The Pleistocene Cooling Built Challenger Mound, a Deep-water Coral Mound in the NE Atlantic: Synthesis from IODP Expedition 307

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ABSTRACT

IODP Expedition 307 revealed the interior of a deep-water coral mound in NE Atlantic for the first time and improved our understanding of these intriguing structures. From the summit of our drilling target, Challenger Mound at ~800 m deep in the Porcupine Seabight, south west of Ireland, we recovered the entire mound section of 155 m long, which almost entirely consists of coral-bearing sediments and rests on the Miocene siliciclastics.

The mound initiation is temporally correlated to the global cooling at the beginning of Pleistocene, when modern circulation was established in Atlantic. A key oceanographic feature of the mound provinces is the density gradient that developed above the saline Mediterranean Outflow Water where organic particles persist for a longer time and fuel the coral communities.

Growth of the deep-water mounds reflected the glacial/interglacial change. Our age model recognized two growth stages separated by a substantial hiatus; the depositionally continuous lower mound (2.6-1.7 Ma) accumulated under the low-amplitude relative sea-level change, and the discontinuous upper mound (1.0 Ma to mid-Holocene) developed under the high-amplitude relative sea-level change. Low cellular abundances in the geochemical features of the mound sediments did not support the hypothesis that hydrocarbon seepage and associated microbial activity significantly enhanced mound initiation and development.

Key Words: deep-water coral mound, Pleistocene, IODP

ENIGMATIC MOUNDS ON THE SEAFLOOR

That non-photosynthetic coral communities can thrive at great depths of >1000 m has been known since the mid-eighteen century, but only in the 1960s did deep-sea exploration lead to the discovery of mound-like structures covered with corals (Stetson and Squires, 1962). These coral build-ups form up to several kilometer wide and up to 350 m high mounded topography on shelf slopes and seamounts in water-depths down to 1500 m Superficial biota and sediments associated with these unique ecosystems and geological structures have been revealed in subsequent oceanographic surveys over the last decade.

Despite recent and intense exploration, detailed information on the stratigraphy, lithology and geochemistry of deep-water coral mounds is very limited. To establish a depositional and biogeochemical/diagenetic model, Challenger Mound (Fig. 1; Site U1317, 52°23' N, 11°43' W, water depth = ca. 800m) in the Porcupine Seabight was drilled during the IODP Expedition 307 in May 2005. To place Challenger Mounds in the regional stratigraphic framework of the Northeastern Atlantic, we also drilled and examined two other sites: Site U1316 at the basin-ward foot of Challenger Mound and Site U1318 on the shallower shelf slope (Fig. 1).

PORCUPINE MOUND PROVINCE

The Porcupine Seabight, located to the west of Ireland, is a well-studied mound area in north Atlantic. In this 50 km long and 65 km wide embayment (Fig. 1), more than 2000 mounds cluster in four provinces (Magellan, Hovland, Viking, and Belgica; Fig. 1) at water depths ranging from 550 to 1030 m (Foubert and Henriet, 2009).

Mounds appear to align along bathymetric contours (Beyer et al., 2003) suggesting a preferential depth range. The hydrography of the Porcupine mound provinces is characterized by two stratified water masses: the warm Eastern North Atlantic Water (ENAW) flowing northwards within the upper 700 m and the saline Mediterranean Outflow Water (MOW) observed down to 1,200 m (De Mol et al., 2002). Living cold-water coral communities occur around the interface of ENAW and MOW, where the bottom current is strong due to internal waves and increases nutrient availability (White, 2007). Cold-water corals are heterotrophic filter feeders that rely on zooplankton and particulate organic matter (Kiriakoulakis et al., 2007).

Challenger Mound in the Belgica mound province (Fig. 1) has an elongated shape of ~1 km wide and ~150 m high. In the seismic profile, the mound occurs as a transparent seismic unit and roots on the sharp slope break of seismic unit (P1; Fig. 1).

SEDIMENTOLOGY AND STRATIGRAPHY

Challenger Mound (U1317)

Five holes (A-E) were drilled on the Challenger Mound in water depth ranging from 790 to 840 m. The four drilled holes (A-C, and E) a cross-section of the mound, in which the mound unit thins from the summit (Hole E) to the mound shoulder (Hole A; Fig. 2).

At Site U1317, we identified two major sedimentary units; the Pleistocene carbonate mound succession, and the Miocene calcareous silt and sandy silt (Ferdelman et al., 2006; Williams et al., 2006). A firmground consistently marks the contact between the two units (Fig. 3A), without any evidence of lithification. Lithification in the mound unit was recognized only in several intervals as irregular-shaped consolidated crusts (Fig. 3B).

The mound sediments consist of coral floatstone (Fig. 3C, D) to rudstone (Fig. 3E) with a wacke- to packstone matrix. The corals occur

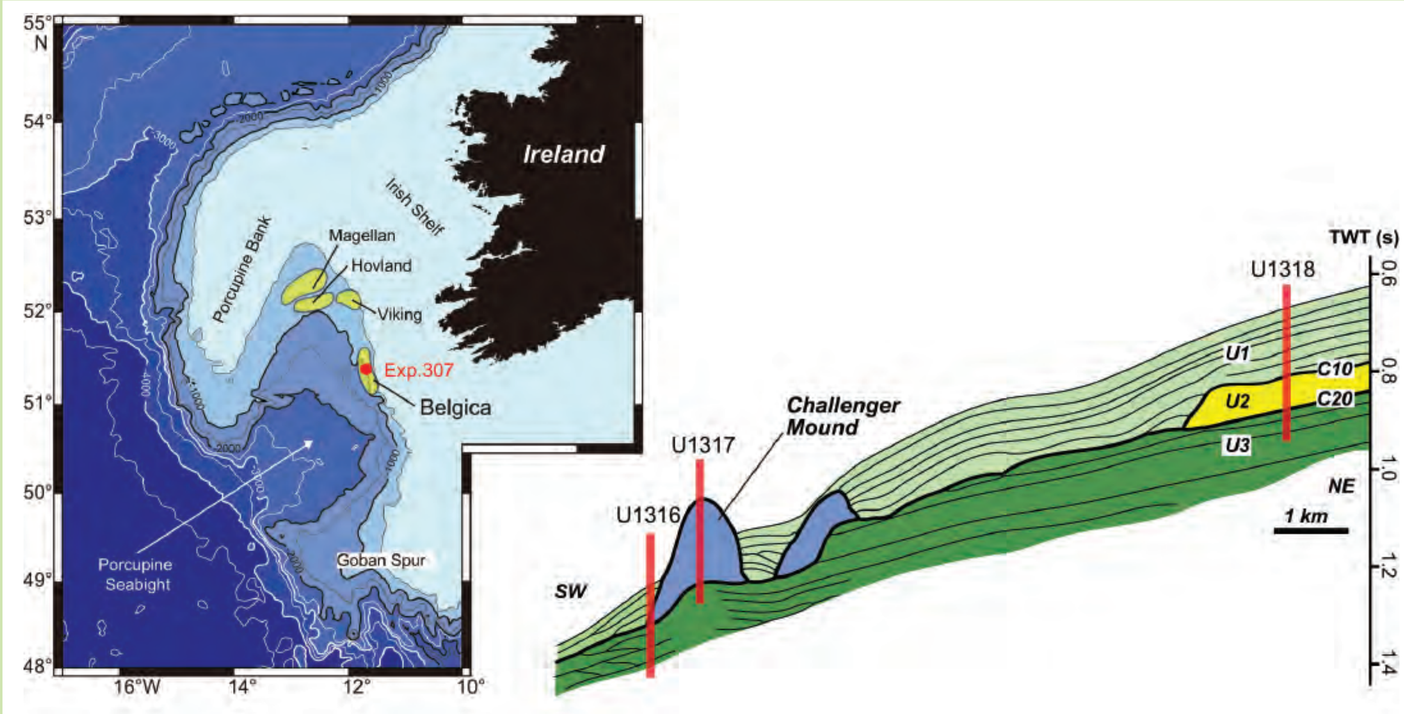

Figure 1. Location map showing the Belgica Mound Province in Porcupine Seabight, and interpreted seismic section (De Mol et al., 2002) showing three drilling sites (U1316-1318).

as branches of *Lophelia pertusa* (rarely *Madrepora oculata*) that forms up to 15% of the total sediment volume. The matrix is mixture of carbonates and siliciclastics.

Shipboard bio- and magneto-stratigraphy help placing the studied interval into a broad age framework. Especially significant are a continuous normal polarity signal in the uppermost 17 m that corresponds to the Brunhes chron (<0.78Ma), and the first appearance datum (FAD) of planktonic foraminifera *Globorotalia inflata* (2.09Ma) at ~65 mbsf (meter below sea floor) of Hole U1317E (Fig. 4). The age model was improved by integrating the Sr isotope stratigraphy of coral skeletons (Kano et al., 2007) resulting in ages generally becoming younger from ~2.60 Ma near the base to 0.57 Ma near the top (Fig. 4). This age model also revealed a significant hiatus of 0.7 Myr (1.7-1.0 Ma) within the mound succession at 23.6 mbsf. The hiatus defines the boundary between the lower mound and the upper mound (Fig. 4) and is accompanied by a sharp decline in the magnetic susceptibility and NGR that were also observed in the other holes (Fig. 2; Foubert and Henriet, 2009).

Cyclic fluctuations of 10-20 m wavelength appear in lithological properties in the lower mound. The lighter colored deposits (Fig. 3C) are high in carbonate content (up to 84%), while the darker colored deposits (Fig. 3D) record high values of magnetic susceptibility, natural gamma radiation and siliciclastic fraction (Titschack et al., 2009). This cyclicity correlates well with Pleistocene glacial-interglacial fluctuations, as confirmed by $\delta^{18}O$ of planktic foraminifer (*Globigerina bulloides*) (Fig. 4; Sakai et al., 2009). The lighter interglacial layers generally have a coarse grained (typically ~50 µm) matrix winnowed by strong contour current, while the darker glacial layers contains much finer fraction (~20 µm) likely originated from ice-rafted clay (Thierens et al., 2010).

Sakai et al. (2009) recognized eleven glacial and ten interglacial intervals from the lower mound succession, which were correlated to the interval from MIS 92 (2.24 Ma) to 72 (1.82 Ma) by slightly adjusting the FAD of G. *inflata* (2.09 Ma) to 63 mbsf. However, development of the lower mound was not continuous, especially at the mound initiation stage, in which Titschack et al. (2009) observed four possible erosional surfaces.

Erosional surfaces are more common in the upper mound where a subtle cyclic change in the $\delta^{18}O$ records (Fig. 4) is observed. Since the upper mound includes the boundary between the Brunhes/Matuyama chrons, this interval was correlated to MIS 19 and 18 (0.8-0.7 Ma) by Sakai et al. (2009). However, this correlation disagrees with the longer age range (~1.0-0.5 Ma) estimated by Sr isotopic ages (Kano et al., 2007). The inconsistency can be interpreted as a result of the discontinuous deposition that has lasted at least until middle Holocene. The upper mound obviously includes several hiatal horizons, for which the age gaps have not accurately evaluated by the available methods.

Off-Mound Sites (U1316 AND U1318)

The most extensive sedimentary sequence below the mound-base unconformity was recovered upslope at Hole U1318B (Fig. 1). The 155-m-thick Miocene sequence (Late Burdigalian to Late Serravallian; Louwye et al., 2008) includes two seismic units U3 and U2 that are separated by an interpreted unconformity C20 (Fig. 1; Stocker et al., 2001). However both dinoflagellate biostratigraphy and magnetostratigraphy did not show any hiatus corresponding to the C20 unconformity (Louwye et al., 2008) compared to the mound-base angular unconformity (C10 in Fig. 1) which corresponds a substantial age gap of more than 7 Ma.

In well U1316, a 2-4 m thick coral-bearing unit overlies the Miocene sequence at the base of the mound. This unit is made of coral floatstone alternated with sandstone facies. At the shelf margin site (U1318), the post-Miocene sequence consists of a 4-6 m thick glauconitic sandstone which includes black apatite nodules, bivalves (Fig. 3F), and dropstones. The Sr isotopic ratio of a bivalve indicates an age ranging from 1.3 to 1.1 Ma (Kano et al., 2007), which corresponds to the major hiatus interval of Challenger Mound. The age is consistent with nannofossil assemblage indicating the early Pleistocene

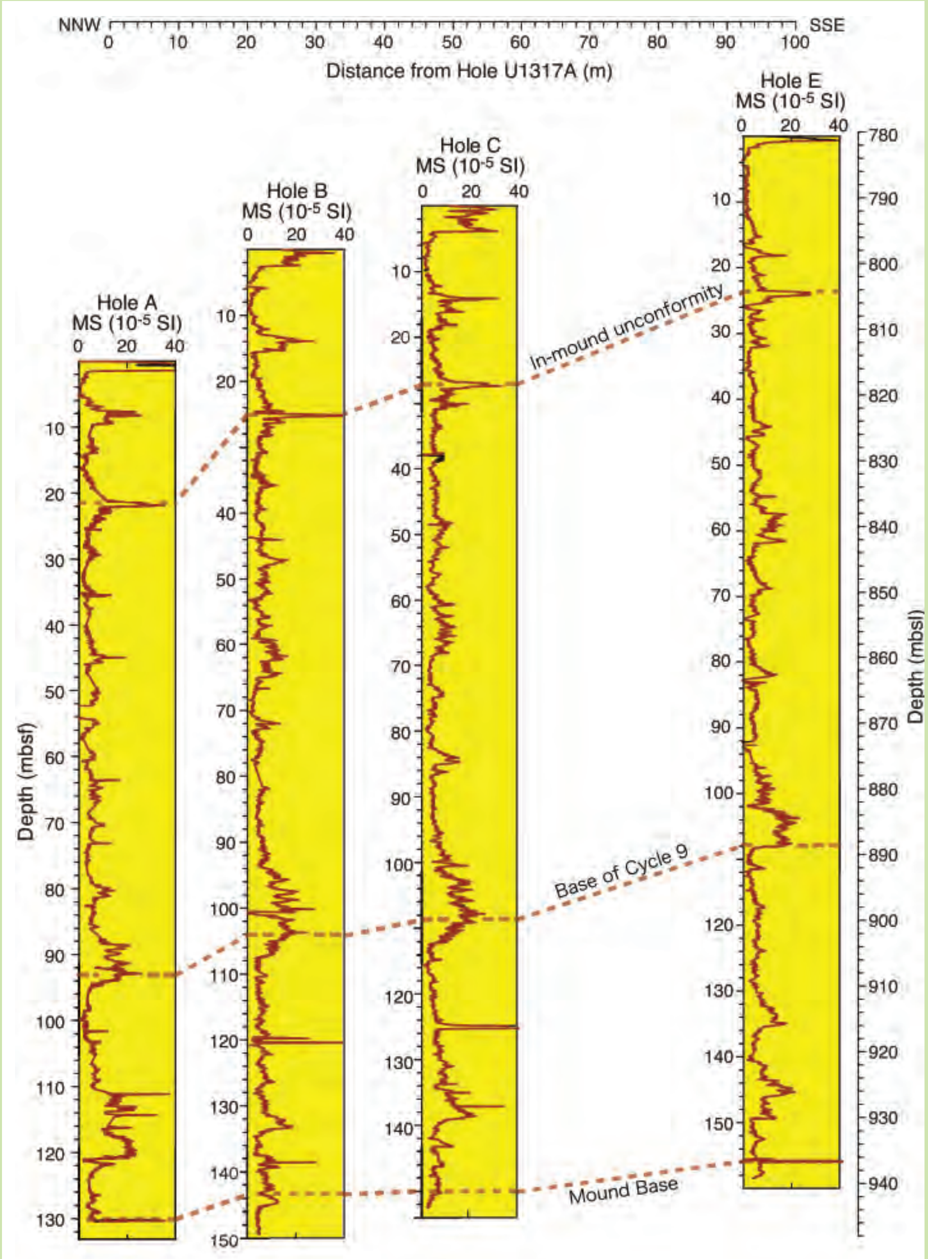

Figure 2. Correlation of the four drilled holes at Site U1317 based on stratigraphic profile of magnetic susceptibility (SI).

small *Gephyrocapsa* Zone (0.96-1.22 Ma).

The uppermost unit at Sites U1318 and U1316 consists of greyish brown silty clay interbedded with sandy layers, correlated with the seismic unit U1 (Fig. 1). This unconsolidated silty clay has characteristic cm-scale lamination (Fig. 3G) or is otherwise bioturbated. Dropstones are common in the upper part of the unit. Except for the lowermost part, the silty clay yields *E. huxleyi* indicating an age younger than 0.24 Ma.

MOUND GROWTH AND INTERNAL LIFE

Analysis of the IODP Expedition 307 data indicates a link between paleoclimates and the growth of the deep-sea coral mound. Challenger Mound started growing around 2.6 Ma, approximately corresponding to newly-ratified base of the Quaternary (2.58 Ma; Gibbard et al., 2010) when there was a step to cooler global temperatures and modern Atlantic circulation began. At this time when the density gradient developed between the Mediterranean Outflow Water (MOW) and the overlying Eastern North Atlantic Water (ENAW) (De Mol et al., 2002), organic particles became concentrated at this boundary, providing food to the coral mound community. Moreover, living cold-water corals appear to be confined to a narrow range of water density (Dullo et al., 2008); suggesting that this condition first arose in the Porcupine Seabight at ~2.6 Ma. The Pleistocene global cooling amplified the glacial/interglacial cycles that were recorded in the mound sediment (Fig. 4). The amplified climate change may also have inhibited the mound growth itself. We observe that the lower mound appeared to have grown quickly when the amplitude of the change in sea-level was small. A large change in sea-level and concurrent change in the positioning of the density gradient between MOW and ENAW would have diminished food supply and coral growth.

Beside these environmental controls, processes associated with hydrocarbon seepage have been proposed to initiate and enhance mound development, as high seawater methane concentrations have been reported in near some of the mound provinces (Hovland et al., 1998). Furthermore, Paull et al. (1992) proposed that anaerobic oxidation of methane (AOM) induces increased alkalinity that results in enhanced hardground development that in turn provides suitable substrate for the corals.

Expedition 307 tested this hydrocarbon hypothesis. The first geochemical and lithological analyses quickly discounted a role for methane seepage and subsequent AOM (Ferdelman et al., 2006). The present-day zone of AMO is not within the mound sediments, but occurs in the sub-mound Miocene sediments, and there appears to be no indication of a present or past AOM signal in the dissolved methane (Mangelsdorf et al., 2010).

Mound coral ecosystems have been proposed to be "hotspots" of organic carbon mineralization and deep sub-seafloor microbial systems. However, compared with other deeply-buried, continental-margin microbial ecosystems, the Challenger Mound sediments exhibit very low rates of organic carbon turnover (Table 1). Moreover, abundances of bacteria and archaea were consistently low throughout the mound sediments itself (Webster et al., 2009). Biomarker data analysis also shows evidence of low abundance of past populations, whereas present-day bacterial populations were below the detection limit for intact phospholipid determination (Mangelsdorf et al., 2010). Interestingly, both biomarker lipid distributions and cell abundances (Webster et al., 2009) suggest that the underlying Miocene sediments, as well as the sediments from the off-mound Site U1318 contain higher abundances of living microbes. Thus, rates of microbial processes within the mound sediments are extremely low and largely decoupled from the highly diverse, active surface ecosystem (Wehrmann et al., 2009). Such microbial processes play a role in pore water and mineral diagenesis (Frank et al., 2010), but are very unlikely to contribute to the initiation and growth of the coral mound.

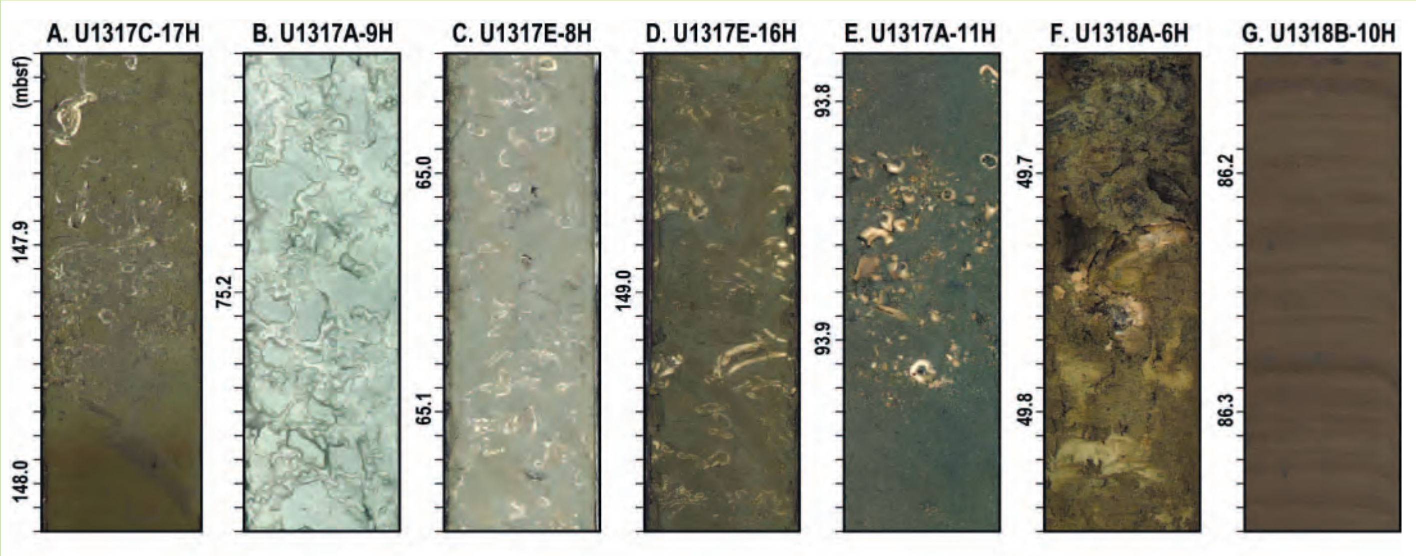

Figure 3. Selected core images (20 cm long) from IODP Expedition 307. A. Mound base in Hole U1317C. B. Lithified mound sediment in U1317A. C. Lighter colored coral bafflestone in U1317E. D. Darker colored coral bafflestone in U1317E. E. Coral rudstone in U1317A. F. Bivalve-bearing sandy sediment in U1318A. G. Laminated silty clay in U1318B.

CONCLUSIONS

Our results imply that global and local oceanographic conditions were essential for the mound initiation and growth. The coral community started growing as the same time as the onset of the Pleistocene cooling. Subsequent mound growth was divided into two stages in response to different amplitudes in the climatic change; the relatively continuous lower mound accumulated under the low-amplitude relative sea-level change, and the discontinuous upper mound developed under the high-amplitude change (Fig. 4). Accumulation of drift sediment around the mound did not start until after mound growth ceased (Huvenne et al., 2009).

This control on the initiation and development of Challenger Mound may not be generalized to other deep see mounds but it does suggest future research perspectives such as whether the onset of mound development is a global geological episode that corresponds to the onset of Quaternary. Mounds in the Belgica province all root on the post-Miocene unconformity (van Rooij et al., 2003), but some, like Challenger Mound, are currently dormant and not growing, while others host active growing coral communities. We predict that each mound has its own growth history, depending on its latitude, depth, and position in the oceanographic circulation. Drilling other deep sea mounds will test this prediction.

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	10^{-4}mol m^{-2} a^{-1}	
	SO42-	CH4
Mound **0 - 130 mbsf**	-6.5	-0.4
Sub-Mound Miocene Sediments **130 - 270 mbsf**	-1.6	-1.2
Total	-8.1	-1.6
Peru Margin (ODP 201)	-90 to -250	

Table 1. Fluxes of methane and sulfate as indicators of anaerobic oxidation of methane and sulfate reduction. Interstitial water distributions of SO_4^{2-} and methane were modelled using a one-dimensional, steady-state diagenetic model. Formation factors were estimated from porosities (ϕ) obtained onboard during Exp 307 (Ferdelman et al., 2006), and the relationship Ds= ϕ2D to correct the diffusion coefficients for tortuosity. For comparison, integrated sulfate reduction rates from the continental margin of Peru are included (D'Hondt et al., 2004).

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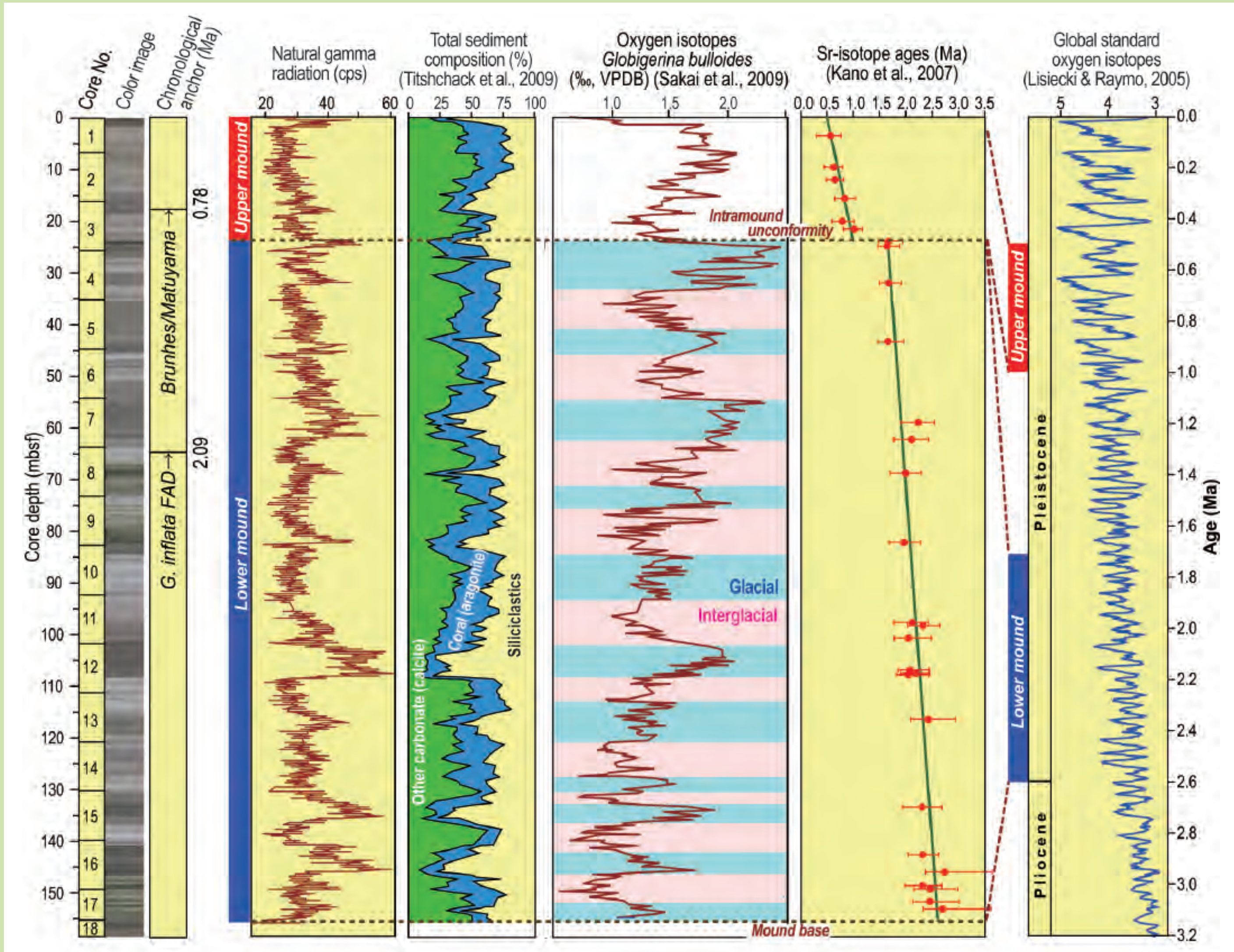

Figure 4. Stratigraphic and geochemical profiles of the mound sequence at Hole U1317E.

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