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SUPPLEMENTARY MATERIAL

Mid-Holocene extinction of cold-water corals on the Namibian shelf steered by the Benguela oxygen minimum zone

Tamborrino et al.

Material and Methods

All data and material from the Namibian cold-water coral mound province (CMP) used for this study were obtained during R/V *Maria S. Merian* expedition MSM20/1 in January 2012 (mapping; Geissler et al., 2013) and during R/V *Meteor* expedition M122 ANNA in December 2015/January 2016 (mapping, CTD measurements, benthic lander deployment, ROV video surveys, sampling of surface sediments and core material; Hebbeln et al., 2017)

Multibeam echosounder mapping

Instrument specifications and applied settings for the mapping by multibeam echosounder systems (MBES) are described in detail in Geissler et al. (2013) and Hebbeln et al. (2017). For all the hydroacoustic measurements, sound velocity profiles were obtained from CTD casts. Seabed mapping was performed utilising two different hull-mounted KONGSBERG MBES: EM1002 (95 kHz) during expedition MSM20/1 and EM710 (70-100 kHz) during expedition M122. The EM1002 emitted 111 beams per ping, covering a depth range of 2-1000 m and achieving a depth resolution of 2-8 cm, depending on the pulse length (0.2-2 ms). Achievable swath width on a flat bottom was up to 5 times the water depth, depending on the depth and character of the seafloor. During mapping, the swath width was adjusted to 120° (~3.5 times water depth). The EM710 acquires 200 beams per ping and 400 soundings ("soft-beams") in the used high-density mode, while covering a depth range of several meters up to ~800 m and achieves a depth accuracy of 0.3% of the depth.

Spatial integrity of the mapping data was achieved by combining the ship's SEAPATH 200 inertial navigation systems (INS) including differential global positioning system (DGPS) information with motion data (roll, pitch, heave) provided by the motion reference units (MRU5+). The open-source software package MB-System v.5.3.1 (Caress and Chayes, 1995) was used for bathymetric data post-processing, editing and evaluation. ESRI ArcGIS v.10 was used to create maps (grid cell size: 10 m, hillshade with 10 times vertical exaggeration), for spatial data management and for the quantification of coral mounds on the Namibian shelf. Bathymetric raw data and products will be available in PANGAEA (www.pangaea.de).

Quantification of coral mounds

The processed MBES map (grid cell size: 10 m) was used for a further quantification of coral mounds occurring in the Namibian CMP. Using ESRI ArcGIS v.10, a total number of 2027 coral mounds was (manually) detected. Single peaks with a minimum height of ~3m of merging and clustering mounds have been counted separately. The distribution of coral mounds on the Namibian shelf as well as detailed maps showing examples for the three sub-clusters of the Namibian CMP defined as Squid Mounds (n=959 mounds), Coral Belt Mounds (n=896 mounds) and Escarpment Mounds (n=138 mounds) are presented in Figure 1S.

ROV video surveys

Video and photo footage was obtained during seven dives with the ROV MARUM SQUID (SAAB Seaeye, UK, adapted and operated by MARUM, Bremen, Germany) crossing various coral mounds of the Namibian CMP. Technical specifications of ROV SQUID are described in Hebbeln et al. (2017). Some ROV images showing the typical faunal coverage of the Namibian mounds, which is dominated by fossil coral rubble and framework of the cold-water coral *Lophelia pertusa* and colonized by scarce living fauna, are presented in Fig. 2S.

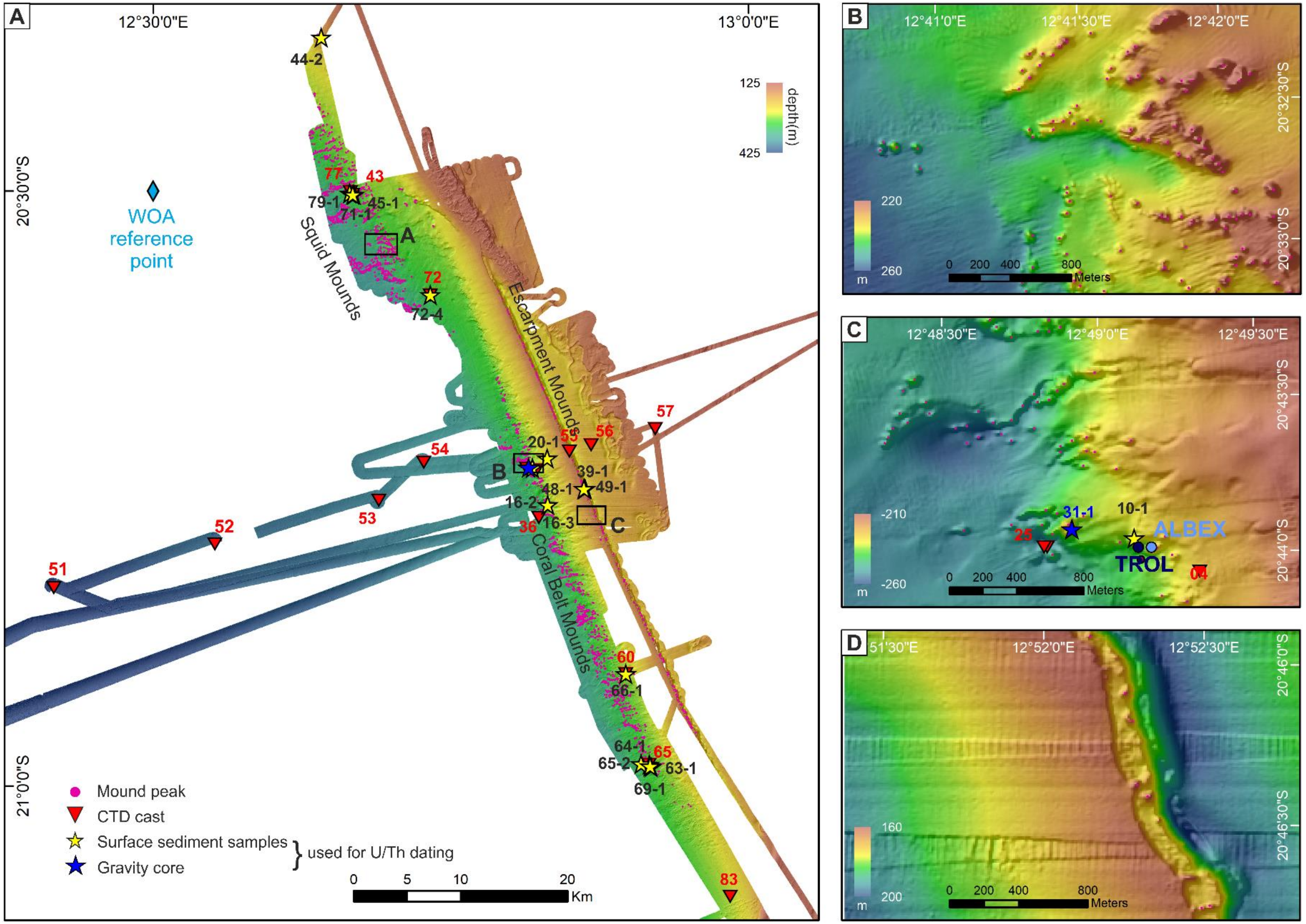

Figure 1S. A)Bathymetric map (based on MBES data obtained during expeditions M122 and MSM20/1) showing the distribution of >2,000 coral mounds (pink dots) on the Namibian shelf. Positions of CTD casts (red triangles), surface sediment samples (yellow stars) and the gravity core (blue star) used for this study are indicated. Labels next to the symbols refer to the last two and three digits of the GeoB-ID (GeoB 205xx-x) presented in Table S2 and Table S4, respectively. WOA reference point indicated in light blue. A-C. Detailed maps showing examples for mounds from the three sub-cluster present in the Namibian CMP: (B) *Squid Mounds*, (C) *Coral Belt Mounds* showing the deployment sites of the benthic landers (ALBEX and TROL; blue dots) and (D) *Escarpment Mounds*.

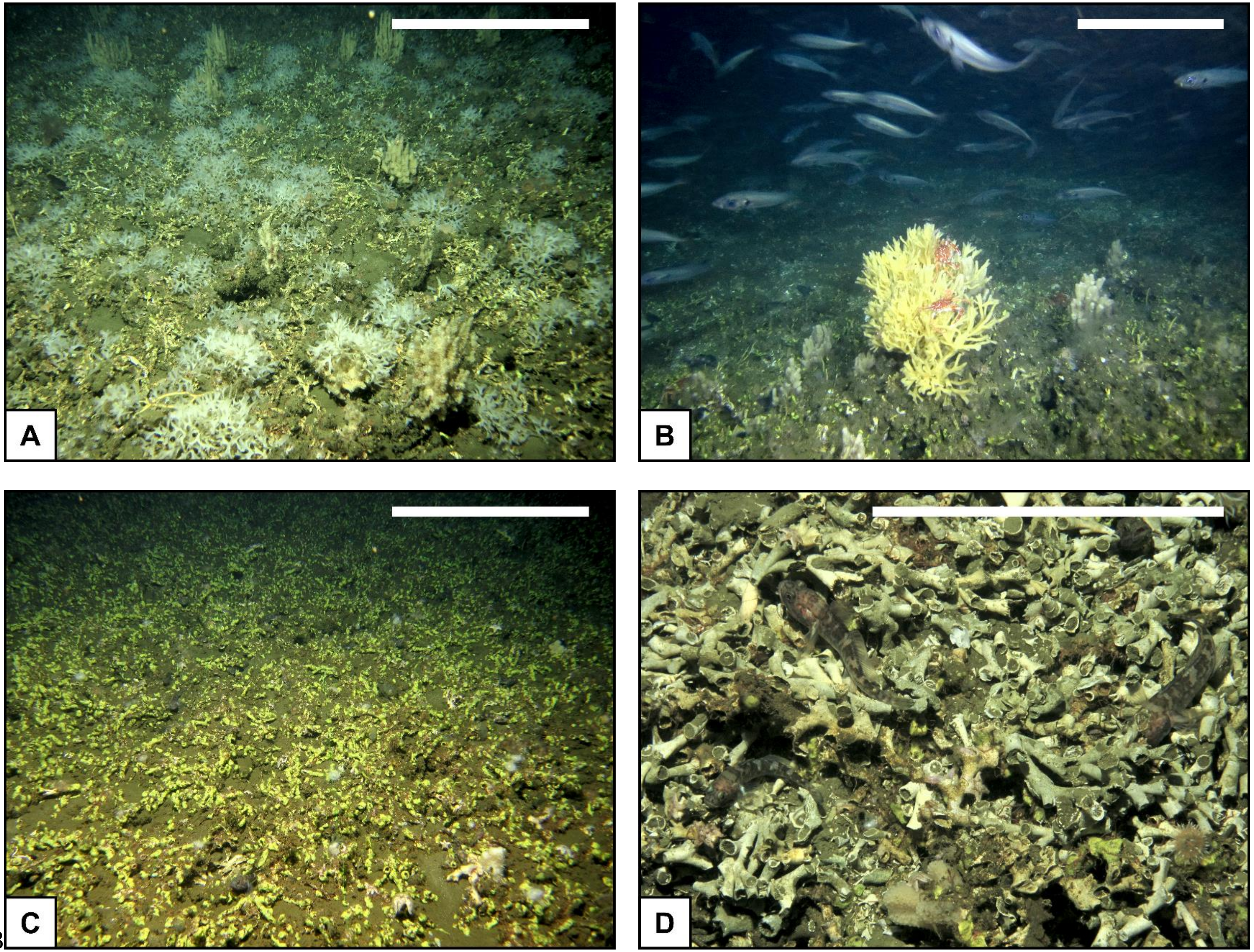

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Figure *2*S. ROV images collected during the M122 ANNA cruise. A) Coral mound surface densely covered by different sponges (cathedral-like and fingerstick-like sponges). B) A carangid swarm swimming over a mound surface with few sponge colonies. C) Mound surface with coral frameworks infested by the yellow bryozoan *Metroperiella* sp. D) Dense dead framework of *L. pertusa* with several gobiid fish. Scale bar: ~30cm

CTD measurements

To determine the physical parameters of the water masses, 12 CTD casts were performed in the area of the Namibian CMP, arranged parallel and perpendicular to the shelf (water depth range: 150-250 m), while four casts were performed in deeper areas (water depth range: 286-391 m) west of the Namibian CMP (Fig. 1S). The CTD measurements were conducted using a SEABIRD “SBE 9 plus” underwater unit and a SEABIRD “SBE 11 plus V2” deck unit. Vertical profiles over the water column provided standard data for conductivity, potential temperature, pressure, and dissolved oxygen concentrations. All data presented here refer to the down casts of the individual CTD deployments and are presented in Fig. 3S. Metadata of the CTD casts are provided in Table 2S. Raw CTD data will be available in PANGAEA (www.pangaea.de).

World Ocean Atlas data

All the CTD data collected during austral summer (M122 ANNA cruise, January 2016). In order to understand the oceanographic setting throughout the year, we compare the CTD data with the information derived from the World Ocean Atlas (WOA; Boyer et al., 2013). The ranges of the dissolved oxygen concentrations (DO) and temperatures from the WOA refer to the monthly means obtained from the closest reference point to the surveyed area (Table 3S; position displayed in Fig. 1S (20°30'S, 12°30′E), 17 km W from the Namibian CMP). The WOA statistical mean is the average of all unflagged interpolated values at each standard depth level for each variable in each 1° square, which contains at least one measurement for the given oceanographic variable. Generally, the WOA data (Fig. 3S) reveal a similar depth-depended trend compared to the shipboard CTD data obtained during M122 during austral summer, but show slightly higher DO and lower temperatures. This is likely due to the origin of the data (statistical mean based on interpolation of previously-collected oceanographic data) and the position of the reference point (Fig. 1S), 17 km west from the Namibian CMP. Indeed, the WOA data show higher closeness with data collected from the deeper CTD stations on the slope west of the Namibian CMP (Fig. 1S). Both datasets highlight how the Benguela OMZ dissolves westward as result of the gradual deviation from the high-productive surface waters on the

Namibian shelf and mixing of the SACW (oxygen-depleted water mass carried along the shelf break by the PUC) with the oxygen-rich ESACW waters (further details are provided in the main text).

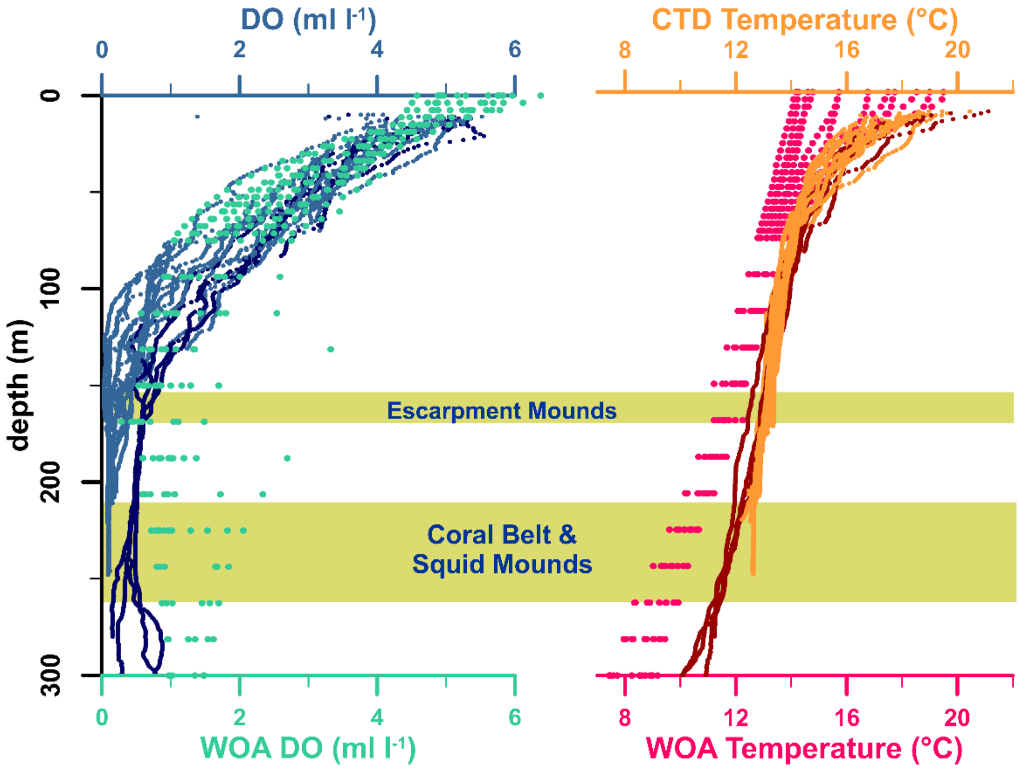

Figure 3S. Comparison of data for dissolved oxygen concentrations (DO) and temperature obtained from WOA (monthly mean values; Boyer et al., 2013) and from CTD deployments conducted during R/V *Meteor* cruise M122 in January 2016. DO values: WOA - green; CTD data from the Namibian CMP - light blue; CTD data from the deeper stations west of the Namibian CMP - dark blue. Temperatures: WOA - pink; CTD data from the Namibian CMP - orange; CTD data from the deeper stations west of the Namibian CMP – red.

TABLE 2S. METADATA OF CTD CASTS DEPLOYMENTS

GeoB ID	Latitude (S)	Longitude (E)	Depth (m)	Day and time of deployment (dd.mm.yyyy / UTC)
20504-1	20° 44.067´	12° 49.330´	220	01.01.2016 07:58
20525-1	20° 43.990	12° 48.830	247	03.01.2016 17:31
20536-1	20° 46.470´	12° 49.450´	250	04.01.2016 15:32
20543-1	20° 30.180´	12° 40.060´	224	05.01.2016 12:03
20555-1	20° 43.118´	12° 50.985´	163	06.01.2016 23:10
20556-1	20° 42.802´	12° 52.079´	178	06.01.2016 23:55
20557-1	20° 41.979´	12° 52.079´	150	07.01.2016 00:51
20560-1	20° 54.341'	12° 55.303´	217	07.01.2016 15:12
20565-1	20° 58.913'	12° 53.818´	233	08.01.2016 11:05
20572-1	20° 35.249'	12° 55.002´	233	09.01.2016 09:04
20577-1	20° 30.049'	12° 43.970´	221	10.01.2016 14:21
20583-1	21° 5.565'	12° 39.948´	212	11.01.2016 14:08
CTD casts conducted on the slope, west of the Namibian coral mounds				
20551-1	20° 50.000´	12° 25.000´	391	06.01.2016 17:51
20552-1	20° 47.792´	12° 33.110´	333	06.01.2016 19:25
20553-1	20° 45.588´	12° 41.383´	310	06.01.2016 20:55
20554-1	20° 43.681´	12° 43.639´	286	06.01.2016 21:55

Surface sediment and core sampling

Surface sediments were collected by grab sampler (GS, n=9) and the giant box corer (GBC, n=7) from the top of various coral mounds of the Namibian CMP (Hebbeln et al., 2017). Additionally, a gravity core (GeoB 20531-1) was collected from one of the Coral Belt Mounds, even penetrating the base of this mound (Fig. 4S). Fragments of *Lophelia pertusa* were selected from each surface sample from various core depths and used for uranium-series dating.

Age determination on coral fragments

In total, a set of 36 fragments of *L. pertusa* have been selected for uranium-series absolute age dating: 19 coral samples from the material collected with GS and GBC and 17 coral samples collected along a mound-penetrating gravity core. Prior to the analyses, all coral fragments were cleaned mechanically to remove contaminants from the external surface of the fossil skeletons (e.g., borings by organisms, iron–manganese crusts, coatings) and prepared chemically using weak acid leaching and water rinsing procedures as described by Frank et al. (2004). The dating analyses were carried out with a multi-collector inductively coupled plasma mass spectrometer (Institute of Environmental Physics, University of Heidelberg, Germany; Wefing et al., 2017). The reproducibility of mass spectrometric measurements was assessed using the international Uranium standard material HU1 (Cheng et al., 2000; Frank et al., 2004; Wefing et al., 2017). Metadata and ages are reported in Tables 5S and 6S. Ages are given in kilo years before present (ka BP; BP defined as 1950). All CWC fragments indicated minor physico-chemical alteration or dissolution, which may disturb Uranium-series ages. Measured ^{232}Th concentrations are small with <2.5 ppb for 94% of all samples (Tables 5S, 6S). Initial $\delta^{234}U_i$ values are variable and range between 146.6 ± 0.7‰ and 150.7 ± 0.6‰ (Tables 5S, 6S). All samples rely on $\delta^{234}U_i$ values within the narrow band of ±10‰ compared to the value of modern seawater (146.8‰; Andersen et al., 2010) and can therefore be treated as being reliable.

Coral ages obtained from the core record range from 9.5 to 5 ka BP. Coral mound aggradation rates (ARs) were calculated from age to age, following a continuous chronological order (Table 6S). The oldest and youngest coral ages in relation to the maximum and minimum core depths of the respective core interval were used for the calculation of the average AR (Fig. 5S).

TABLE 4S. METADATA OF THE SEDIMENT MATERIAL USED FOR THE COLLECTION OF FOSSIL *L. PERTUSA* FRAGMENTS USED FOR URANIUM-SERIES DATING

Area	GeoB ID	Gear	Latitude (S)	Longitude (E)	Depth (m)	Sampling depth
NW Squid Mounds	20544-2	GS	20° 22.265´	12° 38.468´	160	0-10 cm
Squid Mounds	20545-1	GBC	20° 30.184´	12° 40.067´	224	0-32 cm
Squid Mounds	20571-1	GBC	20° 30.194´	12° 40.122´	225	0-30 cm
SE Squid Mounds	20572-4‘	GBC	20° 35.249´	12° 43.968´	221	0-20 cm (layer 1)
SE Squid Mounds	20572-4‘‘	GBC	20° 35.249´	12° 43.968´	221	20-30 cm (layer 2)
Squid Mounds	20579-1’	GS	20° 30.128´	12° 39.901´	223	0-10 cm
Squid Mounds	20579-1‘‘	GS	20° 30.128´	12° 39.901´	223	0-10 cm
Escarpment Mounds	20539-1	GBC	20° 45.018´	12° 51.733´	166	Bulk
Escarpment Mounds	20548-1	GS	20° 45.025´	12° 51.715´	162	0-10 cm
Escarpment Mounds	20549-1	GS	20° 45.014´	12° 51.778´	175	0-10 cm
N Coral Belt Mounds	20510-1	GBC	20° 43.962´	12° 49.119´	230	0-15 cm
N Coral Belt Mounds	20516-2	GBC	20° 45.834´	12° 49.887´	223	0-40 cm
N Coral Belt Mounds	20516-3	GC	20° 45.834´	12° 49.887´	225	(?) core top
N Coral Belt Mounds	20520-1	GS	20° 30.128´	12° 49.866´	234	0-10 cm
S Coral Belt Mounds	20563-1	GS	20° 59.040´	12° 55.096´	232	0-10 cm
S Coral Belt Mounds	20564-1	GS	20° 59.006´	12° 55.045´	234	0-10 cm
S Coral Belt Mounds	20565-2	GS	20° 58.918´	12° 55.003´	232	0-10 cm
S Coral Belt Mounds	20566-1	GBC	20° 54.346´	12° 53.829´	223	0-12 cm
S Coral Belt Mounds	20569-1	GS	20° 58.892´	12° 54.586´	243	0-10 cm

GBC: giant box core, GS: grab sample, GC: gravity core

For GeoB20572-4 and 20579-1, two *L. pertusa* fragments were collected for dating: ’ sample 1; ‘‘ sample 2

TABLE 5S. U-SERIES AGE, ISOTOPE CONCENTRATIONS AND RATIOS FROM *L. PERTUSA* FRAGMENTS FROM SURFACE SEDIMENT SAMPLES

GeoB ID	Lab-ID	^{232}Th (ppb)	± (abs.)	$\delta^{234}U_m{}^*$ (‰)	± (abs.)	$\delta\,^{234}U_i{}^*$ (‰)	± (abs.)	Age (ka BP)	± (abs.)	Age^{cor} (ka BP)	± (abs.)
20544-2	IUP-7667	0.2693	0.0007	145.6	0.9	147.7	0.9	5.032	0.021	5.015	0.022
20545-1	IUP-9818	0.1785	0.0004	145.5	0.4	147.7	0.4	5.169	0.015	5.155	0.015
20571-1	IUP-7836	n.d.		146.8	2.2	149.2	2.2	5.653	0.040	5.653	0.040
20572-4’	IUP-7838	n.d.		147.1	2.4	149.2	2.4	4.854	0.028	4.854	0.028
20572-4‘‘	IUP-7669	0.6731	0.0012	144.5	0.7	146.6	0.7	5.032	0.019	4.986	0.030
20579-1’	IUP-7837	n.d.		146.4	0.9	148.4	0.9	4.796	0.026	4.796	0.026
20579-1‘‘	IUP-9816	0.2641	0.0004	146.2	0.5	148.2	0.5	4.826	0.019	4.804	0.020
20539-1	IUP-7842	0.5767	0.0026	145.6	0.8	148.6	0.8	7.047	0.036	7.019	0.039
20548-1	IUP-9814	0.2646	0.0006	148.6	0.6	150.7	0.6	5.004	0.025	4.983	0.024
20549-1	IUP-7843	0.1755	0.0007	144.9	1.2	147.5	1.2	6.046	0.034	6.033	0.035
20510-1	IUP-7666	7.3430	0.0220	147.1	1.2	149.2	1.3	5.508	0.033	4.963	0.280
20516-2	IUP-7840	0.0038	0.0000	146.3	0.9	148.6	0.9	5.396	0.029	5.396	0.029
20516-3	IUP-7841	n.d.		145.3	0.6	147.5	0.6	5.291	0.029	5.291	0.029
20520-1	IUP-9817	2.1160	0.0031	146.5	0.6	148.3	0.6	4.518	0.018	4.353	0.09
20563-1	IUP-7845	0.6158	0.0026	144.5	1.1	146.9	1.1	5.794	0.029	5.76	0.033
20564-1	IUP-9815	0.1012	0.0002	145.8	0.5	148.0	0.5	5.387	0.016	5.38	0.015
20565-2	IUP-7846	0.0357	0.0005	143.7	1.1	145.9	1.1	5.245	0.030	5.242	0.030
20566-1	IUP-7844	n.d.		145.7	1.0	147.6	1.0	4.515	0.026	4.515	0.026
20569-1	IUP-7668	0.0759	0.0002	145.3	0.8	147.5	0.9	5.133	0.023	5.126	0.024

* Measured $^{234}U/^{238}U$ activity ratios ($\delta^{234}U_m$) are presented as deviation permil (‰) from the equilibrium value. Decay corrected $^{234}U/^{238}U$ activity ratios (δ^{234}Ui) are calculated from the given ages and with $\lambda^{234}U$: 2.8263 x 10^{-6} yr^{-1}.

Age^{cor} Corrected ages, according to Frank et al. (2004) and Wefing et al., (2017).

n.d.: not determinable because lower than the analytical blank (<0.003 ng/g).

For GeoB20572-4 and 20579-1, two *L. pertusa* fragments were collected from the bulk sample for dating: ’ sample 1; ‘‘ sample 2

TABLE 6S. U-SERIES AGES, ISOTOPE CONCENTRATIONS AND RATIOS FROM *L. PERTUSA* FRAGMENTS FROM GRAVITY CORE GEOB20531-1

Core depth (cm)	**Lab ID**	**^{232}Th (ppb)**	**± (abs.)**	**$\delta^{234}U_m$* (‰)**	**± (abs.)**	**$\delta^{234}U_i$* (‰)**	**± (abs.)**	**Age (ka BP)**	**± (abs.)**	**Age^{cor} (ka BP)**	**± (abs.)**	**AR** (cm kyr^{-1})**
6	IUP-8168	0.2959	0.0006	145.4	0.5	147.5	0.5	5.046	0.019	5.024	0.022	
20	IUP-8169	0.1036	0.0004	146.9	0.5	149.2	0.5	5.586	0.020	5.579	0.020	25
75	IUP-8170	1.4375	0.0027	148.1	0.9	150.7	0.9	6.110	0.022	6.015	0.053	126
98	IUP-8171	0.6229	0.0009	145.9	0.5	148.4	0.5	6.012	0.017	5.970	0.028	
139.5	IUP-8172	0.2344	0.0009	145.5	0.8	148.3	0.8	6.690	0.078	6.671	0.079	59
201	IUP-8173	0.0828	0.0003	142.7	0.5	145.5	0.5	6.776	0.023	6.770	0.024	621
250	IUP-8174	0.4998	0.0015	142.4	0.7	145.3	0.7	7.055	0.032	7.023	0.036	194
311	IUP-8175	0.5084	0.0013	143.6	1.1	146.6	1.1	7.352	0.025	7.310	0.033	213
371.5	IUP-8176	0.8498	0.0022	144.0	0.6	147.1	0.6	7.496	0.028	7.433	0.043	492
435	IUP-8177	0.0566	0.0004	144.5	1.2	147.8	1.2	7.928	0.034	7.924	0.033	129
501	IUP-8178	0.3578	0.0007	143.7	0.5	147.2	0.5	8.593	0.024	8.571	0.028	102
545	IUP-8179	0.1294	0.0004	143.3	0.5	146.9	0.5	8.652	0.028	8.645	0.030	595
589	IUP-8180	2.5156	0.0080	143.9	0.6	147.5	0.6	9.006	0.034	8.833	0.094	234
635	IUP-8181	0.4137	0.0011	143.2	0.5	147.1	0.5	9.356	0.033	9.328	0.035	93
674.5	IUP-8182	0.3358	0.0007	142.6	0.5	146.5	0.6	9.480	0.025	9.459	0.029	
684.5	IUP-8183	0.1929	0.0005	142.7	0.6	146.5	0.6	9.440	0.026	9.425	0.027	
687.5	IUP-8184	0.6496	0.0013	143.7	0.7	147.5	0.7	9.405	0.034	9.350	0.044	2386

* Measured $^{234}U/^{238}U$ activity ratios ($\delta^{234}U_m$) are presented as deviation permil (‰) from the equilibrium value. Decay corrected $^{234}U/^{238}U$ activity ratios ($\delta^{234}U^i$) are calculated from the given ages and with $\lambda^{234}U$: 2.8263 x 10^{-6} yr-1.

** AR: Aggradation rate. AR is negligible within the uncertainties for all data except for the values at 75 cm and 589 cm core depth. See age-depth plot (Fig. 4S).

Age^{cor} Corrected ages, according to Frank et al. (2004) and Wefing et al., (2017). Ka BP refers to 1950.

n.d.: not determinable because lower than the analytical blank (<0.003 ng/g).

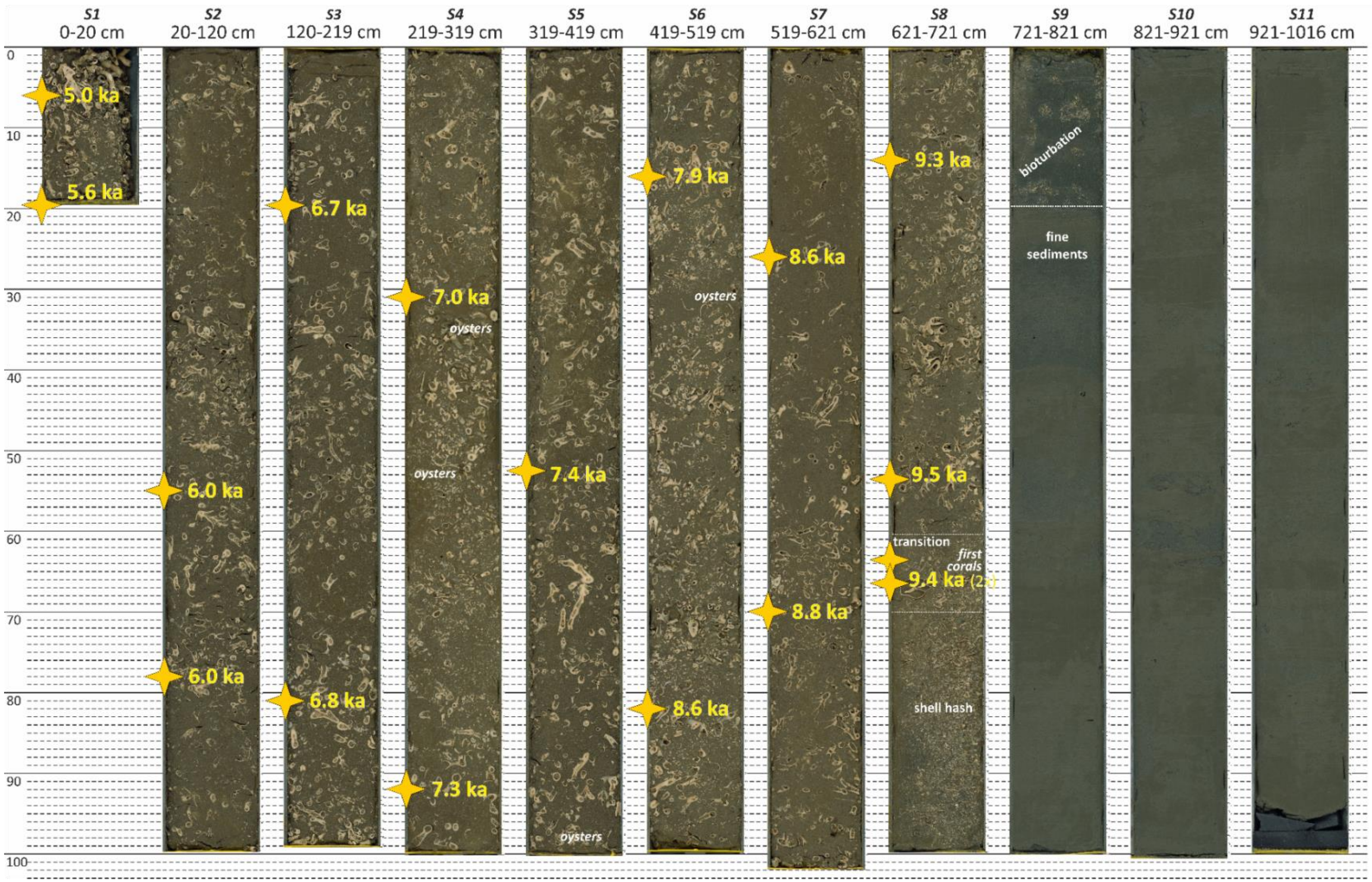

Figure 4S. Line scan of gravity core GeoB 20531-1 collected from one of the small Coral Belt Mounds of the Namibian CMP (total recovery: 1021 cm; water depth: 231 m). From the core base to 741 cm core depth, the core is composed of fine hemipelagic sediments. From 741-670 cm core depth, the core is composed of bioturbated sediments (741-721 cm core depth) and shell hash within fine sediments (721-661); note: first coral fragments appear already in the upper part of the shell hash layer (671-661cm core depth).From 661 cm to the core top, the core is entirely composed of *Lophelia* fragments embedded in fine sediments, with an occasional occurrence of oyster shells and other bioclasts. U-series datings obtained from coral fragments collected throughout the core are displayed (yellow stars).

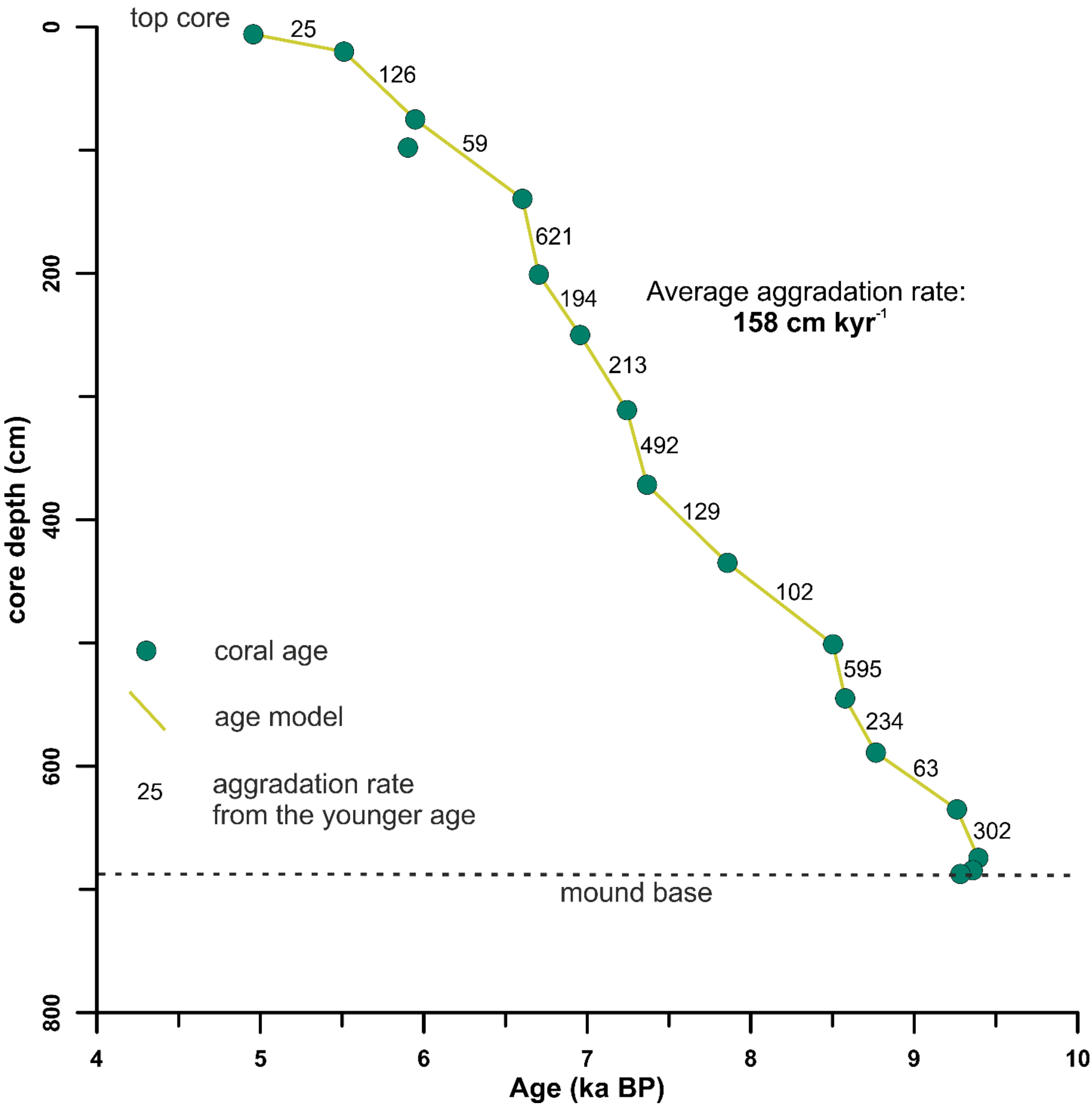

Figure 5S. Coral ages vs. core depth. Coral ages were obtained from fragments of the cold-water coral *Lophelia pertusa* collected at various core depths from core GeoB 20531-1 (see Table 6S). The core was collected from one of the small Coral Belt Mounds (Fig. 1S) and penetrated the mound base at ~6.51 m (see core image in Fig. 4S). Coral mound aggradation rates (given in cm kyr^{-1}) were calculated from age to age and are given next to the green line. The average aggradation rate is 158 cm kyr^{-1}.

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