Growth of north-east Atlantic cold-water coral reefs and mounds during the Holocene: A high resolution U-series and $^{14}$C chronology

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A B S T R A C T

We investigated the Holocene growth history of the Mingulay Reef Complex, a seascape of inshore cold-water coral reefs off western Scotland, using U-series and radiocarbon dating methods. Both chronologies revealed episodic occurrences of the reef framework-forming scleractinian coral Lophelia pertusa during the late Holocene. Downcore U-series dating revealed unprecedented reef growth rates of up to 12 mm a$^{-1}$ with a mean rate of 3–4 mm a$^{-1}$. Our study highlighted a persistent hiatus in coral occurrence from 1.4 ka to modern times despite present day conditions being conducive for coral growth. The growth history of the complex was punctuated at least twice by periods of reduced growth rates: 2.8 ka, 3.2–3.6 ka and to a lesser extent at 3.8–4.4 ka and at 4.2 ka. Timing of coral hiatuses and reduced reef growth rates at Mingulay were synchronous with those occurring across the wider northern European region, which suggests a close relationship between these ecosystems and large-scale shifts in palaeo-environmental regimes associated with changes to the North Atlantic subpolar gyre.

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1. Introduction

One of the most globally widespread cold-water corals is the reef framework-forming scleractinian Lophelia pertusa, which to date is known from all oceans except the Southern Ocean (Roberts et al., 2009). In the north-east Atlantic, Lophelia occurs preferentially along the European continental margin (de Mol et al., 2002; Kenyon et al., 2003; Wheeler et al., 2007) where it is often associated with areas of positive topographic relief such as banks, seamounts and ridges that create ideal environmental conditions (Davies et al., 2008). Local hydrodynamics are crucial for coral dispersal and recruitment, preventing corals from being smothered by sediments, and as a food supply mechanism for sessile suspension feeders such as corals (Genin et al., 1986; Frederiksen et al., 1992; White et al., 2005; Mienis et al., 2007, 2009; White, 2007; Davies et al., 2009).

Some of the best studied Lophelia reefs are those found on coral carbonate mounds, which grow hundreds of metres high and several kilometres long (Wheeler et al., 2007). Several models of coral carbonate mound ontogeny have been proposed to explain the initiation and development of such structures, which generally converge on the importance of a complex interaction between sediment accumulation and cold-water coral colonisation and growth under favourable environmental regimes (Henriet et al., 2001; de Mol et al., 2002; Dorschel, 2003; Roberts et al., 2006; Rüggeberg et al., 2007; Eisele et al., 2008; de Haas et al., 2009). The last 11 ka, as well as previous warm interglacial periods such as marine isotope stages (MIS) 5, 7 and 9, have been favourable for coral growth and thus coral carbonate mound development in the north-east Atlantic between 50°N and 70°N (Frank et al., 2009, 2011; Douville et al., 2010). To date no Lophelia from glacial periods have been found at these latitudes (Dorschel, 2003; Kenyon et al., 2003; Schröder-Ritzrau et al., 2003; Frank et al., 2004; Dorschel et al., 2007; Rüggeberg et al., 2007; Mienis et al. 2009), hence glacial conditions are assumed to be detrimental to the growth of individual coral colonies and thus to coral carbonate mounds in this region (Kenyon et al., 2003; Frank et al., 2009, 2011). Interestingly, at lower latitudes...
(between 20°N and 50°N) in the eastern North Atlantic, *Lophelia* reef growth is reported during cool events and glacial periods such as the Younger Dryas and during MIS 2, 4, 6 and 8 in the Gulf of Cádiz, Mediterranean Sea and off Mauritania (Wienberg et al., 2009, 2010; McCulloch et al., 2010; Eisele et al., 2011; Frank et al., 2011). It has been suggested that the early Holocene northern migration of the polar front would have contributed to the restoration of optimal environmental conditions for *L. pertusa* occurrence (e.g. temperature, productivity, sedimentation processes) (Pirlet et al., 2011; Frank et al., 2011). Thus, it could be hypothesised that relative changes in AMOC associated with North Atlantic subpolar gyre (SPG) dynamics have also affected coral occurrence and growth over the last 11 ka.

U-series dating of cold-water coral fragments from coral carbonate mounds on the European continental margin allows quantification of the vertical mound growth rate (VMGR), a method that reveals periods of mound build-up coupled to palaeoceanographic changes (Frank et al., 2009). Because coral framework acts as a sediment trap for both laterally and vertically advected sediment, the VMGR is consistently higher during conditions favourable for coral growth. Such conditions are met when local hydrodynamics support repeated coral recruitment events that eventually coalesce to form large reef frameworks (Genin et al., 1986; Frederiksen et al., 1992; White et al., 2005; Mienis et al., 2007, 2009; White, 2007; Davies et al., 2009; Frank et al., 2009, 2011; Douarin et al., in preparation).

Since cold-water coral mounds and continental shelves are both frequently characterised by high growth and sedimentation rates, it is assumed that shallow inner-shelf cold-water coral reefs may have especially high growth rates. Sediment cores through these structures could therefore offer the potential for high-resolution palaeoenvironmental reconstructions. Cold-water coral reefs occur on the British continental shelf in the Sea of Hebrides (also known as The Minch), 13 km east of the island of Mingulay (Fig. 1; Roberts et al., 2005). Vibrocores containing mixed sediment/coral fragments were taken through the Mingulay Reef Complex in 2007 by the British Geological Survey, and are the subjects of our present study. The aims were to (1) define the spatial and temporal evolution of the Mingulay Reef Complex, (2) estimate and compare north-east Atlantic *Lophelia* occurrence and reef/mound growth during the Holocene, and (3) establish whether large-scale shifts in palaeoenvironmental regimes have controlled coral occurrence and reef/mound growth during the Holocene.

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Core +56-08/929VE (hereafter referred to as Core 929)</th>
<th>Core +56-08/930VE (hereafter referred to as Core 930)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>56°49'19&quot;N</td>
<td>56°49'20&quot;N</td>
</tr>
<tr>
<td>Longitude</td>
<td>7°23'27&quot;W</td>
<td>7°23'47&quot;W</td>
</tr>
<tr>
<td>Depth</td>
<td>127 m</td>
<td>134 m</td>
</tr>
<tr>
<td>Recovery</td>
<td>3.61 m</td>
<td>5.25 m</td>
</tr>
</tbody>
</table>

### 2. Cold-water coral sampling

#### 2.1. Vibrocores

Coral samples from two vibrocores on the Mingulay Reef Complex were studied. The cores +56-08/929VE and +56-08/930VE (hereafter referred to as cores 929 and 930) were collected in October 2007 by the British Geological Survey during a survey on board the NERC vessel the *RRS James Cook* Cruise 015 (Stewart and Gatilff, 2008) (Table 1 and Fig. 2).

Because the cores contained coral fragments embedded in sediment, they were frozen prior to splitting to avoid disrupting the position and state of preservation of the coral fragments. Once opened and defrosted, the cores were dissected at 1 cm intervals, documenting the position and state of preservation of each coral fragment within the cores and archiving the sediment and coral fragments.

#### 2.2. Surface sample locations

Surface videograbs of coral rubble were taken from random locations at three reefs (Mingulay Reef 1, Mingulay Reef 5 North, and Banana Reef) during cruises on the research vessels *MY Esperanza* (2005), *RRS Discovery* Cruises 340b and 367 (2009 and 2011, respectively) and *RV Calanus* (2010). Three other surface samples were taken from the top of cores collected by the 2007 BGS cruise. Surface sample information is detailed in Fig. 2 and Table 3.
2.3. Hydrological setting

Waters of Atlantic origin occupy the outer parts of the continental shelf and the deeper (> 100 m) coastal waters of west Scotland (Craig, 1959; Hill et al., 1997; Inall et al., 2009). At the surface the northwards flowing Scottish Coastal Current (SCC) brings cooler and fresher waters from the Irish and Clyde Seas (Ellett and Edwards, 1983). Today L. pertusa reefs from the Mingulay Reef Complex are largely restricted to this Atlantic-origin water (Dodds et al., 2007) where strong SW–NE currents enhance the food supply to the coral reefs (Davies et al., 2009).

The Norwegian coral/sediment cores considered for this study were retrieved from Sjørnund (262 m) and Trænadjupet (315 m; López Correa et al., 2012). These two sites are bathed in North Atlantic Current (NAC) waters. The surface waters of the Norwegian shelf are characterised by the fresher Norwegian Coastal Current (NCC).

The NAC follows the boundary between the subpolar gyre (SPG) waters (fresher and cooler) and the subtropical gyre (STG; warmer and saltier) (Hátún et al., 2005). The NAC strength, direction and composition respond to SPG dynamics (Hátún et al., 2005): when the SPG circulation is stronger and presents a more pronounced east–west shape, the SPG waters influence relative to the STG waters to the NAC is increased. Conversely, when the SPG circulation is weaker and forms a more pronounced north–south shape, a lower contribution of the SPG waters relative to the STG waters to the coral sites is observed.

Cold-water corals from sediment cores on Rockall Bank (core MD 01-2454G, 747 m water depth) and in the Porcupine Seabight (MD 01-2459G, 610 m water depth) were dated by Frank et al. (2009) and analysed by Colin et al. (2010) and Copard et al. (2012). The relative contributions of water masses at these coral sites are also directly influenced by SPG dynamics (Colin et al., 2010). The relatively homogenous Atlantic water flowing through Rockall Trough (Holliday, 2003) is formed by a mixture of SPG water, Subpolar Mode Water (SPMW) (Lacan and Jeandel, 2004) and water originating in the STG: the saline Eastern North Atlantic Water (ENAW) and the saline and warm North Atlantic Central Water (NACW) (Piepgras and Wasserburg, 1987; Copard et al., 2010). The SPMW itself results from mixing of warm, saline NACW with relatively fresh, cold Sub-Arctic Intermediate Water (SAIW) (Piepgras and Wasserburg, 1987; Lacan and Jeandel, 2004).

Finally, it is important to note that the northwards flow of Mediterranean Outflow Water (MOW) and its influence at the different coral sites remains a matter of debate. Hydrological evidence suggests that MOW flows into the Porcupine Seabight (Holliday et al., 2000). However, at Rockall only episodic MOW influence occurs when the eastwards extension of the SPG is reduced (Lozier and Stewart, 2008). It has been suggested that coral larvae from the Mediterranean Sea are transported along the north-east Atlantic margin through the action of MOW (De Mol et al., 2005). Thus, this water mass would be of significant importance for coral larvae recruitment in the north-east Atlantic.

3. Methods

Coral samples were dated using two methods. The downcore samples (n=34) were dated by U-series and the surface samples were radiocarbon dated (n=19).

3.1. Sample preparation

Before dating, only relatively pristine corals were selected and ultrasonically cleaned in distilled water to avoid contamination from sediments and surface deposits. Inner and outer surfaces of corals were mechanically removed using a DREMEL tool until samples appeared completely clean under a binocular microscope in order to remove contamination from iron and manganese oxides/hydroxides and surface sample re-crystallisation of aragonite into calcite. Following physical removal of the surfaces, samples were leached with hydrochloric acid (0.1 N) and rinsed three times with MilliQ water (e.g. Schröder-Ritzrau et al., 2003).

Once cleaned, a piece of each coral fragment was powdered using an agate mortar and pestle and screened by X-ray diffraction (XRD) at the University of Edinburgh for aragonite content and purity. Radiocarbon and U-series analyses were undertaken on fragments with > 99% aragonite content.

3.2. U-series dating

U and Th chemical separation and mass spectrometry were carried out at the NERC Isotope Geosciences Laboratory (NIGL),
British Geological Survey, Keyworth. Samples were ultrasonicated in dilute HNO₃ and MilliQ water before dissolution in 15 M HNO₃. Dissolved samples were spiked with a mixed ²³⁹Th-²³⁴U tracer calibrated against gravimetric solutions prepared from CRM 112a U metal and Amers Laboratory high purity Th metal. All acids were prepared by double sub-boiling-distillation starting with RomilSpA grade stock. Pre-concentration by Fe co-precipitation prior to U-Th separation used a Fe in 1 M HCl solution prepared from Puratronic Fe nitrate and the initial chemical separation of U and Th on 0.6 ml columns using AG-1 × 8 anion resin followed procedures established by Edwards et al. (1988). Separated Th aliquots were further purified using a second pass through AG-1 × 8 columns, while separated U was purified on UTEVA columns following Andersen et al. (2008). Pilot U isotope data were obtained on a Thermo Triton thermal ionization mass spectrometer (TIMS) employing a Mascom SEM and RQO, U was loaded as a nitrate on double zone-refined Re filament assemblies. Mass bias was monitored via replicate CRM 112a analyses, and mass gain was corrected during sample analysis using ²³⁵U/²³⁸U measured sequentially on static SEM/Faraday and Faraday/Faraday detectors. Corresponding Th data were obtained on a Nu instruments NuHR multicollector inductively coupled mass spectrometer (MC-ICP-MS). The bulk of the U and Th data for this study, however, were obtained on a latterly acquired Thermo Neptune Plus MC-ICP-MS-MC. Samples were introduced with an Aridus II desolvating nebulizer in 0.2 M HCl–0.05 M HF, while sample washout used sequential 0.25 M HCl-0.1 M HF and 0.2 M HCl-0.05 M HF following Andersen et al. (2008). U mass bias and SEM/Faraday gain correction of unknowns was based on standard bracketing; exponential correction for U mass bias was determined by analysis of CRM 112a spiked with a ²³⁴U/²³⁸U tracer (IRMM 3636), while SEM gain was monitored using the static SEM/Faraday measurement of ²³⁵U/²³⁸U on mass bias-corrected unspiked CRM 112a data. On peak zero, hydride and tailing corrections followed Hiess et al. (2012). Accuracy (within 0.1%) and reproducibility (within 0.2%) were monitored by replicate ²³⁴U/²³⁸U analyses of Harwell uraninite HU-1. Mass bias and SEM gain for Th measurements were corrected using an in-house ²²⁹Th–²³²Th–²³⁵Th reference solution calibrated by ICP-MS against CRM 112a. Total ²³⁸U and ²³⁵Th blanks were <10 pg and <4 pg, respectively, during this study and were negligible relative to the sample U and Th. Data were reduced using an in-house Excel spreadsheet and ages calculated with Isoplot version 3 add-in (Ludwig, 2003a) following Ludwig (2003b) using the decay constants of Cheng et al. (2000). Correction for ²³⁹Th from seawater followed Frank et al. (2005) (²³⁹Th/²³⁵Th=10±4). Quoted uncertainties (Table 2) for activity ratios, initial ²³⁴U/²³⁸U, and ages are given at the two sigma level. These included a 0.2% uncertainty calculated from the combined ²³⁶U/²²⁹Th tracer calibration uncertainty and measurement reproducibility of reference materials (HU-1, CRM 112a, in-house Th reference solution) as well as the propagated uncertainties from the seawater Th correction and measured isotope ratio uncertainty.

3.3. Radiocarbon dating

Nineteen surface Lophelia fragments were prepared to graphite at the NERC Radiocarbon Facility (East Kilbride). The samples were chemically etched to remove the outer 20% (by weight) of each coral fragment by controlled hydrolysis using 0.02 M HCl. The samples were rinsed, dried and homogenised. A known weight of the pretreated sample was hydrolysed to CO₂ using 85% orthophosphoric acid (H₃PO₄) at room temperature. An aliquot of CO₂ from each sample was taken to measure δ¹³C (Table 3) on a dual inlet stable isotope mass spectrometer (VG OPTIMA) and was representative of δ¹³C in the original, pre-treated sample material. The remaining CO₂ was converted to graphite by a two-stage reduction over heated Fe and Zn (Sloot et al., 1987).

The δ¹³C in the samples was measured at the Scottish Universities Environmental Research Centre (SUERC) AMS Laboratory and corrected to δ¹³Cvent=−25 using δ¹³C values provided in Table 3. Results are reported as conventional radiocarbon ka BP (relative to AD 1950) at the ±2σ level for overall analytical confidence and as calibrated age-ranges using the OxCal 4.1 calibration software (Bronk Ramsey, 2009) with the Marine 09 dataset (Reimer et al., 2009). A local marine reservoir correction (∆R) of 0 was applied to sample ages <1 ka, in line with the findings of Harkness (1983) and samples with older ages were corrected using ∆R=−79±17 yr as per Ascoth et al. (2004).

4. Results

4.1. U-series chronology

The downcore U-series dates acquired for this study are displayed in Table 2. Mingulay corals contained between 2.8 and 3.8 ppm of uranium. A total of 13 and 21 U-series dates were obtained from cores 929 and 930, respectively. These data permit the construction of age/depth profiles for the two cores (Fig. 3).

The δ²³⁴Uinitial values of the samples considered in this study ranged from 142.9±2.4‰ to 150.0±3.5‰ (2σ uncertainties). These values are indistinguishable from published δ²³⁴U values of seawater (149.6±3‰ 15D, n=23; Delanghe et al., 2002; 146.6±2.5‰ 15D; Robinson et al., 2004) and are close to modern cold-water coral values from the Pacific, Atlantic, Indian and Southern Oceans sampled from various water depths (145.5±2.3‰, 2σ, n=20; Cheng et al., 2000). ²³⁴Th values for all corals (Table 2) were relatively low at <0.48±0.07 ppb, supporting the notion that most of the corals analysed here are primarily aragonitic (Frank et al., 2004). Finally, one coral fragment collected alive was dated in duplicate, with measured ages of 22±13 a and 21±5 a. Assuming the growth rate of an individual coral is 15–17 mm a⁻¹ (Orejas et al., 2008), and that the uppermost calcites were removed during the cleaning procedure, the 1–2 cm of the coral fragments analysed provide very accurate and reproducible ages giving us confidence in our fossil data.

After screening by δ²³⁴U values, six dates were out of stratigraphic sequence (samples 6, 22, 28, 30, 31, and 33; Table 2). Three hypotheses could explain this issue: (1) collapse and mixing of coral fragments from the same colony, (2) older material from adjacent reefs has been reworked and transported to the actively accumulating reef site, or (3) entrainment of young coral fragments into the deeper core section (de Haas et al., 2009; Frank et al., 2009). Samples 22, 31 and 33 were significantly older than would be interpolated from the U-series age/depth relationship (Fig. 3). This indicates potential reworking and transport of older material from an adjacent reef. The base of the reef (the last 100 cm of core 930) included two age reversals towards older ages indicating that at the early stages of coral reef growth the height of the reef allowed more frequent transport of older material. These ages were not included in our growth rate estimations. Samples 6, 28 and 30 presented significantly younger ages given the U-series age/depth relationship, implying that the younger material may have become entrained during sampling. Note that two samples (27 and 29) from the same stratigraphic layer as samples 28 and 30 present ages in agreement with the stratigraphic sequence. Thus, we have only considered samples 28 and 30 for the rest of our study.

4.2. Mingulay complex growth rates

Sufficient reliable high-resolution U-series data were acquired to characterise cold-water coral reef growth. With the exception of a few age inversions, 80% of the coral fragments present along the cores from the Mingulay Reef Complex were in stratigraphic order.
All fragments dated in this study were mid- to late-Holocene. The stratigraphic model of core 929 exhibited ages from 3.41 to 4.29 ka and between 1.75 and 3.64 ka for core 930. The oldest L. pertusa fragment age at 7.68 ka was measured from one out of stratigraphic order sample in core 930. Core 929 had a vertical growth rate averaging 4 mm a\(^{-1}\), although this varied between 0.5 and 12 mm a\(^{-1}\) (Fig. 3). Three major peaks in growth rate are centred at 3.7, 4.2, and 4.9 ka. The spike in growth rate reached 19.5 mm a\(^{-1}\) as estimated from one U-series age presenting an error of 0.1 a, therefore, it is possible that this value was slightly underestimated. Core 930 showed an average growth rate of 3 mm a\(^{-1}\), ranging from 0.6 to 10 mm a\(^{-1}\) (Fig. 3).

Two major reductions in growth rate (< 2 mm a\(^{-1}\)) were observed at 1.75–2.8 ka and 3.2–3.6 ka. Two minor reductions were noted in core 929 at 3.8–4 ka and at ~4.2 ka. The growth rate decline at ~3.5 ka was recorded in both cores, suggesting that coral growth was affected over a wider area across the reef complex.

4.3. Radiocarbon chronology

The age of the core tops (1.7 ka and 3.5 ka) were close to previously published radiocarbon dates from the surface of Minigulay Reef 1 and Milingulay Reef 5 (North), 3.54 ± 0.06–3.86 ± 0.03 ka BP, respectively (Roberts et al., 2005). These samples revealed that dead coral rubble found adjacent to living corals was much older than anticipated. Data from the 21 surface corals suggested that all samples were late Holocene (0–4.2 ka; Table 3 and Fig. 4). The ages of dead coral spread more or less evenly across the period from 1.4 to 4 ka, with some evidence for clusters of ages 1.4 to 2.05 ka, 2.77 ka, 3.16 to 3.25 ka, 3.6 ka, 3.8 to 4 ka and 4.2 ka. This could indicate episodic mortality events and/or reductions in reef growth. Most importantly the absence of any coral between modern times and 1.4 ka strongly suggests that Milingulay reef growth was significantly disrupted sometime around 1.4 ka ago.

5. Discussion

5.1. Holocene reef growth rates

Our data can be compared with other intensively dated coral-bearing sediment cores from the north-east Atlantic (Frank et al., 2009; López Correa et al., 2012; Fig. 5). We chose to only consider L. pertusa dating in light of the probability that each cold-water coral species has specific environmental requirements.

The most intensively dated coral/sediment cores from mounds on the Celtic margin are cores MD 01-2454G from Rockall Bank and MD 01-2459G from the Porcupine Seabight (Frank et al., 2009). U-series dating revealed a VMGR from about 0.05 to 2.2 mm a\(^{-1}\) with values on average ~0.2 mm a\(^{-1}\) (Frank et al., 2009). By comparison, Holocene growth at Milingulay was on average 15–20 times greater (Fig. 5). The lower resolution of the dating around one U/Th date every 450 yr from the Celtic Margin cores (MD 01-2454G and MD 01-2459G) might have averaged out some of the peaks in growth rates, but probably not enough to...
explain the difference in VMGR with the Mingulay cores, which had on average one date every 100 a.

‘Single generation’ cold-water coral reefs (such as those within the Mingulay Reef Complex) are distinguished from larger ‘coral carbonate mounds’ in that they result from single intervals of growth rather than from multiple periods of reef growth (e.g. during interglacials) with periods of intervening sedimentation (e.g. during glacials; Roberts et al., 2006, 2009). Within the north-east Atlantic, most single generation Holocene-age cold-water coral reefs reported to date are from the Norwegian continental shelf and fjords (Hovland et al., 1998; Lindberg and Mienert, 2005; Lindberg et al., 2007; López Correa et al., 2012). The first estimates of growth rates from reefs on the Sula Ridge were about 2–3 mm yr⁻¹ (Freiwald et al., 1999). Recently, studies from Stjernsund and Trænadjetp coral-sediment cores (POS-325-472 and POS-325-359, respectively) revealed growth rates of 2–6 mm a⁻¹ (López Correa et al., 2012). The average growth rates measured from the Mingulay Reef Complex were more comparable with those from the Norwegian shelf, but were still far higher and more variable with growth up to 12 mm a⁻¹ (Fig. 5). However, this might be at least partially explained by the greater number of dates taken during the present study from the Mingulay reefs, revealing also high local reef growth rates, compared to the earlier studies. Overall our study at Mingulay confirms the trend for exceedingly rapid Holocene growth rates compared with bathyal coral carbonate mounds examined in the Rockall and Porcupine regions.

5.2. Holocene Lophelia occurrence in the north-east Atlantic

During the Holocene, centennial to millennial fluctuations in the influence of the SPG that affect the North Atlantic inflow and wider North Atlantic climatic conditions have been documented (Thornalley et al., 2009; Colin et al., 2010; Copard et al., 2012). These fluctuations had potentially adverse effects on Atlantic Ocean ecosystems (e.g. Stenseh et al., 2003). During the Holocene, changes in coral reef and mound growth rates have already been attributed to climate driven changes (Frank et al., 2009; López Correa et al., 2012). In this section we compile all the available L. pertusa ages from the north-east Atlantic alongside reef and mound growth rates to test whether the relative changes in the North Atlantic inflow to the coral sites could explain variations in L. pertusa occurrence throughout the entire region (Fig. 6). We will especially focus our attention on the last 5 ka as the high resolution dating of the coral/sediment cores from the Mingulay Reef Complex may allow short-scale oceanic changes to be identified from changes in growth rates and coral occurrence.

5.3. Present–2 ka: decline of Lophelia

From 2 ka to present, lower growth rates were observed across the entire Mingulay Reef Complex, along with a significant decrease in coral occurrence as evidenced by the total number of ages for the north-east Atlantic (Fig. 6). At the Mingulay Reef Complex, we can exclude a bias in sediment core sampling strategy as 21 additional dates at the surface of the reef were obtained. There was a clear gap with no evidence of coral growth between 1.4 ka and the present, despite the fact that dense occurrences of live L. pertusa are documented today at the complex (Roberts et al., 2005, 2009). Interestingly, in Norway there is an interruption of reef growth at 1.6 ka recorded from coral/sediment cores and very little evidence of coral occurrence from 1.2 ka until recent times, and like Mingulay, corals occur there today (Mikkelsen et al., 1982; Hovland et al., 1998; Lindberg and Mienert, 2005; López Correa et al., 2012). Very few coral samples from the north–east coral carbonate mounds were dated from 0.8 to 2 ka (Frank et al., 2009; Schröder-Ritzrau et al., 2005).
The compilation of coral mound growth rates from Rockall Bank and the Porcupine Seabight also shows a reduction at 0.9 ka (Frank et al., 2009). However, this is not evident only from considering the age model of core MD 2454G, where a growth rate of 0.2 mm a$^{-1}$ was estimated. This may highlight the need to perform a more intensive downcore dating strategy to reveal more short-term climatic events that could have impacts on coral occurrence and/or to compile growth rate estimates from several locations.

Several climatic anomalies over the last 2 ka have been documented that tend to group into three major episodes: 0.1–0.7 ka, 1–1.2 ka, and 1.4–1.8 ka (Mayewski et al., 2004; Thornalley et al., 2009; Wanner et al., 2011; Copard et al., 2012). A drop in neodymium isotopic composition ($\varepsilon$Nd) recorded from Rockall Bank cold-water corals highlighted a stronger influence of SPG water from 0.8 to 1 ka (Copard et al., 2012). Further north, the decreasing near-surface salinity and temperature at 1 ka suggested an enhanced influence of the SPG water to the NAC (Thornalley et al., 2009). Thus, despite the distinct temporal resolution of the records, they all imply an abrupt enhanced influence of the SPG water relative to the STG water to the coral sites. This oceanic shift could have significantly impacted cold-water coral growth and may thus explain the occurrences of Lophelia within the north-east Atlantic (Fig. 6). Interestingly, Thornalley et al. (2009) reported that SPG strength declined 1.8 ka. Unfortunately, a gap in the SPG records from Rockall Bank does not allow us to easily confirm this.
interpretation (Fig. 6). However, we cannot exclude that this would have contributed to destabilising cold-water coral ecosystems since our results show decreasing coral occurrence and growth within the north-east Atlantic from 1.8 ka (Fig. 6). We hypothesise that the succession of abrupt oceanic shifts reported over the last 2 ka linked to the increasing influence of SPG circulation significantly destabilised this ecosystem.

5.4. 2 ka–5 ka: optimum conditions for Lophelia?

On Rockall Bank and in the Porcupine Seabight, three major high growth rate (> 1 mm a^{-1}) events were recorded at about 2.5, 3.4 and 5 ka. Our records from inshore western Scottish waters also suggest persistent occurrence of L. pertusa and relatively high growth rates as early as 4.3 ka lasting until 2.7 ka. This period is however punctuated by a few events of lower occurrence/growth rates at 2.7 ka, 3.2–3.6 ka and to a lesser extent at 3.9 ka and 4.2 ka (Fig. 6). The same trend has been observed in Norway, with two major peaks of growth recorded at 3–3.2 ka and 3.3–3.7 ka (López Correa et al., 2012). These coral records suggest that overall the 2–5 ka period was particularly favourable for Lophelia growth in the north-east Atlantic despite occasionally less intense coral growth across all locations at 2.6–2.8 ka and 3.2–3.6 ka.

During the late Holocene, the upper-intermediate waters from around Rockall were characterised by higher εNd values indicating less influence of the SPG water compared to the rest of the Holocene (Colin et al., 2010). Those conditions appear to have been relatively favourable for cold-water coral reef growth. However, the late Holocene has also been characterised by rapid climate changes (Bond et al., 2001; Mayewski et al., 2004). A small increase in the influence of the SPG was recorded in the North Atlantic at about 3.4 ka (Thornalley et al., 2009; Colin et al., 2010). This event seems to have affected coral growth within the Mingulay Reef Complex as reflected by a decrease in growth rates recorded in between 3.2 and 3.6 ka. In Norway, a cooling event was also reported at 3.3 ka in Stjernsund and associated with an overall cooling of the NAC that could also explain the decline in reef growth rate reported in this area (López Correa et al., 2012; Joseph et al., in press). The rapid climate change occurring ~2.7 ka ago is probably one of the best documented periods of rapid climate change in the late Holocene (Mayewski et al., 2004). This relatively cold event has been associated with a shift in the SPG circulation (Thornalley et al., 2009). Such changes have apparently significantly affected shallower north-east Atlantic cold-water coral reefs by reducing their growth and could also partly explain the lack of a εNd record due to a lower availability of coral samples from Rockall Bank and Porcupine Seabight (Colin et al., 2010; Fig. 6). At Mingulay this event is clearly highlighted by an abrupt decrease of coral reef growth rate and no evidence of intense coral growth has been recorded in this area from then until the present day. For these shallower coral reef systems (Norway and Mingulay) ocean dynamics did not allow the system to fully recover while coral carbonate mounds from the Celtic margin showed a faster recovery.

5.5. Early and mid Holocene Lophelia occurrence

No corals older than 4.3 ka were dated from Mingulay, with the exception of one out of sequence coral fragment dated at 7.7 ka, the oldest age from the complex so far. Despite potential sampling biases for this period, the data reveal that L. pertusa occurrence and growth within the north-east Atlantic are in agreement with the global hydrological changes over this period (Fig. 6). Therefore, the compilation of coral data from this region should enable us to investigate the long-term changes in L. pertusa occurrence and growth from 5 to 11 ka.

Holocene L. pertusa occurrence within the north-east Atlantic appears to have started as early as 11.3 ka in Rockall Bank and 10.9 ka in Stjernsund (Norway) (Frank et al., 2009; López Correa et al., 2012). Subsequently, high growth rates were measured at 9.7–10 ka (> 3 mm a^{-1}) in the Porcupine Seabight. Rockall Bank sediment cores show relatively high growth rates (0.6 mm yr^{-1}) between 8.5 and 9.5 ka (Frank et al., 2009). In Stjernsund, high growth rates (> 6 mm a^{-1}) were similarly recorded from 9.4 to 9.8 ka.

The early Holocene (11–8 ka) was characterised by maximal orbital forcing (high summer insolation in the Northern Hemisphere). However, the large North Hemisphere ice sheets and major sea level changes still had a significant influence on climate, water mass organisation and circulation (e.g. Wanner et al., 2008). The growth rate records we discuss from the coral reef frameworks in the early Holocene suggest processes allowing the return of L. pertusa ecosystems to high latitudes in the north-east Atlantic (50–70 N) and relatively favourable environmental conditions for coral settlement and growth (Frank et al., 2009, 2011; López Correa et al., 2012). This could be explained by the early establishment of near-modern North Atlantic circulation that produced suitable hydrological conditions (temperature, productivity, sedimentation processes) for coral occurrence (Frank et al., 2004, 2011; Thornalley et al., 2009, Colin et al., 2010; Pirlet et al., 2011; López Correa et al., 2012; de Mol et al., 2005; Fig. 6).

Data available from the Norwegian shelf coral/sediment cores show a long-term hiatus from 3.9 to 9.4 ka (López Correa et al., 2012). However, Lophelia samples aging from 6 to 8 ka were reported within the area (Mikkelsen et al., 1982; Hovland et al., 1998; Lindberg and Mienert, 2005). The available coral/sediment cores from the area did not allow us to report the relative occurrence of Lophelia during this period, but surface sample dating revealed its presence from 6 to 8 ka. Rockall Bank and Porcupine Seabight cores presented very low growth rates from 6 to 7.6 ka, followed by increasing VMGR until 5 ka (Frank et al., 2009).
Cold-water coral based εNd records show a strengthened mid-depth SPG influence to Rockall Bank from 5 to 8 ka (Colin et al., 2010). In response, the Irminger Current was significantly reduced but a constant influence of NAC to the Northern Norwegian water remained (Koç et al., 1993; Colin et al. 2010; Thornalley et al., 2009; Joseph et al., in press). The stronger influence of SPG water to Rockall Bank may have impacted on the relative occurrence and growth rate of coral mounds from Rockall until 6 ka. Along the Norwegian shelf however, the constant influence of the NAC water would have maintained a suitable environment for coral growth until 6 ka. Although the number of cold-water coral ages covering this period remains limited, long-term changes in L. pertusa occurrence and growth seem coherent with local hydrological changes.

5.6. The last century

Dense occurrences of living L. pertusa corals and reef framework are presently observed at the Mingulay Reef Complex, which indicate that the environmental conditions are conducive for coral growth in this area (Roberts et al., 2009). Coral εNd data from Rockall Bank suggest that the last century was mostly dominated by a strong SPG (Copard et al., 2012; Fig. 6), but that higher resolution records are needed to confirm these observations. However a weakened SPG has been documented at interannual to interdecadal time scales including the last two decades (Håkkinen and Rhines, 2004; Hátún et al., 2005; Sherwin et al., 2012), which supports our hypothesis that environmental conditions associated with the SPG are more conducive to coral growth in the north-east Atlantic. Large centennial time scale
shifts in SPG dynamic seems to have influenced coral occurrence and reefs/mounds growth during the Holocene. The mechanisms associated with the SPG variability on interannual to interdecadal and its response to the global climate change need to be better constrained to evaluate the potential impacts of SPG dynamics on coral growth.

5.7. Summary

The compilation of the L. pertusa dates from the north-east Atlantic coral reefs and mounds reveals periods of synchronous L. pertusa occurrences during the Holocene. Estimates of the growth rates provide additional information about the relative increase in coral growth due to stable and/or favourable environmental conditions.

The comparison of our data with centennial SPG circulation changes suggests that corals are very sensitive to changes in water mass properties probably associated with changes in productivity, hydrology, sedimentation processes and dispersal. We therefore propose that changes in the relative composition, intensity and direction of the Atlantic inflow during the Holocene on centennial time scale (resulting from changes in the strength and position of the SPG) have significantly influenced the growth, abundance and distribution of L. pertusa in the NE Atlantic.

In the deeper mounds off the Celtic margin, it appears that L. pertusa was almost always present during the Holocene although significant variations in growth rates imply that they are vulnerable to changes in oceanic regimes. However, our data suggest reefs from shallow inshore environments (such as in Norway and Mingulay) are even more sensitive to oceanic changes, and more time is needed for the ecosystem to recover after disruption. This could be partly explained by the local hydrology and geographic proximity to coral refuges.

6. Conclusion

High-resolution downcore dating of two cold-water coral cores from the Mingulay Reef Complex has allowed us to examine variations in reef growth rates. The average dating resolution was about 100 yr, allowing very accurate reconstruction of growth rate changes between 1.75 and 4.3 ka. Radiocarbon dates were also performed on surface samples from Mingulay reefs to map the age of the complex. By dating both downcore and surface samples we strove to avoid the effect of any patchy coral growth across the reef complex, and our results strongly implicate periods of favourable and unfavourable coral and reef growth.

The growth rates of shallow cold-water coral reefs were significantly higher than those observed for coral carbonate mounds. Growth rates for the Mingulay Reef Complex reached up to 12 mm a⁻¹ which is the highest growth rate so far found in any cold-water coral reef. Two main phases of reduction/interruption of growth in the Mingulay Reef Complex were found at 1.75–2.8 ka, 3.2–3.6 ka, and to a lesser extent at 3.8–4 ka and 4.2 ka. We found no evidence of coral growth from 1.4 ka to modern times despite more than 50 dates collected within the complex suggesting that environmental conditions were not suitable for L. pertusa growth, and this also seems to be the case for similar reefs in Norway.

From the compilation of dates from the north-east Atlantic cold-water coral reefs and mounds, the period from 2 to 5 ka was a remarkable period for L. pertusa growth in this region, albeit punctuated by less favourable events. Holocene coral reef growth rates seem to have responded synchronously over a wide region likely as a result of large-scale shifts in palaeoeceanographic regimes. We proposed here that changes in the relative strength and position of the SPG could have significantly impacted not only on the water mass properties but also food supply, sediment processes and dispersal within the coral sites, thus affecting both coral colony and reef growth. Our study further illustrates that the exceptionally high growth rates found in shallow cold-water coral reefs could provide novel records that allow very high-resolution palaeoenvironmental reconstructions of North Atlantic oceanography.

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Appendix A. Supporting information

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References


