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The Holocene occurrence of cold water corals in the NE Atlantic: Implications for coral carbonate mound evolution

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ABSTRACT

U-series dating of constructional cold-water corals is a powerful tool to reconstruct the evolution of corals on carbonate mounds. Here we have investigated the time framework of corals such as *Lophelia pertusa* and *Madrepora oculata* on five different mound settings of the eastern North Atlantic (on Rockall Bank and in Porcupine Seabight), sampled at variable depth and location (610–880 m water depth). We have found that the past 11 ka reflect a period generally favourable for coral development. We further determined local mound growth rates and identified mound surface erosion (framework collapse) during times of active coral framework construction. "Local" vertical mound growth rates vary between less than 5 cm ka^{-1} and up to 220 cm ka^{-1}. We interpret rates exceeding 15 cm ka^{-1} as representative of densely populated coral reefs. During times of reduced or absent coral development, mound evolution rates are by far smaller (0 to <5 cm ka^{-1}). The time resolution achieved here furthermore provides first evidence for reduced coral (ecosystem) activity at 1.8–2.0 ka, 4.2–4.8 ka and between 6 and 8.2 ka within the Holocene that may be related to climate driven changes of the coral growth environments. During Glacial periods coral growth in those areas seems apparently extremely reduced or is even absent on mounds.

1. Introduction

Extensive deep-water coral ecosystems exist along the northeast Atlantic continental margins of Ireland, Scotland and Norway (Freiwald and Roberts, 2005). Since about a decade these deep-water coral reefs are subject to extensive European research efforts to better constrain ecosystem functioning and coral reef development (Henriet et al., 1998; Hovland et al., 1998; de Mol et al., 2002; Dorschel et al., 2005; Freiwald and Roberts, 2005; White et al., 2005; Roberts et al., 2006; van Rooij et al., 2006; Dorschel et al., 2007; Mienis et al., 2007; Wheeler et al., 2007). These mounds can achieve a height of several hundred meters and measure several square kilometres at the base (Hovland et al., 1994; de Mol et al., 2002; Huvenne et al., 2003; Kenyon et al., 2003; van Weering et al., 2003). The sedimentary environment is complex due to strong directional bottom water currents (White et al., 2005; Mienis et al., 2007). The main framework builders are known to be the branching corals *Lophelia pertusa* and *Madrepora oculata* also associated with other species such as the solitary coral *Desmophyllum dianthus*. Much progress has been made on our understanding of coral reproduction, food web and environmental factors steering modern coral growth (see Roberts et al. (2006) and for review (Roberts et al., 2009). IODP 307 expedition in the Porcupine Seabight has further revealed that a carbonate mound in Porcupine Seabight (Challenger Mound) is entirely the result of deep-water coral growth since about 2.6 Ma ago (Williams et al., 2006; Kano et al., 2007). But mound evolution is discontinuous, diagenesis is important, and mounds are shaped through erosion ones coral growth is absent (Rüggeberg et al., 2003; Frank et al., 2005; Dorschel et al., 2005; Foubert et al., 2007; Kano et al., 2007).

Deep-water corals can be accurately dated by means of U-series dating (Smith et al., 1997; Adkins et al., 1998; Mangini et al., 1998; Lomitschka and Mangini, 1999; Cheng et al., 2000a; Schröder-Ritzrau et al., 2003; Frank et al., 2004; Frank et al., 2005; Schröder-Ritzrau et al., 2005), which provides a tool to determine the age–depth relationship of coral fragments.

Dating coral fragments from "on-mound sediment cores" allows to determine Vertical Mound Growth Rates (VMGR) in cases were such cores represent the successive growth and degradation of the open coral framework (Frank et al., 2005; de Haas et al., 2009). It further allows measuring the timing above and below hiatuses often invisible

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in the sedimentary record (Rüggeberg et al., 2003; Dorschel et al., 2005; Frank et al., 2005; Rüggeberg et al., 2007; Eisele et al., 2008). Finally, dating provides a direct measure of the timing of open framework construction and thus reveals periods favourable of coral growth i.e. with respect to major climate change. Moreover, dating of corals is important to provide a time framework needed for paleo-environmental studies that can be carried out on coral skeletons.

Here, we present a detailed chronological survey based on mass spectrometric U-series dating of constructional deep-water coral fragments. The primary objective is to determine (i) the time framework of coral growth on different mounds, i.e. in different mound provinces and environments, (ii) to provide measures of the local vertical mound growth rates and (iii) to provide further evidence of the geological mound processes such as erosion and diagenesis. We also demonstrate for the first time that "almost continues coral age records can be established" needed to carry out paleo-environmental studies.

2. Environmental setting

The Rockall Trough and Rockall Bank form part of the British and Irish continental margin consisting of several deep basins, separated by basement ridges. Within Porcupine Seabight, along Porcupine Bank and on Rockall Bank, numerous carbonate mound provinces have been found at water depth between 400 m and 1100 m (Hovland et al., 1994; de Mol et al., 2002; Huvenne et al., 2003; Kenyon et al., 2003; van Weering et al., 2003; Wheeler et al., 2005; van Rooij et al., 2006; van Wheeler et al., 2007; Foubert et al., 2007; Huvenne et al., 2007).

Today, the hydrodynamic regime within those mound areas is stipulated through strong bottom currents driven by northward moving Eastern North Atlantic Water (ENAW) (Rockall Bank) and Mediterranean Overflow Water (MOW) (solely in Porcupine Seabight) both overlying Labrador Sea Water (LSW) which re-circulates at depth below 1200 m (Ellett and Martin, 1973; Huthnance, 1986; van Aken and Becker, 1996; Holliday et al., 2000; New and Smythe-Wright, 2001). In addition, the local topography results in internal basin scales waves and internal tides favoring nutrient and food storage in mound regions (White and Bowyer, 1997; White et al., 2005; Mienis et al., 2007). Strong wind forcing through the westerlies result in a deep mixed layer during winter time that may occasionally reach down to 1000 m depth and which occurs over several months (Holliday et al., 2000). Consequently, corals develop in well ventilated near thermocline waters of generally 4–12 °C, close or within the oxygen minimum zone. In addition to large scale oceanographic patterns local hydrodynamic regimes can influence the coral reef settings and in particular organic matter supply and storage near the reef area (White et al., 2005). This is done through deflection of the main currents along the topographic structure resulting in anti-cyclonic recirculation and potentially the creation of Taylor columns (isopycnal doming over an obstacle on the mounds) and/or Ekman drainage along the mound flanks (White et al., 2005).

3. Material and methods

3.1. Core locations

During the *R/V Marion Dufresne* cruise "MD123" in September 2001, 5 gravity cores have been taken at various depths close to the summit of Mounds Perseverance, Challenger, and Thérèse in Porcupine Seabight and on two unnamed mounds on Rockall Bank (Table 1 and Fig. 1).

On Rockall Bank gravity cores MD01-2454G (54G) and MD01-2455G (55G) were taken at 747 m and 637 m water depth (Table 1, Fig. 1a). Both mounds are part of two mound clusters on the margin of Rockall Bank close to each other (van Rooji et al., 2001). These mounds, part of the Logachev mound province (Mienis et al., 2009; Wheeler et al., 2007) (Fig. 1a), reflect a flourishing coral ecosystem with abundant associated fauna. The coring location of 54G lies in fact between the summits of two small south–north elongated mounds, near a lithified hardground outcrop observed during Victor dive 10 of the Caracole campaign (Olu Le-Roy and Shipboard Scientific Crew, 2002). Core 55G was recovered close to the top on the northern steep flank of the south–north elongated mound (Fig. 1a). Both cores did recover solely a small part (2.73 m and 1.73 m) of the initially anticipated length (18 m and 13 m depth) due to the presence of hardgrounds through which the gravity cores could not penetrate. Hardgrounds were not recovered, but have been sampled in several piston cores taken previously in close vicinity during the *R/V Pelagia* cruise 64PE182 (van Weering and shipboard scientific party, 1999; de Haas et al., 2009).

Table 1
Gravity core locations (see Fig. 1).

Core	Coordinates	Depth (m)	Length (m)	Site
(1) MD01-2454G	55°31′N 15°39′W	747	2.73	Top unnamed mound — Southwest Rockall Bank
(2) MD01-2455G	55°33′N 15°40′W	637	1.93	Top unnamed mound — Southwest Rockall Bank
(3) MD01-2459G	52°18′N 13°03′W	610	10.79	Top mound Perseverance — Northern Porcupine Seabight
(4) MD01-2463G	51°26′N 11°46′W	888	10.75	Top mound Therese — Eastern Porcupine Seabight
(5) MD01–2451G	51°23′N 11°46′W	762	12.84	Top mound Challenger — Eastern Porcupine Seabight

Gravity core MD01-2459G (59G) was taken on Mound Perseverance in Porcupine Seabight. Situated in the Magellan Mound province mainly consisting of buried mounds (de Mol et al., 2002; Huvenne et al., 2005), this mound is one of few to reach above the sea floor. It has a southwest–northeast elongated shape and an active coral fauna of *Lophelia pertusa* and *Desmophyllum dianthus* corals (Olu Le-Roy, 2004; Huvenne et al., 2005) (Fig. 1b). Core 59G was sampled on the south-western flank and no live corals have been recovered (Fig. 1b). Gravity core MD01-2451G (51G, 762 m depth) was recovered on top of Challenger Mound within the Belgica Mound province, which has a south–north elongated shape and rises about 153 m above the seabed (Williams et al., 2006; Kano et al., 2007) (Fig. 1c). Today, this mound is covered by dead coral rubble in contrast to the flourishing coral ecosystems recorded on Thérèse Mound (Olu Le-Roy, 2004; de Mol et al., 2007) and Galway Mound (Foubert et al., 2005; Eisele et al., 2008) situated nearby but at deeper depth (Williams et al., 2006). The core was taken on the north-western tip of the summit off the mound flank facing the northward moving currents and it is situated next to the site of recent IODP drilling 307 (Fig. 1c). Gravity core MD01-2463G (63G, 888 m) was recovered from top of Thérèse Mound (Fig. 1d). This mound has again a south–north elongated shape (Wheeler et al., 2005; Williams et al., 2006) and is covered with a strikingly active coral ecosystem (Olu Le-Roy, 2004). Sampling occurred slightly on the eastern flank close to the top of the mound near the presently active *L. pertusa* and *Madrepora oculata* coral ecosystem (Fig. 1d), which reaches from the south-western flank to the top with dense coral populations (Olu Le-Roy, 2004). Overall, sediment coring within Porcupine Seabight using gravity corers has been very successful on mounds as most cores achieved the initially anticipated length. But core MD01-2459G hit a carbonate hardground layer that was recovered at 10 m core depth.

All cores from SW Rockall Bank and within Porcupine Seabight have been investigated on board *R/V Marion Dufresne* using a GEOTEK Multi Sensor core Logger at a resolution of 2 cm, measuring magnetic susceptibility (Barlington loop senor MS2B) and GRAPE density (Cs^{137} source with energies principally at 0.622 MeV) on whole round sections. Then, cores were send to University Bordeaux to perform X-ray

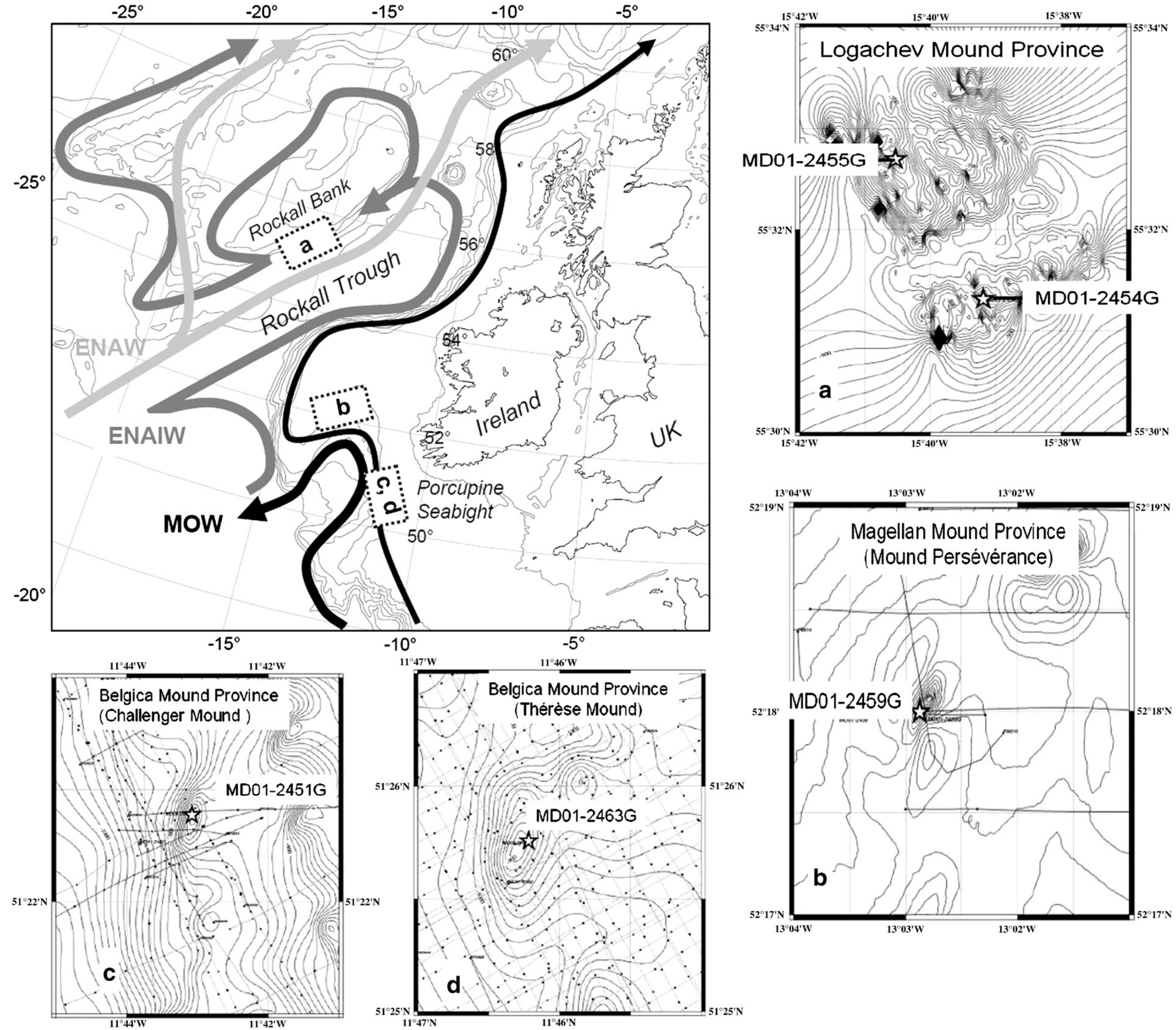


Fig. 1. Core locations and regional scale bathymetry. The dashed grey arrows indicate eastern North Atlantic water (ENAW) and eastern North Atlantic intermediate water (ENAIW). The black lines show the present day location of the Mediterranean outflow water (MOW) (thick line) and the shelf edge current (thin line). a–d) Zoom on the coring locations within different mound provinces. a) Logachev Mound province of clustered mounds on SW Rockall Bank. Core MD01-2454G is taken between two small mound features and core MD01-2455G is taken on the northern steep flank of an unnamed mound. b) Mound Perseverance (Porcupine Seabight): situated in a rather flat area of the Magellan Mound Province this mound reaches to the seafloor and core MD01-2459G was taken near its summit on the south-western flank. c-d) Thérèse and Challenger Mound from Belgica Mound Province. Both mounds are situated on the southern slopes of Porcupine Seabight at different water depth. Core MD01-2451G was taken on the northern-western edge of the summit of Challenger Mound and core MD01-2463G was sampled on the eastern flank near the summit of Thérèse Mound.

radiographies using the SCOPIX X-ray equipment (DGO UMR5805) (Foubert et al., 2007), which provides constrains on coral content and distribution (Fig. 2). Following a first evaluation of the coral abundance and core physical parameters corals have been selected for U-series dating and to determine coral species and state of preservation. In the following we focus solely on the upper most coral rich core sections to study the most recent recorded coral growth interval.

3.2. Mass spectrometric ^{230}Th/U dating of coral skeletons

The technique of U-series dating of deep-water corals follows closely previously published procedures (Frank et al., 2004; Frank et al., 2005). Mass spectrometric analyses were carried out on the LSCE (Gif-sur-Yvette, France) thermal ionization mass spectrometer (Finnigan MAT262).

Reference material HU-1 was used to determine the internal reproducibility of U and Th isotope analyses with values identical to the ones previously published (Frank et al., 2005). Activity ratios were calculated from measured atomic ratios using the decay constants of ^{238}U, ^{234}U and ^{230}Th of $\lambda_{238}=1.5515.10^{-10}$ years^{-1}, $\lambda_{234}=2.8263.10^{-6}$ years^{-1}, $\lambda_{230}=9.1577.10^{-6}$ years^{-1} (Cheng et al., 2000b), respectively. In total, 75 samples from 5 sediment cores have been investigated by U-series dating, with the Rockall Bank cores (55G and 54G) being the most intensively studied ($n=50$). In total, 7 U-series ages have been rejected due to significant contamination (>10 ng g^{-1}) with ^{232}Th.

To complete the coral growth records in cases, a few AMS ^{14}C ages were measured. Those AMS ^{14}C ages have been obtained according to the procedures described by (Frank et al., 2004) and have been calibrated using the marine ^{14}C calibration of CALIB510 (Stuiver et al., 1998) with a mean sub-surface water reservoir age of 500 ± 100 a (Frank et al., 2004).

4. Results

4.1. U-series dating results

Results of U-series dating of coral fragments are presented in Table 2. The U concentration of cold-water species *Lophelia pertusa*

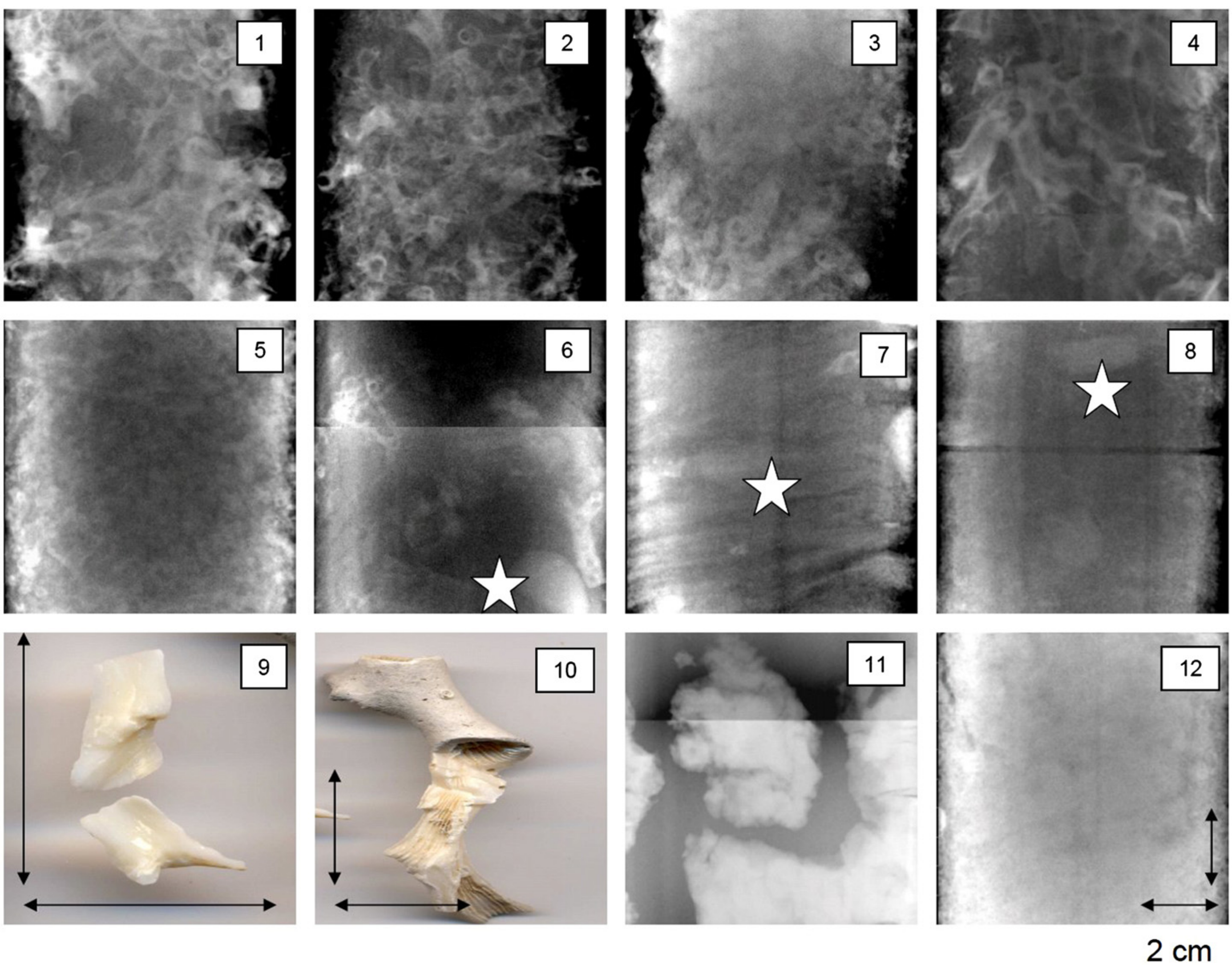


Fig. 2. SCOPIX image sections of different cores and coral photos before and after mechanical cleaning [(10) and (9)]. Note the scale of the SCOPIX images is ~10 × 10 cm. (1) and (2) Typical *Lophelia pertusa* coral fragments in core MD01-2454G. (3) Coral fragments of mostly *Madrepora oculata* from the Hiatus (~120 cm core depth) of core MD01-2455G. (4) Typically large coral fragments of *L. pertusa* from core MD01-2459G between 0 and 5.35 m core depth. (5) Small and barely visible coral fragments from the deeper section of core MD01-2463G (~10 m core depth). (6) Dropstone together with *L. pertusa* coral fragments of Holocene age (see text) from core MD01-2463G at ~1.28 m core depth. (7) Dropstones recorded in laminar hemipelagic sediments from core MD01-2451G (~4 m core depth). (8) Dropstones within "non-laminated" sediments of core MD01-2451G (~0.35 m core depth). (11) Pieces of lithified hardground from the base of core MD01-2459G and (12) carbonate rich sediments containing footprints of coral equally from core MD01-2459G (section below 5.35 m core depth).

Table 2
Ages, initial d^{234}U, ^{232}Th concentration and calibrated AMS ^{14}C ages.

Sample-ID	No.	Depth in core (cm)	Age (years)	δ^{23}4U (‰)	^{232}Th (ppb)
MD01-2454					
MD01-2454 liv P1	1	0	18 ± 6	144.8 ± 4.0	0.058 ± 0.001
MD01-2454 liv P2	2	0	15 ± 15	149.1 ± 3.6	1.202 ± 0.012
MD01-2454 Top	3	2	360 ± 140	142.0 ± 3.0	3.050 ± 0.031
MD01 2454G 7–9 cm	4	8	891 ± 89	148.6 ± 5.3	1.400 ± 0.016
MD01 2454G 20–22 cm	5	21	1128 ± 81	142.3 ± 5.3	2.389 ± 0.006
MD01-2454G-31	6	31	1456 ± 100	145.7 ± 2.1	3.539 ± 0.012
MD01-2454 50–52 cm (14C)		51	2371 ± 115	Calibrated ^{14}C age (R = 450 yr)	
MD01-2454G 60–62 cm	7	61	2560 ± 130	148.8 ± 4.7	0.384 ± 0.012
MD01-2454 70–72 cm top (14C)		71	2463 ± 110	Calibrated ^{14}C age (R = 450 yr)	
MD01-2454G 85-86c578	8	85.5	3345 ± 295	155.4 ± 3.1	7.106 ± 0.014
MD01-2454G 85-86c6	9	85.5	Rejected	141.6 ± 2.3	10.038 ± 0.020
MD01-2454G 90 cm	10	90	3190 ± 240	145.9 ± 4.3	5.680 ± 0.011
MD01 2454G 100 cm	11	100	3523 ± 91	142.1 ± 4.0	1.737 ± 0.005
MD01 2454G 100 cm dup.	12	100	3510 ± 91	146.2 ± 2.9	1.737 ± 0.005
MD01 2454G 113–117 cm	13	115	3600 ± 130	149.4 ± 4.6	2.878 ± 0.012
MD01-2454G-121	14	121	3831 ± 27	147.9 ± 2.2	0.142 ± 0.001
MD01 2454G 138–140 cm	15	139	4976 ± 78	143.2 ± 3.1	0.761 ± 0.003
MD01 2454G 138–140 cm dub.	16	139	4961 ± 77	146.2 ± 2.8	0.761 ± 0.003
MD01-2454G 143–145	17	144	4869 ± 42	153.7 ± 2.9	0.632 ± 0.001
MD01-2454 150	18	150	5040 ± 61	147.8 ± 3.1	0.669 ± 0.001
MD01-2454G 160–168 cm top	19	164	5270 ± 110	148.8 ± 2.6	0.276 ± 0.006
MD01-2454G 175–180 cm	20	177.5	5667 ± 38	146.5 ± 2.9	0.360 ± 0.001
MD01-2454G 189 cm	21	189	6080 ± 140	152.6 ± 3.6	0.534 ± 0.002
MD01-2454G 192–194 cm	22	193	5620 ± 240	147.7 ± 4.8	6.805 ± 0.011
MD01-2454G 204–205 cm	23	204.5	6992 ± 214	146.6 ± 3.5	0.920 ± 0.022
MD01-2454G 204–205–1 cm	24	204.5	6687 ± 160	150.6 ± 3.4	0.856 ± 0.007
MD01-2454G 210–217 cm	25	213.5	7679 ± 72	154.1 ± 4.7	0.833 ± 0.002
MD01-2454G 220 cm	26	220	7730 ± 230	150.7 ± 4.1	2.741 ± 0.013
MD01-2454G 225–227 cm	27	226	8430 ± 200	147.1 ± 3.9	2.052 ± 0.007
MD01-2454G-247	28	247	Rejected	148.0 ± 2.9	30.15 ± 0.21
MD01-2454 273	29	273	9400 ± 160	148.5 ± 3.2	3.719 ± 0.007
MD01-2454 core cutter 1	30	275	10,880 ± 340	148.4 ± 3.3	5.861 ± 0.018
MD01-2454 core cutter 2	31	275	Rejected	148.5 ± 3.5	10.472 ± 0.043
MD01-2459G					
MD01-2459G top	41	0	4368 ± 95	151.4 ± 6.8	0.402 ± 0.002
MD01-2459 top II	42	0	Rejected	149.1 ± 3.0	12.761 ± 0.023
MD01-2459G 46–53 cm top	43	49.5	7540 ± 180	147.4 ± 4.1	0.259 ± 0.001
MD01-2459G 94–99 cm (14C)		96.5	8535 ± 84	Calibrated ^{14}C age (R = 450 yr)	
MD01 2459G 110–114 cm	44	112	8765 ± 190	150.4 ± 13.8	0.740 ± 0.002
MD01-2459G 130–140 cm top (14C)		135	8604 ± 96	Calibrated ^{14}C age (R = 450 yr)	
MD01-2459 150	45	150	8520 ± 100	152.0 ± 3.1	1.763 ± 0.003
MD01-2459G 157–165 cm top (14C)		161.5	8560 ± 110	Calibrated ^{14}C age (R = 450 yr)	
MD01 2459G 201–208 cm	46	205	8930 ± 170	148.4 ± 5.4	0.274 ± 0.002
MD01-2459 300	47	300	9290 ± 210	147.3 ± 2.4	4.337 ± 0.006
MD01-2459 450	48	450	9742 ± 74	148.1 ± 3.1	0.080 ± 0.000
MD01-2455G					
MD01-2455G top	50	0	188 ± 32	144.0 ± 11.0	0.600 ± 0.006
MD01-2455G 20	51	20	680 ± 250	150.2 ± 3.9	6.484 ± 0.013
MD01-2455G 45–46	52	45.5	2880 ± 220	149.2 ± 5.3	3.866 ± 0.015
MD01-2455G 70	53	70	10,670 ± 460	144.9 ± 4.4	8.864 ± 0.017
MD01-2455G 91	54	91	9370 ± 220	143.8 ± 4.6	3.362 ± 0.005
MD01-2455G 126–127	55	126.5	11,270 ± 170	143.6 ± 3.6	3.568 ± 0.007
MD01-2455G 150	56	150	10,270 ± 320	148.3 ± 3.1	7.734 ± 0.015
MD01-2455G 155–157	57	156	10,660 ± 230	147.7 ± 4.0	0.681 ± 0.002
MD01-2455G 166–167	58	168	2238 ± 68	144.3 ± 3.5	0.647 ± 0.001
MD01-2455G 193	59	193	5420 ± 140	151.0 ± 6.1	0.133 ± 0.004
MD01-2455G cc 1	60	193	7980 ± 280	149.3 ± 3.5	3.585 ± 0.020
MD01-2455G cc 2	61	193	Rejected	147.2 ± 2.0	26.28 ± 0.17
MD01-2463G					
MD01-2463G top	70	0	261 ± 33	148.1 ± 9.5	0.800 ± 0.010
MD01-2463G 10 cm (14C)		10	851 ± 99	Calibrated ^{14}C age (R = 450 yr)	
MD01-2463G 100 cm (14C)		100	6811 ± 88	Calibrated ^{14}C age (R = 450 yr)	
MD01-2463G 139–142 cm	71	140.5	9810 ± 220	154.5 ± 2.4	3.583 ± 0.010
MD01-2463G 144–146 cm	72	145	Rejected	143.6 ± 3.6	24.500 ± 0.150
MD01-2463G 178–179 cm	73	178.5	9700 ± 350	154.0 ± 2.7	9.451 ± 0.014
MD01-2463G 300 cm	74	300	247,800 ± 10,500	153.8 ± 9.8	6.854 ± 0.048
MD01-2451G					
MD01-2451G top	80	0	Rejected	151.8 ± 5.8	21.000 ± 0.400
MD01-2451G 6 cm	81	6	3233 ± 106	145.2 ± 2.8	0.391 ± 0.005
MD01-2451G 27 cm	82	27	6110 ± 153	147.2 ± 3.8	0.341 ± 0.004
MD01-2451G 31 cm	83	31	6520 ± 140	154.1 ± 2.9	1.610 ± 0.006
MD01-2451G 223 cm	84	223	78,790 ± 490	140.3 ± 2.9	3.791 ± 0.011
MD01-2451G 248 cm	85	248	109,200 ± 773	152.4 ± 4.4	0.392 ± 0.009
MD01-2451G 326 cm	86	326	188,900 ± 2300	*160.7 ± 4.6*	0.595 ± 0.027

Table 2 (*continued*)

Sample-ID	No.	Depth in core (cm)	Age (years)	$\delta^{234}U$ (‰)	^{232}Th (ppb)
MD01-2451G					
MD01-2451G 407 cm	87	407	230,400 ± 2900	*190.7 ± 10.0*	1.153 ± 0.005
MD01-2451G 450 cm		450	Not datable: activity ratios are above		3.791 ± 0.022
MD01-2451G 900 cm		900	equilibrium		5.889 ± 0.020
MD01-2451G 1050 cm		1050			3.401 ± 0.016

Radiocarbon ages are indicated with bold-italic in contrast to U-series age and isotope data.

and *Madrepora oculata* varies strongly between ~2.80 and ~5.0 µg g^{-1}. Initial $\delta^{234}U_0$ values range between 140‰ and 155‰ with a mean of 148 ± 3.5‰ ($n = 63$; standard deviation = ±2σ) identical to measured present day seawater values of 146.6–149.6‰ (Delanghe et al., 2002; Robinson et al., 2004). Measured ^{232}Th concentrations are small (<10 ng g^{-1}) for most samples. In cases were ^{232}Th exceeded values of 10 ng g^{-1}, data was rejected ($n = 7$) to avoid propagating large uncertainties into the age estimate derived from correction models. Small amounts of ^{232}Th and ^{230}Th from detritus and from seawater may affect however the $^{230}Th/U$ age. Consequently a correction model considering precipitation of ^{230}Th from seawater was applied taking seawater ($^{232}Th/^{230}Th$) activity ratios ranging from 14 to 6 into account (Frank et al., 2004). The uncertainty of this correction was propagated into the age uncertainty, resulting in a slight decrease of ages (within uncertainty of the mean age) but a significant increase of age errors as a consequence of error propagation (Table 2).

U-series ages from the upper most coral rich section of all investigated sites range from 0 to 12 ka. Solely a few ages from the second coral rich units are presented for core 63G and 51G to identify the age difference between the recent coral growth and last coral occurrence prior to this interval. The section underneath the recent coral development recorded in core 63G dates back to 240 ka, while the one of core 51G dates back to ~80 to 110 ka (Table 2). Consequently, on those two sites corals of Holocene age developed on ancient reef surfaces that remained from marine isotope stage 7 and 5.

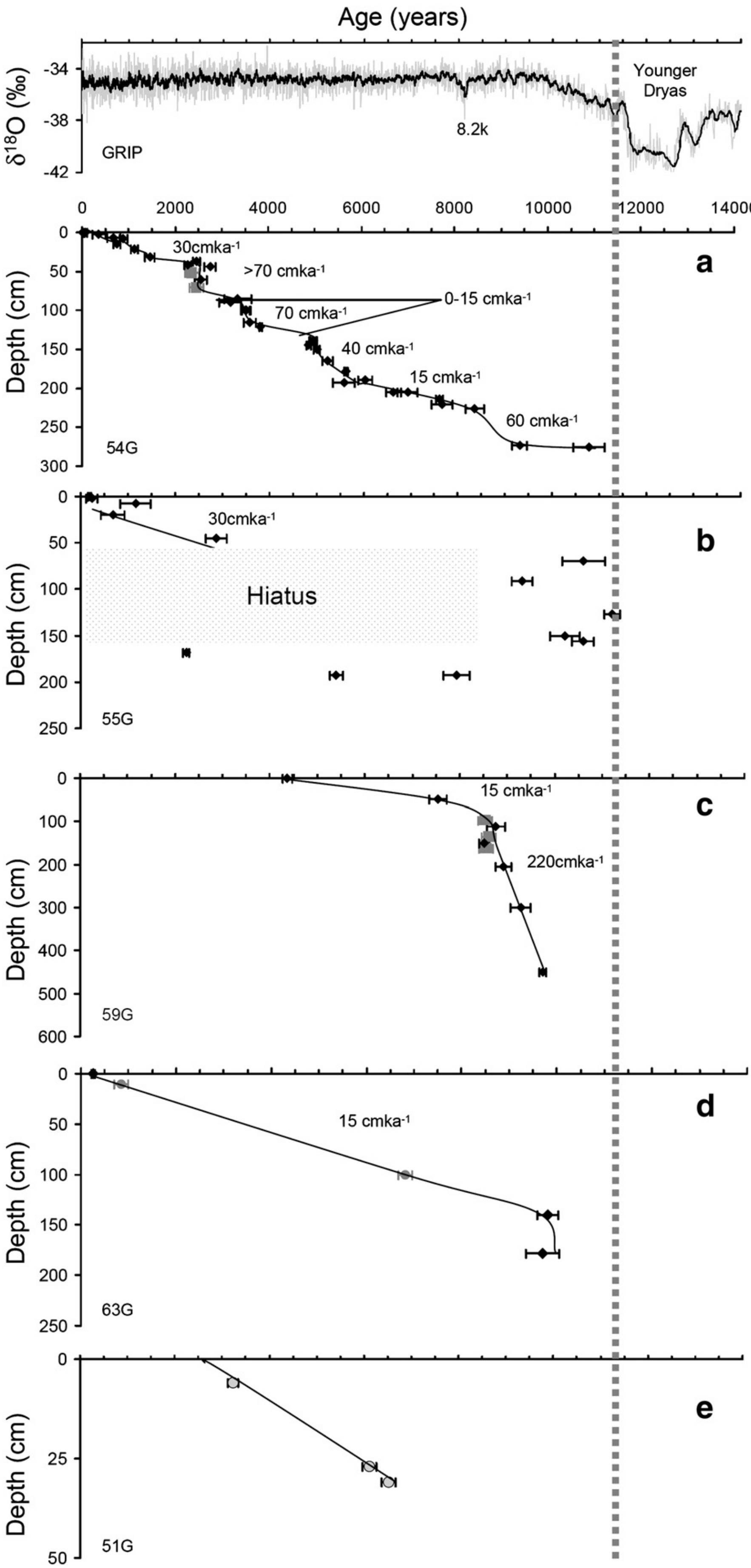
4.2. Mound evolution during the Holocene

The most detailed Holocene record is established in gravity core 54G from Rockall Bank showing almost continuous but irregular growth of mainly *Lophelia pertusa* corals over the past 11 ka until present (Fig. 3). Coral fragments have been recovered on top of a hard-substrate (lithified carbonate) consequently corals of pre-Holocene origin were not recovered. Based on the relationship of coral ages and depth in the core we can estimate VMGRs. In core 54G VMGRs are highly variable and rang from <15 cm ka^{-1} to >70 cm ka^{-1} (Fig. 3a). The initial start of the reef after the Younger Dryas cold reversal (12.9–11.5 ka calibrated BP) is followed by a period of rapid mound growth between 9.5 and 8.5 ka (~60 cm ka^{-1}), which is unfortunately poorly dated so far (Fig. 3a). Next, VMGR is 4 times lower (~15 cm ka^{-1}) until 6 ka followed again by a period of more rapid coral fragment accumulation from 6 to 5 ka. The VMGR is close to zero or at least strongly reduced thereafter at 4.4 ± 0.4 ka, 2.9 ± 0.1 ka, and at 1.9 ± 0.3 ka. In between those intervals of almost absent coral fragment deposition, VMGR are high (40 to 70 cm ka^{-1}). Finally during the past 1.5 ka the reef evolves again at a rate of ~30 cm ka^{-1} (Fig. 3a).

Core 55G located in close vicinity of core 54G but at shallower depth of 640 m reveals similar coral ages, but a strongly disturbed age–depth relationship (Fig. 3b). Note that the core is composed of mainly *Madrepora oculata* fragments, a species which construct a thinner and likely more unstable open framework. The dominant age reversal recorded between 70 and 156 cm core depth demonstrates clearly coral debris redistribution likely through physical erosion. This layer corresponds to a core section filled mainly with “coral rubble” (small broken fragments barely visible in the X-ray images) (Fig. 2 - [3]). Corals in this section are about 9.4 ka to 11 ka old and are thus of equal ages compared to corals obtained at the base of core 54G. Consequently, we may assume that the *M. oculata* reef started to develop on top of exposed hardgrounds about 11 ka ago as did the *Lophelia pertusa* reef at deeper water depth (core 54G). During the Holocene, corals have than been displaced as a consequence of physical mound erosion. Below this section corals seem in chronological order and the few fragments dated reveal ages between 8 and 3 ka, but the resulting VMGRs are <5 cm ka^{-1}. On top of the hiatus corals are again in chronological order with one age at ~2.88 ka and several between 1 and 0.2 ka. The resulting VMGR is approximately 30 cm ka^{-1}, thus similar to the one observed for the topmost 50 cm in nearby core 54G. Therefore, during the past 1 ka corals did well develop on both sites until present.

Within Porcupine Seabight coral rich sediment sequences underneath the most recent coral growth interval have been recovered, with the exception of core 59G situated in the Magellan Mound Province. Within this last core 59G from Mound Perseverance corals appear ones more on top of a lithified carbonate layer at 5.35 m core depth about 9.7 ka to 10 ka ago (Fig. 3c). Vertical mound growth is continuous but irregular again between 10 ka and 4.3 ka, with a high VMGR of up to 220 cm ka^{-1} between 9.8 ka and 8.5 ka, followed by a lower VMGR of ~25 cm ka^{-1} between 8 ka and 4.3 ka (Fig. 3c), respectively. Today, this mound is known to have an actively growing but patchy coral reef ecosystem (Olu Le-Roy and Shipboard Scientific Crew, 2002) and therefore the mid-Holocene end of coral growth recorded here does not reflect a shut down of coral growth lasting for 4.3 ka. This sudden stop of local mound evolution is a result of missing accessibility (loss of the top sediment during coring), reef erosion through deep trawling as found on some mounds of the Magellan Mound province (Fossa et al., 2003), or a collapse of the recent coral framework such as observed in sediment core 55G from Rockall Bank. In this case corals are lost rather than re-deposited. Thus, we observe a similar timing for the start of the coral ecosystems on SW Rockall Bank and within the Magellan Mound Province in Porcupine Seabight. The reefs develop quickly between 9.5 and 8 ka and then between 8 and 4.3 ka the local reef activity declined.

In the southern Porcupine Seabight corals have been recovered from Thérèse Mound (core 63G) and from Challenger Mound (core 51G) both within the Belgica Mound Province. The upper most core sections again reflect Holocene coral development, but the temporal resolution obtained here is very limited and the respective core sections are small; 120 cm depth in core 63G and solely 32 cm depth in core 51G (Fig. 3d and e). In core 63G corals build their framework on top of an exposed ancient reef that dates back to some 250 ka (Table 2). But coral ages are around 10 ka (Fig. 3) just on top of the ancient reef. Hence, ones more the timing of corals is similar to the one within the Magellan Mound Province and the one in SW Rockall Bank. The first appearance of corals in core 63G is intersected with remains of glacial sedimentation containing a dropstone (between 160 cm and 178 cm depth), resulting from early Holocene iceberg discharge along the Irish margin. Whether the growth of corals was then continuous or irregular cannot be decided from the scares ages. VMGR from 10 ka to present amounts to ~15 cm ka^{-1} and is thus on the lower end of those observed on the other mounds. Thérèse Mound


Age (years)
δ18O (‰)
-34
-38
-42
GRIP
8.2k
Younger Dryas
0
2000
4000
6000
8000
10000
12000
14000
Depth (cm)
30cmka-1
>70 cmka-1
0-15 cmka-1
70 cmka-1
40 cmka-1
15 cmka-1
60 cmka-1
54G
a
Hiatus
55G
b
15 cmka-1
220cmka-1
59G
c
15 cmka-1
63G
d
51G
e

is known for its presently active *Lophelia pertusa* and *Madrepora oculata* coral ecosystem, which reaches from the south-western flank to the top with dense coral populations (Olu Le-Roy, 2004). Consequently at 880 m water depth coral growth conditions have been favourable for the past 10 ka, but whether or not certain time intervals are more or less important can yet not be resolved. Challenger Mound (core 51G) situated a few hundred meters higher in the water column also shows Holocene coral development, but throughout a very small sedimentary interval of solely 32 cm. Ages progressively increase from 31 cm to the top. Corals appear around 6.3 ka on the sampled location and thus by far later than at the other investigated Mounds (Fig. 3e). In addition, the VMGR derived from the coral age–depth relationship is solely ~8 cm ka^{-1} and corals “disappeared” on the investigated spot most likely about 3000 years ago as today Challenger Mound is covered entirely with dead coral rubble (Williams et al., 2006). Interestingly, corals appear directly on glacial sediments containing ice rafted debris and thus a hard-substrate is missing, which certainly did not favour coral settlement. Corals situated within the second coral fragment rich sediment section between 220 and 250 cm depth date back to marine isotope 5 (Table 2).

5. Discussion

Lophelia pertusa and *Madrepora oculata* corals build their open framework with high individual and colony growth rates of tens of millimeters per year (meters per ka) (Mikkelsen et al., 1982; Freiwald et al., 1997; Mortensen and Rapp, 1998; Gass and Roberts, 2006). This framework acts as sediment trap for horizontal and lateral sediment fluxes. Overall rates of mound growth are much lower than the ones of the open framework construction (de Haas et al., 2009), but largely outpace background sedimentation (de Haas et al., 2009; de Mol et al., 2002). Dating of coral fragments has revealed that the past 11 ka are in general favorable for coral growth. Older coral reef growth episodes occurred during previous climate warm stages such as marine isotope stage 5 and 7 (Rüggeberg et al., 2003; Dorschel et al., 2005; Frank et al., 2005; Kano et al., 2007; Rüggeberg et al., 2007; Eisele et al., 2008; Mienis et al., 2009) (Table 2). Mound records are thus often discontinuous in particular between coral growth intervals and in many cases glacial sedimentation is missing or almost absent (Rüggeberg et al., 2003; Dorschel et al., 2005; Frank et al., 2005; Kano et al., 2007; Rüggeberg et al., 2007; Eisele et al., 2008; Mienis et al., 2009). Yet, no corals of glacial environments have been discovered on and off mounds in Porcupine Seabight and on SW Rockall Bank (Rüggeberg et al., 2003; Schröder-Ritzrau et al., 2005; Dorschel et al., 2005; Frank et al., 2005; Kano et al., 2007; Rüggeberg et al., 2007; Eisele et al., 2008; Mienis et al., 2009). Our results largely reinforce the scares previous observations but we further achieved a time resolution allowing the study of secular variations of coral growth on mounds during the most recent period of mound development: the Holocene.

Northern Hemisphere warming during the early Holocene and the establishment of similar to modern hydrological conditions in the near thermocline waters are accompanied by an increase in surface productivity and a retreat of the polar fronts towards more northern locations. Consequently, productivity increases as recorded by a 3 to 4 fold increase in planktonic foraminifera abundance and $CaCO_3$ content of sediments from the Faeroe Margin following directly on the Younger Dyras cold reversal (Abrantes et al., 1998) and reduced terrigeneous sediment fluxes (Manighetti and McCave, 1995). Following upon the Younger Dryas cold reversal at about 11 ka corals re-appear on mounds of Porcupine Seabight and on mounds of SW Rockall Bank and likely also further to the North synchronous to environmental changes recorded in sediments. Over the course of the Holocene, productivity is then unlikely to change in a dramatic way, and millennium scale oceanographic changes (Bond et al., 2001) are unlikely to alter dramatically the local hydrodynamic regime near mounds driven by strong bottom water currents and tidal waves (White et al., 2005; Dorschel et al., 2007; Mienis et al., 2007). Moreover, deep-water corals develop today over a large range of environmental conditions from the Mediterranean Sea to the northern margin of the Norwegian shelf.

The temporal variability of the local VMGR is the product of coral open framework construction–skeleton degradation–bioerosion–sediment trapping and compaction. Thus, VMGRs are related to coral population density through time. Low coral growth activity will provide numerous exposed sediment surfaces that are subject to erosion in an environment of high bottom water currents, while densely populated reefs produce more degraded coral fragments on the seafloor that cover the sediment surfaces and which will pile up on top of each other. Furthermore, a well developing open coral framework will more efficiently trap sediment. Hence, we therefore interpret VMGRs as representative of densely populated reefs, while low rates or absent coral ages are likely indicative of reduced coral activity and mound erosion.

All sites reflect a local environment, but we can test whether the overall coral age pattern of all investigated mounds is similar and whether changes of the local VMGRs add evidence to such a regional time framework. Fig. 4 presents all U-series ages for SW Rockall Bank and Porcupine Seabight including a few previously published ages for both regions (Schröder-Ritzrau et al., 2005; Eisele et al., 2008; Mienis et al., 2009). A total 88 ages are presented. Core 54G from SW Rockall Bank ($n = 36$) dominates the age pattern and clearly marks out numerous periods of missing coral ages at 0.6 ka, 1.8–2.0 ka, 4.2–4.8 ka (Fig. 3a), which we interpreted as reduced local reef activity. Moreover VMGR is reduced between 6–8 ka (Fig. 3a). The age pattern is biased in particular at the base of the core 54G in which a high VMGR was observed between 9 to 8 ka based on solely two ages (Fig. 3a). Ages from all other investigated sites, add further evidence to the temporal pattern of coral ages of core 54G. Note that this pattern cannot be biased by the sampling strategy as corals have been selected with depth in the cores first and than sampling continued to fill in the time gaps, which finally revealed the absence of corals at certain time laps. The statistical significance of Fig. 4 is obviously weak, with 88 ages out of several hundred coral fragments. However, ages and VMGRs point towards potential synchronous changes of coral population density on all investigated mounds at 1.8–2.0 ka, 4.2–4.8 ka (Fig. 4). At 8.2 ka there is also a pronounced abundance change followed by a period of reduced VMGR until 6 ka (Figs. 3, 4).

Please note that corals are unlikely to disappear, we suggest that population density decreases. This is puzzling, specifically the abundance change at 8.2 ka, an event not yet resolved in the coral age–depth plots. This may be an artifact or in fact represent a crucial moment of changing environmental conditions at thermocline depth triggered by a short “cold” climate excursion in northern Europe around 8.175 ka ago (Kobashia et al., 2007) of less than 0.15 ka duration. The observed lack of coral ages at 1.8–2.0 and 4.2–4.8 ka is even more puzzling together with the observation of high VMGR before and after those times. The Holocene is marked by millennium climate variability, but no records of productivity or current activity exist that may provide a clear hind on changes of corals environmental growth conditions. However periods lacking corals reflect warm climate conditions in the northern Hemisphere, while those having

Fig. 3. Age (ka)–depth (cm) relationship for the Holocene unit of the 5 investigated cores from SW Rockall Bank and Porcupine Seabight. The dashed line marks the timing of first coral appearance during the early Holocene. The shaded area reflects the timing of the Younger Dryas (YD) cold reversal. Top figure gives the stable oxygen isotope record of the GRIP ice core. Mound accumulation rates are shown in cm ka^{-1}.

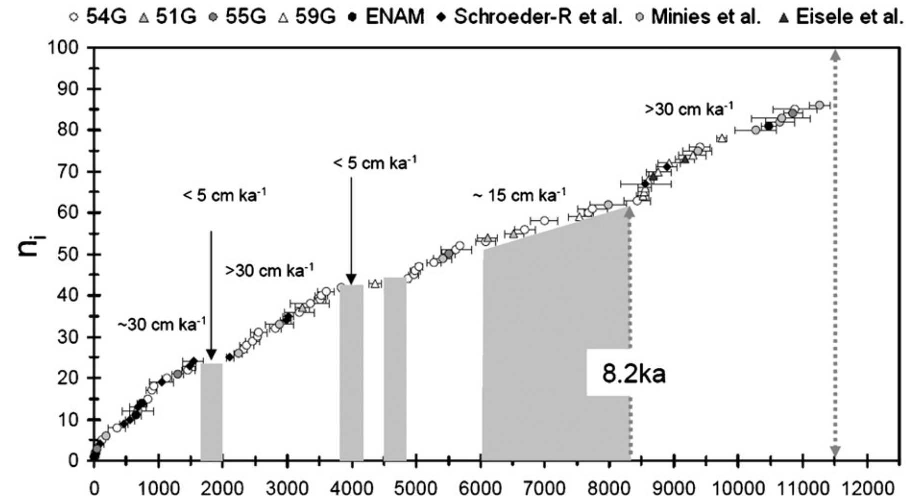


Fig. 4. Age pattern of all investigated corals from top of carbonate mounds representing different growth environments on SW Rockall Bank and within Porcupine Seabight. Several ages obtained during previous studies are included (see text).

high VMGR reflect colder climate conditions as recorded in marine and continental records (Bond et al., 2001; Vollweiler et al., 2006; Mangini et al., 2007). Moreover, periods without corals coincide with increased freshwater discharge of European rivers (Benito et al., 2008). While, glacial environmental conditions apparently inhibit reef development potentially through the absence of sufficient food or reduced bottom current activity and enhanced sedimentation, one may speculate whether particular warm periods seem to decrease coral populations as well. In this case, food supply and current dynamic is unlikely the reason as productivity and northward water mass transport is supposedly rather high during the entire Holocene compared to “cold” boundary conditions. Hence, one may speculate whether changes in vertical mixing affect the nutrient availability, or whether background sedimentation increased hindering corals to effectively filter food. Recently, Dullo et al. (2008) have shown that active coral reefs are situated on the Celtic margin and within the Norwegian Sea at a particular water density envelope of sigma-theta (σ_Θ) = 27.35 to 27.65 kg m^{-3}. Changes of the density structure at upper intermediate depth through time may cause reduced coral reproduction and thus coral reefs may decline. Thornalley et al. (2009) just revealed first evidence of changes of South Iceland density structures for the sub-surface ocean during the Holocene, suspected to be primarily related to changes in the exchange of subpolar and subtropical gyre waters. Times of reduced coral activity at 1.8–2.0 ka and between 6 and 8 ka do correspond to periods of similar surface and sub-surface densities contrasting periods of significantly different salinity values (Thornalley et al., 2009). However, for the period between 4.2 and 4.8 ka this correlation is not well evident. Upper intermediate depth water masses at Rockall Bank are well situated at the interface of both gyres today, but water masses at Porcupine Seabight are in addition influenced by MOW. Assuming a link between South Iceland density variations and coral activity on Rockall Bank slopes, we would further expect decreasing coral activity at around 3.2 and 0.9 ka, which is apparently the case in core 54G from SW Rockall Bank (Fig. 3a). Consequently, the density structure of the North Atlantic may in fact play a role in modulating reef activity throughout the Holocene, but it is unlikely the only mechanism. By far more chronological data and information on the dominant biological limits are needed to better constrain these first observations of reduced coral activity throughout Holocene warm phases. But, if those climate related patterns truly exist we need to elucidate the processes causing the decline and growth of corals on mounds as future global warming and ocean acidification imposes an important threat on the survival of such ecosystems.

6. Conclusion

U-series dating of constructional deep-water corals taken on top of carbonate mounds are powerful tools to reconstruct the temporal evolution of such ecosystems of the deep ocean. We have presented first evidence of climate driven changes of coral abundance on mounds during the present climate warm stage. Coral growth on SW Rockall Bank and within Porcupine Seabight occurs early in the Holocene almost simultaneously on several mounds and corals develop prosperously thereafter. Active reef growth result in vertical mound growth rates of >15 cm ka^{-1}, but local VMGRs can exceed 200 cm ka^{-1}. Over the past 11 ka we have found first evidence of temporal changes in reef activity as coral abundances and mound growth rates decline to less than 10 cm ka^{-1} at 1.8–2.0 ka, 4.2–4.8 ka and 6–8 ka. Moreover, the onset of the decline of corals activity coincides with a cold climate reversal at 8.2 ka.

In addition, we have confirmed that periods favourable for coral growth on SW Rockall Bank and in Porcupine Seabight are related to overall climatic warm phases (MIS 1, 5, 7) and that coral growth is largely reduced or even absent “on mounds” during cold phases such as glacial periods and even MIS 3. Thus, coral growth records follow a glacial/interglacial pattern and are discontinuous in time and space. Detailed chronological studies, however, provide first evidence that those ecosystems are sensitive to even small changes of environmental conditions such as productivity, current activity and potentially water mass density affected by climate change. Finally, the reconstruction of mound evolution during the past 11 ka provides further constrains on mound evolution on geological time scales as it clearly highlights the strong variability of the vertical mound growth rates on solely a few thousand years and on less than a few cm core depth.

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