So far, only studies from the NE Atlantic (see Table S1 and references therein) and the Mediterranean Sea are available (this study). Finally, carbonate budget estimation on a global scale and its contribution to the global carbonate and carbon cycles. Besides the lack of a global areal estimate (also lacking for more or less all none-tropical carbonate factories), further studies on CARs of the CWC carbonate factory are needed. So far, only studies from the NE Atlantic (see Table S1 and references therein) and the Mediterranean Sea are available (this study). Finally, carbonate budget estimation on a global scale and its contribution to the global carbonate and carbon cycles.

In conclusion, the evaluation of aggradation and CAR for various Mediterranean CWC deposits clearly indicates that the CWC carbonate factory has to be regarded as one of the potentially most important carbonate factories in the Mediterranean Sea, which might play a significant role in the Mediterranean carbonate budget. Taking into account that most CWC reports from the Mediterranean Sea are sub-fossil (Delibrias & Taviani, 1985; McCulloch et al., 2010), it is likely that its influence was even larger in the geological past. The data from the Mediterranean Sea also support former studies from CWC sites in the NE Atlantic (Lindberg & Mienert, 2005; Dorschel et al., 2007; Titschack et al., 2015) that highlighted the potential of CWCs as a globally significant carbonate factory with CARs approaching those of tropical shallow-water carbonate environments. However, to finally evaluate the contribution of the CWC carbonate factory to the regional or global carbonate budget, areal estimates as well as an improved understanding of the temporal and spatial variability of aggradation and carbonate accumulation rates are needed. Furthermore, the role of the related carbon storage and joined CO$_2$-release to deeper waters should be conceptually considered in carbonate and carbon cycle models.

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**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

**Table S1.** Carbonate accumulation rates and carbonate production (the latter marked by an asterisk) from Mediterranean carbonate factories. **In order to calculate carbonate accumulation rates a density value of 1.52 g cm\(^{-3}\), a mean between terrigenous sediment and calcareous ooze (see Hamilton, 1976), was used.**