Age constraints on the origin and growth history of a deep-water coral mound in the northeast Atlantic drilled during Integrated Ocean Drilling Program Expedition 307

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ABSTRACT

Sr isotope stratigraphy provides a new age model for the first complete section drilled through a deep-water coral mound. The 155-m-long section from Challenger Mound in the Porcupine Seabight, southwest of Ireland, is on Miocene siliciclastics and consists entirely of sediments bearing well-preserved cold-water coral *Lophelia pertusa*. The $^{87}Sr/^{86}Sr$ values of 28 coral specimens from the mound show an upward-increasing trend, correspond to ages from 2.6 to 0.5 Ma, and identify a significant hiatus from ca. 1.7 to 1.0 Ma at 23.6 m below seafloor. The age of the basal mound sediments coincides with the intensification of Northern Hemisphere glaciations that set up the modern stratification of the northeast Atlantic and enabled coral growth. Mound growth persisted throughout glacial-interglacial fluctuations, reached a maximum rate (24 cm/k.y.) ca. 2.0 Ma, and ceased at 1.7 Ma. Unlike other buried mounds in Porcupine Seabight, Challenger Mound was only partly covered during its growth interruption, and growth restarted ca. 1.0 Ma.

Keywords: deep-water coral mound, northeast Atlantic, Porcupine Seabight, $^{87}Sr/^{86}Sr$, Pliocene-Pleistocene, Integrated Ocean Drilling Program.

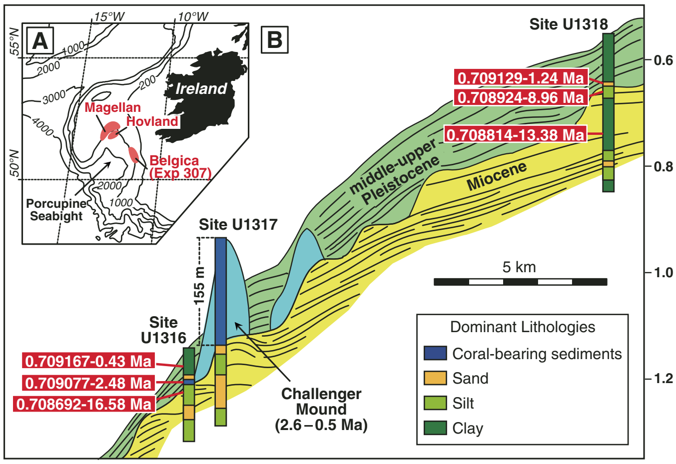

Figure 1. A: Location map showing Belgica Mound Province (Integrated Ocean Drilling Program Expedition 307) in Porcupine Seabight. B: Lithological columns of three drilled sites (U1316–U1318) on interpreted seismic cross section (De Mol et al., 2002). $^{87}Sr/^{86}Sr$ values and ages of some key horizons from U1316 and U1318 are shown. Acoustically transparent mound units are shown in blue.

INTRODUCTION

Although the presence of corals in the aphotic deep sea has been known for centuries, the common occurrence of deep-water coral mounds in all major oceans has only been recognized in the last decade. Porcupine Seabight is one of the best-studied areas of deep-water coral mounds. Swath bathymetry, seismic surveys, ROV deployments, and short piston coring have been employed to characterize the geomorphology, the surface sediments, and surface ecosystems of coral mounds in the 150-km-long, 100-km-wide embayment on the Irish Atlantic Shelf (e.g., Freiwald and Roberts, 2005). The mounds of Belgica Province (one of three mound provinces in Porcupine Seabight; Fig. 1A) are elongated subconical structures in water depths of 600–1000 m. They are as high as 160 m, and are on a seismically discontinuous surface (De Mol et al., 2002; Huvenne et al., 2003). A vibrant coral ecosystem dominated by the cold-water coral *Lophelia pertusa* covers some deeper mounds, while other mounds are topped by dead coral rubble and drift sediments including dropstones (Foubert et al., 2005).

Prior to Integrated Ocean Drilling Program (IODP) Expedition 307, examination of 10-m-long piston cores from several Belgica Province mounds had documented the occurrence of *L. pertusa* throughout the surface Pleistocene sediments (Foubert et al., 2007). Analyses of grain size and benthic foraminifera suggested that the mounds flourished during interglacial periods and diminished during glacial periods (Roberts et al., 2006; Rüggeberg et al., 2007). Mound growth was proposed to be driven by changes in ocean circulation coupled to variations in climate (Dorschel et al., 2005; van Rooij et al., 2007). However, competing hypotheses for mound genesis and development involving light hydrocarbon seeps (e.g., Henriet et al., 2002) persisted until a complete sedimentary record from deeper within the mounds and through the base was obtained.

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In May 2005, Expedition 307 recovered the first complete section through a deep-water coral mound and its surrounding sediments, with the goal of addressing its origin and growth history (Williams et al., 2006). Challenger Mound (52°23′N, 11°43′W, water depth ~800 m) in the Belgica Province has little to no live coral coverage and was therefore chosen as the drilling target to avoid disturbance of living coral ecosystems. Shipboard nannofossil biostratigraphic analysis suggested that the mound developed from 1.95 to 0.46 Ma (Ferdelman et al., 2006). However, significant reworking and dissolution of the microfossils and a paucity of age-diagnostic species led to an unsatisfactory level of age control for the mound initiation. Sr isotope analysis and other post-cruise analyses presented here greatly improve our understanding of the ages and contents of the drilled sediments. This paper discusses the conditions for origin and depositional history of Challenger Mound based on this new age model.

SEDIMENTS FROM THE MOUND

Challenger Mound is on a regional unconformity overlying consolidated Miocene siliciclastic sediments (Fig. 1B). Onlapping fine-grained turbidites younger than 0.26 Ma (*Emiliania huxleyi* zone) partially bury the seismically transparent mound unit. The mound unit is distinct from the lower and lateral sediments, in terms of its rich fossil contents and calcareous matrix. The complete mound sequence recovered from Site U1317 entirely consists of coral-bearing sediments and thickens to 155 m on the summit (Hole U1317E) (Fig. 1B). The corals, mainly *L. pertusa* and less frequently *Madrepora oculata*, occur as gravel-sized fragments to branches of several centimeters long and trending right side up. They are embedded in a fine-grained matrix of clay and calcareous bioclasts, including nannofossils, foraminifers, mollusks, and echinoids. A 6-m-thick coral-bearing unit, overlying the regional unconformity, occurs 750 m downslope at Site U1316 (Fig. 1B).

The initial mound growth phase of a wackestone facies is emplaced directly on the Miocene siliciclastics (Fig. 2A). Above, the mound sequence shows alternating lithologic layers on a 10 m scale that consist of two types: a darker colored clayey layer (Fig. 2B) interpreted to be glacial, and a lighter colored calcareous layer, interpreted to be interglacial (Fig. 2C). This interpretation is supported by corresponding changes in planktonic foraminiferal $\delta^{18}O$, with amplitudes of 0.5‰–1.0‰ for the lower 100 m of the mound section (U1317E; Sakai et al., 2006), and by dropstones that are preferentially found in the darker colored layers. Much of the clay material, therefore, likely had an ice-rafted origin. Transitions between the layers are gradual and appear as downhole changes in sediment color (Fig. 3), carbonate contents, and natural gamma radiation (Ferdelman et al., 2006). Coral pieces and structure are generally well preserved in the darker layers, while they appear strongly dissolved in the lighter layers. The mechanism of the differential preservation and/or dissolution may be linked to changes in sedimentation coupled with microbial sulfate reduction (Ferdelman et al., 2006). On the basis of X-ray diffraction analysis, the corals retain their initial aragonite mineralogy even in the dissolved pieces.

Shipboard biostratigraphy and magnetostratigraphy provided a broad age framework, but some incompatibility between foraminifera and nannofossil dates remained (Ferdelman et al., 2006). The first appearance datum of planktonic foraminifera *Globorotalia inflata* (2.09 Ma) is at 60 mbsf (below seafloor) of Hole U1317E. Magnetostratigraphic records indicated a stable normal signal in the uppermost 17 m, interpreted at the Bruhnes chron (younger than 0.78 Ma); however, the inclination signal below this level becomes unstable. Thus, another method was required to determine a more accurate age model.

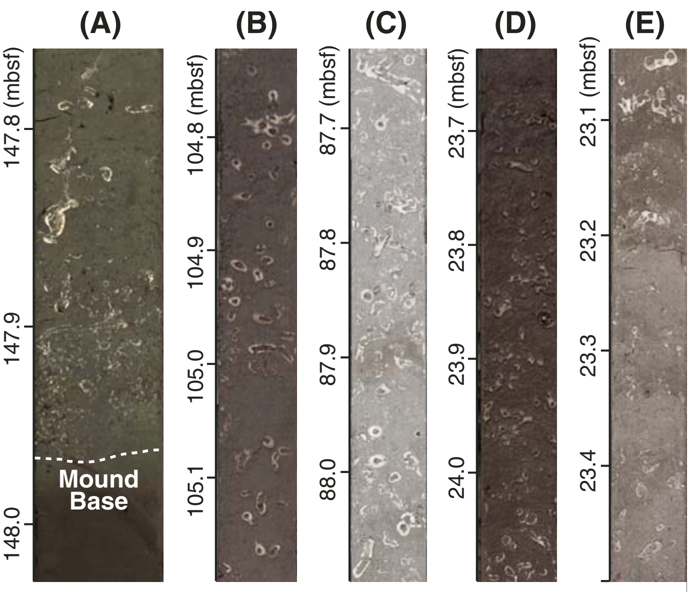

Figure 2. Core sediments from Challenger Mound. A: Mound base at Hole U1317C. B: Darker colored coral floatstone (U1317E). C: Lighter colored coral floatstone (U1317E). D: Darker colored sediment below unconformity at 23.6 m below seafloor (mbsf). E: Lighter colored sediment above unconformity.

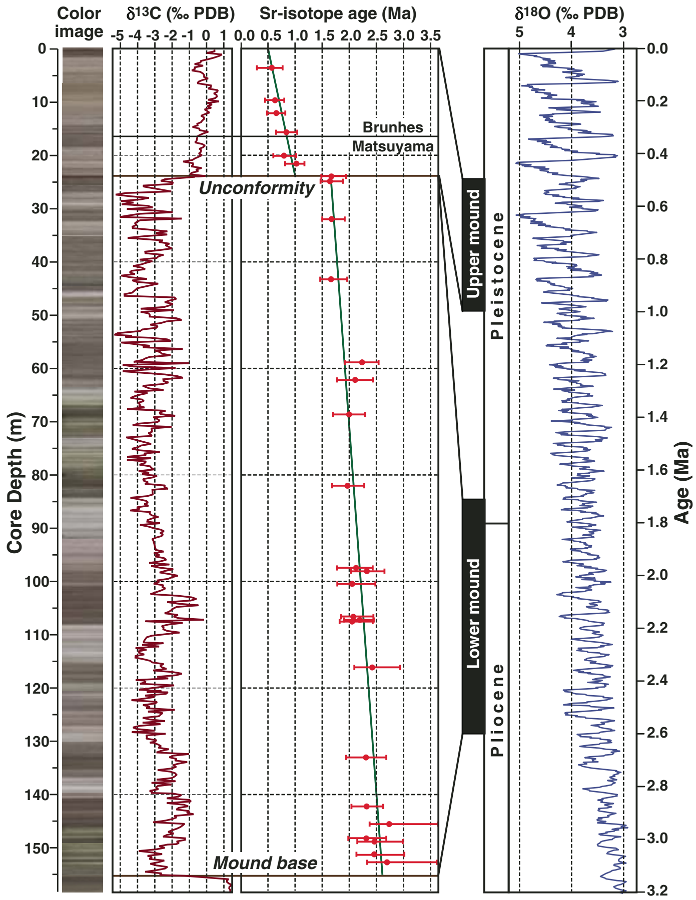

Figure 3. Color image of sediments, $\delta^{13}C$ of matrix, and Sr isotope stratigraphy of mound section (Hole U1317E). Estimated ages from 28 well-preserved coral specimens can be aligned on two straight lines separated at the unconformity. Depositional periods of lower and upper mounds are compared with composite benthic $\delta^{18}O$ curve of Lisiecki and Raymo (2005). PDB—Peedee belemnite. Data are provided in Table DR1 (see footnote 1).

STRONTIUM ISOTOPE STRATIGRAPHY

Aragonite coral skeletons throughout the mound sequence provide good material for Sr isotope dating. Well-preserved skeletons, consisting of 28 specimens of *L. pertusa* from Hole U1317E, 1 *L. pertusa* specimen from U1317D, and 11 corals (*L. pertusa*) and bivalves from 2 other sites (U1316 and U1318; GSA Data Repository Table DR1[1]), were selected for the measurement. After removing fine-grained sediments and rinsing in 1M HCl, the samples were dissolved in purified HNO_3 and Sr was separated on an ion-exchange column (Birck, 1986). The $^{87}Sr/^{86}Sr$ ratio was measured by thermal ionization mass spectrometry (Thermo/Finnigan TRITON) at Kochi Core Center, Japan. Separate analyses (n = 19) of NIST SRM 987 gave the average value of 0.7102543 ± 0.0000069 (2 standard deviation, SD). The reproducibility for the sample measurement (2 SD) was as good as the typical in-run precision of 0.0000070–0.0000090 (2σ). Ages were assigned by projection of the isotopic values to three (young, mean, and old) regression curves of LOWESS Look-up Table version 4 (revised from McArthur et al., 2001). Uncertainty of the estimated ages is <±0.35 m.y. for ages younger than 2.3 Ma, and generally increases with age (Table DR1).

Miocene ages for the siliciclastic units support an angular unconformity below the mound with a hiatus of considerable duration. The $^{87}Sr/^{86}Sr$ age at Site U1316 (16.58 Ma) is considerably older than the ages from the Miocene unit of Site U1318 (13.38–8.96 Ma).

Ages from the mound section (Hole U1317E) generally become younger from the base, 2.70 Ma, to the top, 0.57 Ma (Fig. 3). An abrupt shift from 1.67 to 1.03 Ma at 23.6 mbsf (that exceeds the range of error bars) strongly suggests an intramound unconformity. This horizon also corresponds to a sediment color change from darker (below, Fig. 2D) to lighter (above, Fig. 2E), and to the abrupt increase of $\delta^{13}C$ values of the matrix sediments (Fig. 3).

The depositional rate for the lower mound section, below the intramound unconformity (~15 cm/k.y.; 2.6–1.7 Ma), is three times larger than the rate in the upper mound section (~5 cm/k.y.; 1.0–0.5 Ma). Ages from 142 to 58 mbsf are mostly in a narrow range from 2.32 to 1.97 Ma (Fig. 3), and lead to a higher depositional rate (~24 cm/k.y.). The $^{87}Sr/^{86}Sr$ ages of the lower section are consistent with the first appearance datum of *G. inflata* (2.09 Ma) at 60 mbsf. However, they are older than the nannofossil biostratigraphic age of younger than 1.95 Ma for the base of the mound. In the upper section, the Sr isotope stratigraphy is consistent with both the nannofossil biostratigraphy and the magnetostratigraphy.

We also employed Sr isotopic distributions to evaluate the ages of critical horizons of off-mound Sites U1316 and U1318. *L. pertusa* from the coral-bearing unit at Site U1316 is assigned an age of 2.48 Ma, indicating that the mound started with a broad base and subsequently vertical growth was more focused. The age of a lone *L. pertusa* collected from the turbidites located at Site U1316 was as young as 0.43 Ma, but older than the nannofossil age of surrounding sediment (younger than 0.26 Ma). A mollusk shell of the thin sandstone unit on the Miocene at Site U1318 is dated as 1.24 Ma (Fig. 1B).

CONDITIONS FOR CORAL AND MOUND GROWTH

As a heterotrophic filter feeder, *L. pertusa* requires sufficient food availability and strong currents that provide food and sweep the polyps clean of detritus and sediment burial (Freiwald, 2002). Although it is a cold-water species, *L. pertusa* cannot survive in water masses colder than 4 °C (Roberts et al., 2005). In the Porcupine mound provinces, high organic productivity is related to downslope transport and associated with high chlorophyll concentration in the vicinity of the mounds (White et al., 2005). Conductivity, temperature, and depth (CTD) profiles show an increase in salinity around the depth boundary between Eastern North Atlantic Water (ENAW) and the underlying Mediterranean Water (MW) in a depth range from 800 to 1000 m (White, 2007). Due to the strong gradient in density at this water mass interface, organic material from the sea surface persists for a longer time at this level where the corals benefit from this enrichment of food particles. In general, current velocity of the mound areas is high (>15 cm/s, maximum 70 cm/s) owing to the breaking of internal tidal waves with the local morphology (White, 2007). The position and intensity of the currents associated with this internal wave system in Porcupine Seabight is closely linked to the wider outside oceanographic setting of the North Atlantic, especially the existence of MW (De Mol et al., 2005).

PALEOCEANOGAPHIC INFLUENCES ON MOUND GROWTH

Strontium isotope stratigraphy dates the base of Challenger Mound as ca. 2.6 Ma (Fig. 3), coincident with the major expansion of the Northern Hemisphere ice sheets dated as ca. 2.7 Ma in marine sedimentary records of ice-rafted debris, $\delta^{18}O$, and Mg/Ca (Shackleton et al., 1984; Dwyer et al., 1995). The presence of ice sheets and colder high latitudes led to increased formation of North Atlantic Deep Water, and establishment of modern North Atlantic stratification. A regional hiatus in Deep Sea Drilling Project cores in the northeast Atlantic has been interpreted to represent the reintroduction of MW into the northeast Atlantic at a similar date. This set up the necessary conditions for mound growth in the Porcupine Seabight, and has previously been suggested as a likely date for the start of mound development (Henriet et al., 2002; De Mol et al., 2002).

Once established, the growth of the coral mound responded to changing oceanographic conditions to produce dark glacial and lighter interglacial layers. Corals are abundant in both layers (Figs. 2B, 2C), there are no obvious hiatus surfaces, and $\delta^{18}O$ data vary smoothly (Sakai et al., 2006), so growth of the lower mound was probably continuous. This is in contrast to the upper parts of nearby Propeller Mound, where mound growth was restricted at the last glacial maximum because temperatures dropped below 4 °C and decreased MW caused limited food and nutrient availability at the depth of the mounds (Dorschel et al., 2005; van Rooij et al., 2007).

The amplitude of glacial-interglacial change has increased during the past 2.7 m.y. (e.g., Lisiecki and Raymo, 2005; Fig. 3). From 2.6 to 1.7 Ma, glacial conditions were not as severe as the last glacial maximum, and the amplitude of glacial-interglacial change was lower. We infer from the fast and continuous rate of mound growth during this time that the water temperature remained above 4 °C, and hydrodynamics in the Porcupine Seabight maintained food supply and current intensity at levels for *L. pertusa* to thrive. Environmental conditions became most favorable ca. 2 Ma, when Challenger Mound recorded its maximum growth rate. As the mound grew, its own topography protected it from significant burial, and sediment accumulation around its base forced the mound to grow vertically (De Mol et al., 2005).

Challenger Mound had grown to a height of 130 m before growth was interrupted ca. 1.7 Ma, close to the Pliocene-Pleistocene boundary (Fig. 2D). We infer that sea-bottom temperature or hydrology led to conditions beyond the habitable range of *L. pertusa* at this time, which could be related to an increasingly severe glacial interval ca. 1.6 Ma (Channell et al., 2006; Lisiecki and Raymo, 2005; Fig. 3). Alternatively, the food supply may have become insufficient on the mound summit as it grew above the level of the density gradient between ENAW and MW. We consider a slump possible, but the continuous layers across the mound (Williams et al., 2006) make it an unlikely explanation.

Buried mounds have been observed in seismic profiles of Porcupine Seabight, and their burial is thought to have begun in the late Pliocene or early Pleistocene, suggesting that cessation of mound growth was regional.

[1]GSA Data Repository item 2007255, Table DR1, Sr isotope ages from IODP Expedition 307, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

For example, in the Magellan Mound Province (Fig. 1A), several hundred mounds of smaller size (72 m high, 250 m wide on average) were buried under Pleistocene sediments (Huvenne et al., 2003). Unlike the buried mounds, Challenger Mound restarted its growth ca. 1.0 Ma, indicating that food supply and current intensity were reestablished on the summit of the mound. The abrupt increase of $\delta^{13}C$ values of the matrix sediments (Fig. 3) not only supports existence of the intramound unconformity, it also indicates changes in the circulation of the inorganic carbon or in the provenance of the carbonate sediment during the hiatus.

Sr isotope stratigraphy and nannofossil biostratigraphy indicate that the second growth stage stopped or shifted into erosional regime ca. 0.5 Ma. The lower-lying part of the mound slope was buried with fine-grained turbidites with ages younger than 0.26 Ma. The surface of Challenger Mound is now covered with sand and clay, including dropstones and coral debris (Foubert et al., 2005), while some deeper mounds in the Belgica Province are still alive; we therefore infer that the boundary between the ENAW and the MW deepened over this time.

CONCLUSION

The growth of Challenger Mound was closely related to major changes in Pliocene-Pleistocene paleoceanography, because of the sensitivity of the mound-building cold-water coral, *L. pertusa*, to food supply, temperature, and sediment, all of which are dependent on the presence of Mediterranean Water. Mound establishment coincides with the start of modern northeast Atlantic stratification ca. 2.6 Ma, then the mound grew rapidly until ca. 1.7 Ma (the Pliocene-Pleistocene boundary). A second growth phase lasted from ca.1.0 Ma (close to the mid-Pleistocene transition) until 0.5 Ma.

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