The importance of the terrigenous fraction within a cold-water coral mound: A case study

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ABSTRACT

In the nineties, cold-water coral mounds were discovered in the Porcupine Seabight (NE Atlantic, west of Ireland). A decade later, this discovery led to the drilling of the entire Challenger cold-water coral mound (Eastern slope, Porcupine Seabight) during IODP Expedition 307. As more than 50% of the sediment within Challenger Mound consists of terrigenous material, the terrigenous component is equally important for the build-up of the mound as the framework-building corals. Moreover, the terrigenous fraction contains important information on the dynamics and the conditions of the depositional environment during mound development. In this study, the first in-depth investigation of the terrigenous sediment fraction of a cold-water coral mound is performed, combining clay mineralogy, sedimentology, petrography and Sr-Nd-isotopic analysis on a gravity core (MD01-2451G) collected at the top of Challenger Mound. Sr- and Nd-isotopic fingerprinting identifies Ireland as the main contributor of terrigenous material in Challenger Mound. Besides this, a variable input of volcanic material from the northern volcanic provinces (Iceland and/or the NW British Isles) is recognized in most of the samples. This volcanic material was most likely transported to Challenger Mound during cold climatic stages. In three samples, the isotopic ratios indicate a minor contribution of sediment deriving from the old cratons on Greenland, Scandinavia or Canada. The grain-size distributions of glacial sediments demonstrate that ice-rafted debris was deposited with little or no sorting, indicating a slow bottom-current regime. In contrast, interglacial intervals contain strongly current-sorted sediments, including reworked glacio-marine grains. The micro textures of the quartz-sand grains confirm the presence of grains transported by icebergs in interglacial intervals. These observations highlight the role of ice-rafting as an important transport mechanism of terrigenous material towards the mound during the Late Quaternary. Furthermore, elevated smectite content in the siliciclastic, glaciomarine sediment intervals is linked to the deglaciation history of the British-Irish Ice Sheet (BIIS). The increase of smectite is attributed to the initial stage of chemical weathering processes, which became activated following glacial retreat and the onset of warmer climatic conditions. During these deglaciations a significant change in the signature of the detrital fraction and a lack of coral growth is observed. Therefore, we postulate that the deglaciation of the BIIS has an important effect on mound growth. It can seriously alter the hydrography, nutrient supply and sedimentation processes, thereby affecting both sediment input and coral growth and hence, coral mound development.

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1. Introduction

Cold-water corals have been observed along the north-eastern Atlantic margin from Norway (Freiwald et al., 1999; Lindberg et al., 2007) to the Gulf of Cadiz (Foubert et al., 2008; Wienberg et al., 2009) and even as south as Mauritania (Colman et al., 2005). In the Porcupine
Seabight, southwest of Ireland (Fig. 1), these cold-water corals built large mound structures up to a height of 250 m and with a diameter of several kilometers (De Mol et al., 2002). One of these carbonate mounds constitutes Challenger Mound, located on the eastern flank of the Porcupine Seabight (Fig. 1). Challenger Mound is the first, and so far only, cold-water coral mound that was drilled down to its base during IODP (Integrated Ocean Drilling Project) Expedition Leg 307. This drilling revealed the presence of well-preserved cold-water corals (mainly Lophelia pertusa and Madrepora oculata) throughout the entire mound sequence (IODP 307 Expedition Scientists, 2005). Strontium-dating of the corals indicates that mound growth started 2.7 Ma (Kano et al., 2007) and the mound grew rapidly to a height of 130 m before growth was interrupted at ca. 1.7 Ma BP. A second coral growth phase lasted from ca. 1.0 Ma to 0.5 Ma (top ∼23 m) (Kano et al., 2007).

The mound sediments, that accumulate between the cold-water coral framework consist for more than 50% of terrigenous material (Titschack et al., 2009). However, until now, no in-depth study of this fraction has been conducted. It has been suggested that the alternation of carbonate-rich and siliciclastic sediment is steered by climate changes, with an increased siliciclastic influx and/or reduced production of biogenic carbonate during glacial intervals (Frank et al., 2009; Titschack et al., 2009). A thorough characterization of the terrigenous fraction is also crucial given that it plays an important role in diagenetic processes. Ferdelman et al. (2006) and Wehrmann et al. (2009) already concluded that the reactive iron of the siliciclastic fraction buffers the pore-water carbonate system whereas Larmagnat and Neuweiler (this issue) stated that an argillaceous sediment matrix will act as an inhibitor for organomineralisation. Furthermore, the analysis of the siliciclastic sediment fraction, and the clay minerals in particular, is important to understand the magnetic signal which is recorded in the mound (Foubert and Henriet, 2009). Moreover, the terrigenous sediment also provides crucial information on the hydrodynamics in the study site, weathering intensity on the near-by continents (Colin et al., 2006) and sedimentary processes such as ice-rafting, turbidity flows and current reworking (Huvenne et al., 2009; Revel et al., 1996a), which transport and/or erode sediments to and from the mound. The present paper aims to constrain for the first time the source areas of the siliciclastic sediment fraction in Challenger Mound as well as its mode of transport and the timing of deposition. Furthermore, changes in the terrigenous sediment are linked to climatic variations and the influence of the proximal British-Irish Ice Sheet and their effects on cold-water coral mound growth are discussed.

2. Regional setting

Cold-water coral mounds occur in three well-delineated provinces in the Porcupine Seabight (De Mol et al., 2002). Challenger Mound is situated in the Belgica Mound Province on the eastern slope of the Seabight (Fig. 1). This province comprises 47 mounds, with heights up to 190 m above the present-day seabed, and 17 buried mounds in water depths ranging from 550 to 1025 m (De Mol et al., 2002). The mounds have conical, circular or NNE–SSW elongated shapes and seem to be aligned along the bathymetric contours, parallel to the continental margin (Beyer et al., 2003). Challenger Mound is a typical conical, asymmetrical buried mound, with a more buried upslope side and a well-exposed basin-ward side (Fig. 2), which is subjected to strong bottom currents and active sediment transport as indicated by numerous bedforms (Foubert et al., 2005). The basin-ward side of Challenger still protrudes 120 m above the surrounding seabed, while the upslope side is only 30–40 m exposed. The height of Challenger Mound above its actual base is 155 m (IODP 307 Expedition Scientists, 2005). The slopes of the mound grade steeply at an angle varying...
between 21° and 33° (Foubert and Henriet, 2009). Surface observations and ROV video imagery reveal little to no live coral coverage on the mound (Foubert et al., 2005).

The general hydrography of the Porcupine Basin is described in detail in several studies (Hargreaves, 1984; Rice et al., 1991; White, 2007; White et al., 2005). The depth range of the mound provinces in the Porcupine Seabight coincides with the upper boundary of the Mediterranean Outflow Water (MOW) (800–1000 m), which is overlain by Eastern North Atlantic Water (ENAW). Along the eastern slope of the Porcupine Seabight, strong internal waves and tides are recognized within the depth interval of the outcropping mounds (White, 2007). Current measurements indicate an annual mean northward current with a speed of 3–10 cm/s near the seafloor (Pingree and Le Cann, 1990; Rice et al., 1991) although much stronger bottom currents have been inferred at the eastern margin of the Porcupine Seabight. Dorschel et al. (2007) measured bottom current speeds up to 51 cm/s on the summit of Galway Mound (Belgica Mound Province), while Roberts et al. (2005) recorded peak current speeds of 70 cm/s for the same mound.

3. MD01-2451G lithology and chronological framework

The lithology of this core has been earlier discussed by Foubert and Henriet (2009) and Foubert et al. (2007). Based on the X-Ray fluorescence (XRF) results, magnetic susceptibility (MS) and density, the core MD01-2451G was subdivided in two major units (Fig. 3) (Foubert and Henriet, 2009; Foubert et al., 2007). Unit A (0–400 cm) is characterized by a high-frequent alternation of light-grey and dark layers. The light-grey layers are characterized by abundant cold-water coral fragments whereas in the dark layers, no corals were observed. The XRF-scanning records high Ca content in the light-grey intervals (0–40 cm/219–270 cm/323–375 cm), while the dark layers correspond to an increased content of Fe (40–219 cm/270–323 cm/375–400 cm). The variable, but generally elevated Sr content in the light-grey zones is explained by the presence of small Madrepora oculata fragments and other aragonitic biogenic components (Foubert and Henriet, 2009). The presence of dropstones was observed at 60–70 cm and 350–356 cm (Foubert et al., 2007). The transition from the dark, Fe-rich layers to the overlying light, coral-bearing intervals is gradual. The base of every dark layer, however, reveals a sharp boundary with the underlying layer (Foubert and Henriet, 2009). Unit B (400–1280 cm) reveals high Ca-values and low MS- and Fe-values. The high Sr values are due to the high concentration of big coral chunks, consisting mainly of Lophelia pertusa. In the lower part of unit B, dissolution of the corals was observed and is interpreted to be linked to extremely low values of the MS in unit B (Foubert and Henriet, 2009; Foubert et al., 2007).

Six cold-water corals, collected in the light-grey layers, have been dated by 230Th/U method by Frank et al. (2009) (Fig. 3). The deep-sea corals yield 230Th/U ages ranging between 230.4±2.9 ka and 3.2±0.1 ka (Frank et al., 2009). 230Th/U dating of the corals indicates that coral growth in unit B ended abruptly around 230 ka ago (Marine Isotopic Stage (MIS) 7). 230Th/U dating indicates also that unit A represents a condensed record of three glacial-interglacial cycles during the last 200 ka (Fig. 3). The upper 40 cm of the core corresponds to the Holocene: at 6 cm depth, the coral has an age of 3.2±0.1 ka, at 31 cm an age of 6.5±0.1 ka. The interval between 219 and 270 cm reveals ages between 78.8±0.5 and 109.2±0.8 ka. At 326 cm depth, the coral dates 188.9±2.3 ka. 230Th/U dating demonstrates that these light-grey level layers (rich cold-water corals layers) were mainly deposited during interglacial periods (Foubert and Henriet, 2009).

4. Materials and methods

Core MD01-2451G was obtained with a gravity corer during the MD123-Geosciences campaign with the French R/V Marion Dufresne in September 2001. The core was retrieved from the top of Challenger Mound (51°22′47.99″N and 11°43′03.45″W) at a water depth of 762 m with a recovery of 1284 cm.

4.1. Grain-size analysis

Grain-size distribution measurements of siliciclastic sediments were carried out at the National Oceanography Centre Southampton (NOCS), with a Malvern Mastersizer 2000 with autosampler. An average measurement precision of 4.4% (on grain-size mode) was estimated for similar sediments by Thierens et al. (2010). Samples were analyzed with a resolution of 10 cm in the first 5 m of the core and a resolution of 50 cm in the part below 5 m. Prior to analysis, bulk sediment was first decarbonated via leaching with HCl (10%). In a second step, organic matter was removed through oxidation using H2O2 (10%). Subsequently, the samples were rinsed repeatedly with distilled water until a neutral pH was obtained. Biogenic silica was not removed given the fact that only small amounts were present in the samples. Before measurement the sediment was treated with 0.05% Calgon (Sodium HexaMetaPhosphate) and sonicated for 10 s to reduce the effect of flocculation. For each sample the percentages of clay (<2 μm), silt (2–63 μm) and sand (63–2000 μm) were calculated.
4.2 Petrography and grain-surface microtextures

Thin sections for classic light microscopy and cold cathode luminescence (CL) were manufactured and studied at the Department of Earth and Environmental Sciences (Leuven University). Cathode luminescence was carried out on an in-house built (Technosyn) cold cathodoluminescence model 2800, Mark II in combination with a Zeiss microscope. In this paper, 5 thin sections of the upper 400 cm of the core were selected (9–11 cm, 59–61 cm, 230–232 cm, 275–277 cm and 399–401 cm).

Grain surfaces of sand-sized quartz grains of two samples (18–19 cm and 238–239 cm) were imaged and examined for microtextural evidence of their source/transport history. The subsamples were disaggregated (30 s sonication), dried, mounted on aluminium stubs and gold coated (Polaron E5150 Sputter Coating Unit). Scanning electron microscopic analysis of grain surface features took place at the Electron Microscopy Facility, University College Cork using a JEOL JSM 5510 Scanning Electron Microscope (acceleration voltage of 5 kV at 10 mm working distance) with attached INCA x-sight Energy Dispersive X-ray Spectroscopy Detector (Oxford Instruments), operating in secondary electron mode.

The combination of microtexture occurrence and dominance enables the identification of grain types which allow a differentiation of various sediment transport mechanisms, such as ice-rafting (Mahaney, 2002; Mahaney et al., 2001; Thierens et al., 2010). A qualitative estimate of glacially versus non-glacially transported grains was aimed at in this study.

4.3 XRD analysis of the clay fraction

Clay minerals were identified within 68 samples by standard X-ray diffraction (XRD) analysis using a PANalytical diffractometer at the IDES laboratory (University of Paris XI) on oriented mounts of non-calcareous clay-sized (<2 μm) particles. The oriented mounts were obtained following the methods described by Colin et al. (1999). Samples were split in deionized water and decarbonated, using a diluted hydrochloric acid solution. The <2 μm fraction was isolated by gravity settling. Three XRD runs were performed, following air-drying, ethylene-glycol solvation for 24 h, and heating at 490 °C for 2 h.

Identification of clay minerals was made mainly according to the position of the (001) series of basal reflections on the three XRD diagrams. Semi-quantitative estimates of peak areas of the basal reflections for the main clay mineral groups of smectite (including mixed-layers) (15–17 Å), illite (10 Å), and kaolinite/chlorite (7 Å) were carried out on the glycolated diffractograms using the MacDiff software (Petschick, 2000). Relative proportions of kaolinite and chlorite were determined based on the ratio of the 3.57/3.54 Å peak areas. Replicate analyses of selected samples gave a precision of ±2% (2σ). Based upon the XRD method, the semi-quantitative evaluation of each clay mineral has an accuracy of ∼5%. Illite crystallinity was obtained from the full width at half maximum (FWHM) of the 10 Å peak from the X-ray diffractograms (Chamley, 1989).
4. Neodymium and strontium isotopic analysis

The $^{143}$Nd/$^{144}$Nd and $^{87}$Sr/$^{86}$Sr isotopic ratios of the terrigenous sediment are a reflection of age and lithology of the source rock (e.g. Grousset et al., 1988; Revel et al., 1996b). In the North Atlantic, numerous provenance studies used Nd and Sr isotopic ratios for fingerprinting of the terrigenous material (e.g. Farmer et al., 2003; Grousset et al., 1988, 2000; Hemming et al., 1998; Innocent et al., 1997; Peck et al., 2007; Revel et al., 1996b; Snoeckx et al., 1999). Nd and Sr isotopic measurements were performed on the carbonate-free sediment fraction of 17 samples using a Multi-Collector ICPMS unit (Thermo Scientific Neptune) at the Department of Analytical Chemistry, Chent University. The $\text{Nd}_{-1}$ standard was used as reference material for neodymium ($^{143}$Nd/$^{144}$Nd = 0.51215, $^{146}$Nd/$^{144}$Nd = 0.7219) (Tanaka et al., 2000) to correct for instrumental mass discrimination using external standardization (sample-standard bracketing). For the measurement of the Sr isotopes the NIST SRM 987 standard was used. The standard deviation on these measurements were $\approx 8\times10^{-5}$ for Nd and $5\times10^{-5}$ for Sr. Following the procedure described by Colin et al. (1999) samples were decarboxylated by leaching with 20% acetic acid solution in an ultrasonic bath, then rinsed 5 times with Milli-Q water and centrifuged to eliminate any traces of the carbonate solution. Subsequently, carbonate-free sediments were dissolved in concentrated HF–HClO₄ and HNO₃–HCl mixtures. The first chemical separation utilized Bio-Rad columns packed with AG50WX-8, 200–400 mesh cationic exchange resin. Sr was eluted with 2 M HCl and the light rare-earth elements with 2.5 M HNO₃. The Sr fraction was purified on a 20 μl SrSpec® column, consisting of a polystyrene gel with a 4 mm 0 millex® filter. Nd was isolated by reverse-phase chromatography on HDEHP-coated Teflon powder. Nd isotopic composition has been conventionally expressed as $\varepsilon_{\text{Nd}} = \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}}_{\text{sample}} / \frac{^{143}\text{Nd}}{^{144}\text{Nd}}_{\text{CHUR}} \right) - 1 \times 10000$, where CHUR stands for Chondritic Uniform Reservoir and represents a present day average earth value; $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}} = 0.512838$ (Jacobsen and Wasserburg, 1980).

5. Results

5.1. Siliciclastic grain-size distribution

Unit A reveals an alternation of bimodal grain-size distributions with a pronounced coarse mode in the light-grey, Ca-rich layers and an elevated contribution of the fine mode in the dark, Fe-rich intervals (Fig. 4). The grain-size distributions in the light-grey intervals (40/219–270/323–375 cm) represent fine-skeletal, well-sorted medium to fine sands with a pronounced peak around 100 μm. The sand content (63–2000 μm) in the light-grey layers varies between 54 and 73 V%, the silt-percentage (2–63 μm) between 24 and 43 V%, whereas the clay (<2 μm) ranges from 1 to 3 V%. The grain-size distributions in the intervals (40/219–270/323–375–400 cm) are coarse-skeletal and poorly sorted with a fine mode around 5 μm and a coarse mode at about 100 μm. The sand-percentage in the dark layers varies between 18 and 30 V%, the silt-content between 65 and 74 V%, whereas the clay ranges from 4 to 7 V%.

The grain-size measurements of unit B reveal fine-skeletal, poorly sorted coarse silts with a unimodal distribution (mode between 40 and 50 μm). The sand-percentage of unit B varies between 9 and 39 V%, the silt fraction between 65 and 85 V%, whereas the clay ranges from 2 to 5 V%. There was no clear grading upward cycles observed in any of the intervals mentioned above.

5.2. Petrography and surface microtextures of quartz grains

Thin sections of unit A reveal that the terrigenous sediment fraction of this core is mainly dominated by quartz grains (Fig. 5A, B, D). However, feldspar and calcite are also observed abundantly while dolomite and pyrite occur as minor components in the matrix. In the light-grey layers of unit A, little fine matrix was noticed and embedded grains exhibit diameters of 200 μm (Fig. 5B). In these zones, foraminifers and other biogenic fragments occur abundantly and are commonly broken (Fig. 5C). The microtextures of the sand-sized quartz grains in the light layers of unit A (18–19 cm and 238–239 cm) are dominated by angular, sharp edges, conchoidal and linear fractures and linear and arc-shaped steps (Fig. 5E, F). Furthermore quartz grains with predominantly rounded edges, dissolution etching and solution pits occur (Fig. 5G). Occasionally more rounded quartz grains with frequent V-shaped percussion cracks, moderate fractures and/or steps are observed (Fig. 5H).

In the dark intervals of unit A, the grains are embedded in a fine matrix (Fig. 5A, D). In contrast to the light intervals of unit A, little or no foraminifers or biogenic fragments are observed. This is in line with the low Ca and Sr contents that were recorded in these zones (Fig. 3). The detrital grains in these dark layers have variable diameters up to 1 cm whereas the light layers reveal more uniform grain sizes (Fig. 5A, D). Cold cathode luminescence of the thin sections of unit A revealed the presence of dark brown to dark grey luminescent quartz grains (Fig. 5A, B). Furthermore, green luminescent plagioclase and blue K-feldspar grains and red dolomite were observed. Also, a significant amount of bright-yellow calcite occurred in the samples. The dolomite and calcite observed in these thin sections most likely have a detrital origin since no well-formed, diagenetic crystals or cement sequences as described by Pirlet et al. (2010) were observed. It is important to note that these detrital carbonates were not taken into account in the analyses of the siliciclastic fraction since all samples were decalcified prior to analysis.

5.3. Clay mineralogy

Illite (18–43%) and smectite (14–65%) are the two dominant clay minerals in the core MD01-2451G sedimentary record (Fig. 6). Chlorite (6–24%) and kaolinite (10–21%) are less abundant. In general, the illite, chlorite and kaolinite content are inversely correlated to the smectite content. Variations in the kaolinite content are small throughout the record and are within the analytical limits of the method. Smectite is characterized by high amplitude fluctuations (14–65%) in unit A. The light layers in unit A are characterized by a low smectite content whereas the dark layers reveal higher smectite values. Throughout unit B, the smectite content remains relatively stable with an average around 45%. Illite and chlorite proportions are lower in unit B (30% and 14% respectively) compared to unit A (40% and 22% respectively).

The illite crystallinity reveals 3 peaks in unit A, which are well correlated with the intervals characterized by an increased smectite content (Fig. 6).

5.4. Sr and Nd isotopic results

The $^{87}$Sr/$^{86}$Sr ratios and $\varepsilon_{\text{Nd}}(0)$ values measured on the carbonate-free fraction of core MD01-2451G are listed in Table 1. The $^{87}$Sr/$^{86}$Sr ratio and the $\varepsilon_{\text{Nd}}(0)$ vary significantly between 0.73093 and 0.71512 and between −4.9 and −15.8, respectively (Table 1). Generally, the $^{87}$Sr/$^{86}$Sr ratio is higher in the dark layers of unit A compared to the values in the light-grey layers while the $\varepsilon_{\text{Nd}}(0)$ values are more radiogenic in the light-grey layers. Care has to be taken when interpreting the $^{87}$Sr/$^{86}$Sr isotopic ratios of bulk sediment since they are influenced by the grain-size distribution (Revel et al., 1996a). In this regard, the Nd isotopic composition is more reliable as it is not or less affected by grain-size variations (Goldstein et al., 1984; Revel et al., 1996b).

6. Discussion

6.1. Hydrodynamics

Grain-size distributions of the siliciclastic fraction are used to infer the hydrographic conditions at the time of deposition (Ballini et al.,...
Fig. 4. The results of the grain size analysis of the carbonate-free sediment of core MD01-2451G.
The grain-size measurements throughout unit B display a similar fine skewed, poorly sorted distribution with a mode around 40–50 μm, indicating stable hydrographic conditions during the deposition of these sediments (Fig. 4). However, caution has to be taken when interpreting these grain-size distributions as large coral fragments in unit B indicate the presence of a dense coral framework during the deposition of this layer. Major coral development may have baffled the bypassing
sediment (de Haas et al., 2009; Dorschel et al., 2007) altering the original hydrographic signal. Mienis et al. (2009) already reported that less sediment is resuspended on a coral mound compared to the off-mound site. This might explain why the grain-size distributions are poorly-sorted.

The grain-size distribution in unit A reveals, in contrast to unit B, significant hydrodynamic changes. The dark intervals of unit A show a poorly-sorted bimodal grain-size distribution pointing towards ice-rafting as a likely sedimentation mechanism (Fig. 4). The presence of dropstones (up to several centimeters) and the absence of foraminifers or other biogenic fragments (Fig. 5A, D) in these layers suggest that these sediments are of glaciomarine origin. Hereafter, these siliciclastic, glaciomarine sediments, deposited during or at the end of cold stages, will be referred to as ‘glacial sediment’. The fact that little or no sediment sorting is evident suggests that bottom currents were reduced during glacial intervals. This is also supported by the fine lamination that was observed in these sediments. The abrupt change in grain-size, observed at the base of each of the glacial layers, might indicate the presence of an unconformity.

In contrast, the light-grey zones of unit A, which are mainly deposited during interglacial periods (Frank et al., 2009), are characterized by identical, bimodal grain-size distributions with a pronounced coarse mode, indicating a strong sorting process (Fig. 4). The alternation of sluggish glacial currents and a significant increase of bottom-current speed during interglacials was previously reported (Dorschel et al., 2005; Foubert et al., 2007; Rüggeberg et al., 2007; Van Rooij et al., 2007). These authors attributed the increase in current speed in interglacials to the re-introduction of the northward flowing MOW. Generally, increased bottom currents are considered to be a prerequisite for cold-water coral growth since they prevent the corals from sediment burial and deliver nutrients to the coral polyps (Freiwald et al., 2004). However, the increased bottom currents in the interglacial intervals of unit A did not lead to enhanced mound growth. On the contrary, these intervals are condensed sections with small coral fragments and broken foraminifers suggesting that these biogenic fragments were disintegrated and possibly reworked (Fig. 5C). Moreover, the corals might have been further fragmented by the enhanced activity of bio-eroders during the reduced sedimentation conditions (Beuck and Freiwald, 2005). The fragmentation of the corals can occur shortly after coral growth as evidenced by a
fragmented coral of only 2 ka in the top of the core. Moreover, it is an ongoing process given that nowadays only coral debris is observed at the top of Challenger Mound (Foubert et al., 2005). The subsequent burial of these coral fragments during interglacial periods is a slow process as indicated by the big time differences in the age of corals deriving from the same layer (e.g. 78.8 ka and 109.2 ka between 219 and 270 cm). Hence, the absence of a large coral framework in unit A is a fundamental difference with unit B where a dense framework was able to baffe the sediment, leading to faster burial which caused better coral preservation and increased mound growth.

Quartz grains within the interglacial sediments of unit A bear surface textures that can be attributed to mechanical, glacial abrasion (Fig. 5E, F). Angular quartz-sands with abundant, deeply embedded and sharp mechanical abrasion features, such as conchoidal/linear fractures and arc-shaped/linear steps, are known from environments influenced by glacial erosion and/or transport (Mahaney, 2002 and references therein). The occurrence of these glacially-transported grains suggests the reworking of glacial sediments during interglacial bottom current transport and deposition. This also indicates that an important part of the terrigenous fraction, even in interglacial intervals, was originally transported to Challenger Mound by icebergs during the Late Quaternary cold stages.

6.2. Sediment provenance

6.2.1. Sr–Nd isotopic composition

The average \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios (0.72521) and \( \varepsilon_{\text{Nd}}(0) \) values (−10.4) reveal a dominant contribution of non-volcanogenic, continental crust-derived sediment throughout core MD01-2451G (Fig. 7). Given the proximity of Ireland to the study area, a continental input from the Irish mainland is a premise. The British-Irish Isles feature distinct \( ^{87}\text{Sr}/^{86}\text{Sr} \) and \( \varepsilon_{\text{Nd}} \) values of 0.734 and −12.1 respectively (Revel et al., 1996b). It is suspected that most of the detrital carbonates which were observed in the thin sections also derive from the Irish mainland since Carboniferous limestone deposits cover the entire central part of Ireland.

However, most of the \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios and \( \varepsilon_{\text{Nd}} \) values in MD01-2451G, plot on a mixing hyperbola, indicating the presence of two source-areas: (1) the crustal rocks of the British-Irish Isles and (2) the northern volcanic provinces (Fig. 7). This mixing hyperbola is based on the isotopic composition and element concentration of both end-members sources (Faure, 1986). It also implies a significant contribution of volcanic material in the sediments of Challenger Mound. The presence of numerous blue to green luminescent plagioclase grains in the thin sections (Fig. 5A, B) might indicate the influx of basaltic material (Andrews, 2008). Potential volcanic sources in the North Atlantic include Iceland, the NW British-Irish Isles and the Faeroe Islands (Jeandel et al., 2007), with Iceland \( (^{87}\text{Sr}/^{86}\text{Sr} \approx 0.703; \varepsilon_{\text{Nd}} \approx +8) \) as the most important contributor of volcanic material in the North Atlantic (Revel et al., 1996b) (Fig. 8). However, due to their proximity, it is also necessary to take into account the Tertiary volcanic provinces of the NW British Isles, whereas the Faeroe Islands are considered as a negligible source because of their limited size. Volcanic material from Iceland was most likely transported as ice-rafted debris (IRD) in drifting icebergs. The Porcupine Seabight is located between 40 and 55°N, within the zone of preferential IRD accumulation, i.e. the so-called Ruddiman-belt (Grousset et al., 1993; Ruddiman, 1977) (Fig. 8). During cold stages, Iceland ice-sheet sourced icebergs (amongst others) may have become entrained in the cyclonic gyre of the central North Atlantic (Fig. 8) and in this way, they supplied IRD to the eastern Porcupine Seabight margin. Moreover, during cold stages, surface water movement reversed, flowing southwards as a coastal current west of Ireland (Sarnthein et al., 1995). This southward flowing current likely acted as an additional route for icebergs derived from the volcanic provinces in the NW British-Irish Isles, a hypothesis supported by the presence of north-south trending icebergs ploughmarks on Sylne Ridge (Games, 2001). Besides, Knutz et al. (2001) reported the influx of volcanic material from the Tertiary volcanic provinces of the NW British-Irish Isles during glacial sediment transport in the Rockall Trough. Another potential route for icebergs surges from Ireland and northern Britain which has to be considered is the Irish Sea ice stream, which drained the composite British and Irish Ice-sheet and transported icebergs to the south (Cofaigh and Evans, 2007; Roberts et al., 2007).

All samples, except three (28, 69 and 328 cm) have Sr and Nd isotopic ratios which plot along the same elongated hyperbolic distribution (Fig. 7). Therefore, it is concluded that no major change of the sediment sources occurred. However, the relative contribution of each sedimentary source (end-member) varies significantly throughout the sedimentary record. Based on the mixing-hyperbola, it was inferred that between 3 and 60% of the terrigenous fraction in the samples may derive from a volcanic province. A shift in the isotopic ratios can be recognized between the sediments from the interglacial light layers and the glacial dark layers from unit A (Fig. 7). The interglacial layers of unit A are generally characterized by an enhanced contribution of volcanic sediment compared to the glacial intervals, which show an increased contribution of the non-volcanic, continental crust end-member (Fig. 7). This distinction is attributed to the presence of enhanced bottom currents during interglacial periods, sorting and reworking sediment and hence, creating coarse lag deposits specifically enriched in sediment that was once transported as ice-rafted debris from a volcanic source region.

Three sediment samples (28, 69 and 328 cm) exhibit distinctly lower \( \varepsilon_{\text{Nd}} \) values compared to the British-Irish Isles, ranging between −13.8 and −15.7 (Table 1 and Fig. 7). These lower values are related to a minor contribution of sediment derived from old continental crusts on e.g. Greenland \( (^{87}\text{Sr}/^{86}\text{Sr} \approx 0.712 \text{ to } 0.730; \varepsilon_{\text{Nd}}(0) \approx −23 \text{ to } −40) \), Scandinavia \( (^{87}\text{Sr}/^{86}\text{Sr} \approx 0.728; \varepsilon_{\text{Nd}}(0) \approx −19.3) \) and Canada \( (^{87}\text{Sr}/^{86}\text{Sr} \approx 0.722; \varepsilon_{\text{Nd}}(0) \approx −25) \) (Revel et al., 1996b). As described above, icebergs from these areas were possibly transported westward via the central North Atlantic gyre (Fig. 8). Ice-rafted debris, derived from the Laurentide Ice Sheet (Canada) and Greenland Ice Sheet, has already been reported in the Porcupine Seabight by Peck et al. (2007), supporting our interpretation.

6.2.2. Clay mineralogical evidence

The mineralogy of the clay fraction has the potential to provide information on the continental weathering processes in the source area (Colin et al., 2006) and the type of source rock, i.e. weathering of...
Throughout core MD01-2451G, significant changes are observed in the smectite content (Fig. 6). In the northern part of the North Atlantic Ocean, smectite is often associated with the occurrence of basaltic rocks on Iceland, the Faeroe Islands, and the eastern part of Greenland (Ballini et al., 2006). However, in the case of core MD01-2451G, the elevated smectite content occurs in the glacial intervals where the Sr and Nd isotopic compositions indicate an enhanced contribution from the continental, Irish end-member. Therefore, a volcanic origin of the smectite is less likely for Challenger Mound and it is suggested that most of the smectites in core MD01-2451G are derived from the Irish mainland. Fagel et al. (2001) stated that smectites are common constituents of modern soils in Western Europe, where they are associated with vermiculite and linked to chemical weathering during warmer phases (Chamley, 1989).

The high smectite content observed throughout unit B (Fig. 6), likely indicates that this unit corresponds to a warm period of enhanced chemical weathering. The fact that the assemblage of clay minerals remains unchanged demonstrates that a stable terrigenous input occurred during the deposition of unit B. It is suggested that the abrupt smectite peaks in the glacial sediments of unit A (Fig. 6) point towards sedimentation during deglaciation episodes and associated melt-water pulses (Marinoni et al., 2008; Vogt and Knie, 2008). In this scenario, the increase in smectite may be attributed to the initial stage of chemical weathering processes, which became activated following glacial retreat and the onset of warmer climatic conditions (Marinoni et al., 2008; Vogt and Knie, 2008). This hypothesis is supported by the elevated illite crystallinity in the dark intervals of unit A which suggests strong hydrolysis conditions (Chamley, 1989). Besides, the rise in the smectite content may also be caused by the uncovering of the smectite-rich deposits on the Irish Isles (Fagel et al., 2001) during glacial retreat.

The low smectite content in the light-grey, coral-rich levels of unit A might be surprising since these intervals are associated with warmer phases. However, a likely explanation is that this low content is possibly related to the strong currents during these intervals. Smectites are believed to flocculate less easily than illite, which has a greater surface-charge density (Hillier, 1995). Therefore, the high-energy conditions during interglacials would facilitate the deposition of illite rather than smectite. Chamley (1989) already emphasized that strong currents might severely alter the original clay signature induced by climate.

6.3. The role of the British-Irish Ice-Sheet

The grain-size analyses and the grain-surface textures of the terrigenous fraction in Challenger Mound indicate that an important part of the detrital material has a glacial origin. During cold stages, when most of Ireland was covered by the British-Irish Ice-Sheet (BIIS) (Bowen et al., 2002; McCabe et al., 2005; Scourse et al., 2009; Sejrup et al., 2005), an enhanced flux of terrigenous material was created offshore (Knutz et al., 2002; Van Rooij et al., 2007). This enhanced flux is supported by the elevated XRF Fe-counts in the glacial layers of unit A (Foubert and Henriet, 2009), indicating the dominance of the terrigenous material over the biogenic component (Richter et al., 2006).

Gravity-driven processes such as low-density turbidity currents or hyperpycnal or density flows are possible processes transporting sediment off-slope, as well as deposition from melting sea ice that drifted offshore (Auffret et al., 2002). However, considering the position of the core on top of an elevated structure, most of the gravity processes can be excluded since these currents would bypass the mounds along the surrounding gullies (Van Rooij et al., 2003). Thus, it is proposed that ice-rafting accounted for an important part of the terrigenous sediment supply to Challenger Mound, which is supported by the grain-size measurements, grain-surface micro textures.
and Nd- and Sr-isotopic ratios. This conclusion was also confirmed by the study of Thierens et al. (2010). However, the role of fall-out of fine-grained sediment plumes (Hesse and Khodabakhsh, 2006) derived from the BIIS, transport of fine-grained sediment by nepheloid layers and sediment transport by currents (especially during interglacial periods) play a significant role as well. All these observations indicate that the influx of glacial sediment is an important component in the infill of the coral framework and the build-up of cold-water coral mounds in the Porcupine Seabight. A different situation occurs in the Rockall Through where coral mounds are much less affected by the influx of terrigenous sediment (Noé et al., 2006).

A major control on the influx of terrigenous material from the Irish mainland into the study site seems to be the activity of the BIIS. The grain-size distributions, clay mineralogy and Nd and Sr isotopic compositions support that the dark, silicilastic intervals of unit A are linked to deglaciations of the BIIS. The absence of corals or other biogenic fragments prohibits the dating of these glacial intervals. However, the dating of the corals within the interglacial layers provides a time-frame for the deposition of the glacial zones.

The two lowermost glacial intervals of unit A were deposited respectively between 230 ka–189 ka and 189 ka–109 ka ago (MIS 6–7). These time intervals correspond mainly with the Munsterian cold stage which lasted from ca. 302 ka to ca. 132 ka BP when an ice-sheet covered most of Ireland (McCabe, 2008). The presence of a glacial layer between 189 ka and 230 ka might indicate that ice-rafting also occurs in the cold periods during MIS 7 as already described by Desprat et al. (2006). The uppermost glacial layer of unit A was deposited after 78 ka (MIS 4). The deposition of the latter interval is attributed to ice-rafting of the Midlandian ice-sheet, which has already been described in detail (Bowen et al., 2002; Cofaigh and Evans, 2007; McCabe, 2008; McCabe et al., 2005). Scourse et al. (2009) and Bowen et al. (2002) reported repeated deglacial events between 40 and 12 ka.

During the deposition of these glacial sediments, no coral growth occurred. The change in hydrographic conditions during these deglaciations might have led to variations in the food supply to the cold-water corals and also the enhanced input of terrigenous material during BIIS ice-rafting or a combination of these factors, might explain the lack of coral fragments in the glacial layers. The close relation between cold-water coral growth and hydrography was already addressed by White (2007) and Dullo et al. (2008). Besides, the enhanced influx of terrigenous material might have a negative influence on coral growth (Freiwald et al., 2004). Overall, less favorable conditions for coral growth seem associated with the deglaciation of the proximal BIIS.

7. Conclusion

The study of the terrigenous fraction of the Late Quaternary Challenger Mound reveals important changes in the hydrography, provenance and transport mechanism throughout the upper depositional sequence of this cold-water coral mound.

The Sr and Nd isotopic composition of the sediment in core MD01-2451G point towards Ireland as the dominant contributor of detrital material in Challenger Mound, with a variable contribution from a volcanic source. Two potential volcanic sources, i.e. Iceland and the Tertiary volcanic provinces of the NW British Isles are considered. Most likely, the southward transportation of volcanic material to the Porcupine Seabight was by drifting icebergs. A limited amount of samples indicate a potential third sedimentary source which is characterized by old continental crust Sr and Nd isotopic composition. Potential sources are the old cratons on Greenland, Scandinavia or Canada. Material from these regions was transported to the Porcupine Seabight during cold stages when icebergs got entrained in the cyclonic gyre of the central North Atlantic.

The glacial intervals in Challenger Mound are characterized by a bimodal grain-size distribution, typical for ice-rafting. The fact that little or no sorting occurred indicates that bottom currents were reduced during cold stages. On the contrary, during interglacial times, enhanced bottom currents reworked biogenic fragments and ice-rafted material. This is supported by the surface microtextures of quartz grains in these interglacial layers, showing obvious signs of glacial abrasion. This paper highlights the role of ice-rafting as an important transport mechanism of terrigenous sediment towards the Late Quaternary Challenger Mound. An elevated smectite content indicates that the glacial layers of unit A were deposited during glacial retreat of the BIIS at the onset of warmer climatic conditions. The absence of coral fragments in these glacial intervals shows that coral growth was suppressed. It is put forward that the deglaciation of the BIIS seriously altered the hydrography and terrigenous input in the Porcupine Seabight and therefore affected coral growth. As such the role of the BIIS is ambiguous given that the influx of glacial sediments is an important factor for the infill of the coral framework and thus mound build-up, while deglaciations seem to suppress coral growth.

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