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Carbonate mound development at the SW Rockall Trough margin based on high resolution TOBI and seismic recording

F. Mienis [a,*], T. van Weering [a,b], H. de Haas [a], H. de Stigter [a], V. Huvenne [c], A. Wheeler [d]

[a] *Royal Netherlands Institute for Sea Research (NIOZ), P.O. Box 59, 1790 AB, Den Burg (Texel), The Netherlands*
[b] *Free University, Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*
[c] *National Oceanography Centre, Southampton, Empress Dock, European Way, Southampton SO14ZH, United Kingdom*
[d] *Department of Geology, University College Cork, Cork, Ireland*

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Abstract

In 2002, high-resolution sidescan sonar images of a mound area at the SW Rockall Trough margin were recorded with the TOBI deep towed sidescan sonar. Processed TOBI images with a pixel resolution of 6 m provide a unique overview of the carbonate mound distribution and related sedimentary features around the mounds. Three morphologically distinct areas can be recognised on the TOBI mosaic. In area I (between 500 and 600 m water depth), upslope of the mounds, giant sediment waves are found with wavelengths up to 500 m, with wave crests of more than 10 km long and with an amplitude of up to 30 m, reflected with a high backscatter on the TOBI image. Area II (between 600 and 1000 m water depth), along the upper margin flank, is characterised by clustered and isolated carbonate mounds, forming elongated ridges with an orientation perpendicular to the slope. Sedimentary structures such as flow ridges, sediment waves, local scouring at the foot of some mounds and draping of sediment around mounds indicate the influence of strong near-bed currents, oriented in two main current directions parallel to the margin, as well as in a similar direction as the mound clusters. The mound clusters are several kilometres long, can be over 380 m high and are dissected by downslope directed channels. On the TOBI image, the mounds appear as regions of high backscatter caused by the presence of cold water coral colonies on the sediment and by distinct shadows. All mounds have their tops at a specific depth level (500–600 m water depth). Area III (between 900 and 1200 m water depth) below the mounds is characterised by disturbed sediments with distinct slump scars and flow ridges.

2D high resolution seismic profiling perpendicular and parallel to the slope across the mounds does in general not reveal strong internal reflectors within the mounds. In contrast, three strong reflectors can be observed in the sedimentary sequence underneath the mounds. The upper reflector C10 (of early Pliocene age) is an erosional unconformity, above which most of the mounds and sediment waves seem to have developed. The second erosional unconformity C20 (of middle Miocene age) is formed by an apparent irregular surface that locally is dissected by some small faults. Reflectors C10 and C20 have been found in two different mound clusters in the mound area, indicating that mound development possibly started after formation of reflector C20. The third reflector forms the acoustic basement, which is locally dissected by some small faults that are located below the mounds. At least two stages of mound formation are recognised on the seismic profiles.

Keywords: high-resolution sidescan sonar; TOBI; carbonate mounds; sediment waves; seismic profiles; cold water corals

* Corresponding author. Tel.: +31 222369393; fax: +31 222319674.
E-mail address: fmienis@nioz.nl (F. Mienis).

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1. Introduction

Carbonate mounds have been found at many places on the margins of the North Atlantic Ocean, but are especially common in the Northeast Atlantic region. Mounds have been described from the Norwegian margin, Porcupine Bank and Porcupine Seabight, and of the margins of the Rockall Trough (Le Danois, 1948; Hovland et al., 1994; Freiwald, 1998; De Mol et al., 2002; Freiwald, 2002; Akhmetzhanov et al., 2003; Kenyon et al., 2003; Van Weering et al., 2003a). 2D and 3D seismic profiles of the southwest margin of the Rockall Trough (SW RT) showed the presence of seabed mounds with different shapes, sizes and settings (Akhmetzhanov et al., 2003; Kenyon et al., 2003; Van Weering et al., 2003a,b). Recent studies, including sediment sampling, underwater photography and ROV guided video surveys, have shown that tops of the mounds are covered with a thriving community of living cold water corals, mainly of the a-hermatypic corals *Lophelia pertusa* and *Madrepora oculata* (Van Weering, 1999; De Haas et al., 2000; De Stigter and De Haas, 2001; Olu-Le Roy et al., 2002; De Haas and Mienis, 2003).

The objective of this article is to discuss the distribution, topography, morphology and sedimentary setting of the SW RT mound area (~3500 km^2) (Fig. 1), based on a high-resolution sidescan sonar mosaic composed of the Towed Ocean Bottom Instrument (TOBI) records from a cruise carried out in 2002 with the *R.V. Pelagia*, in combination with and complemented by

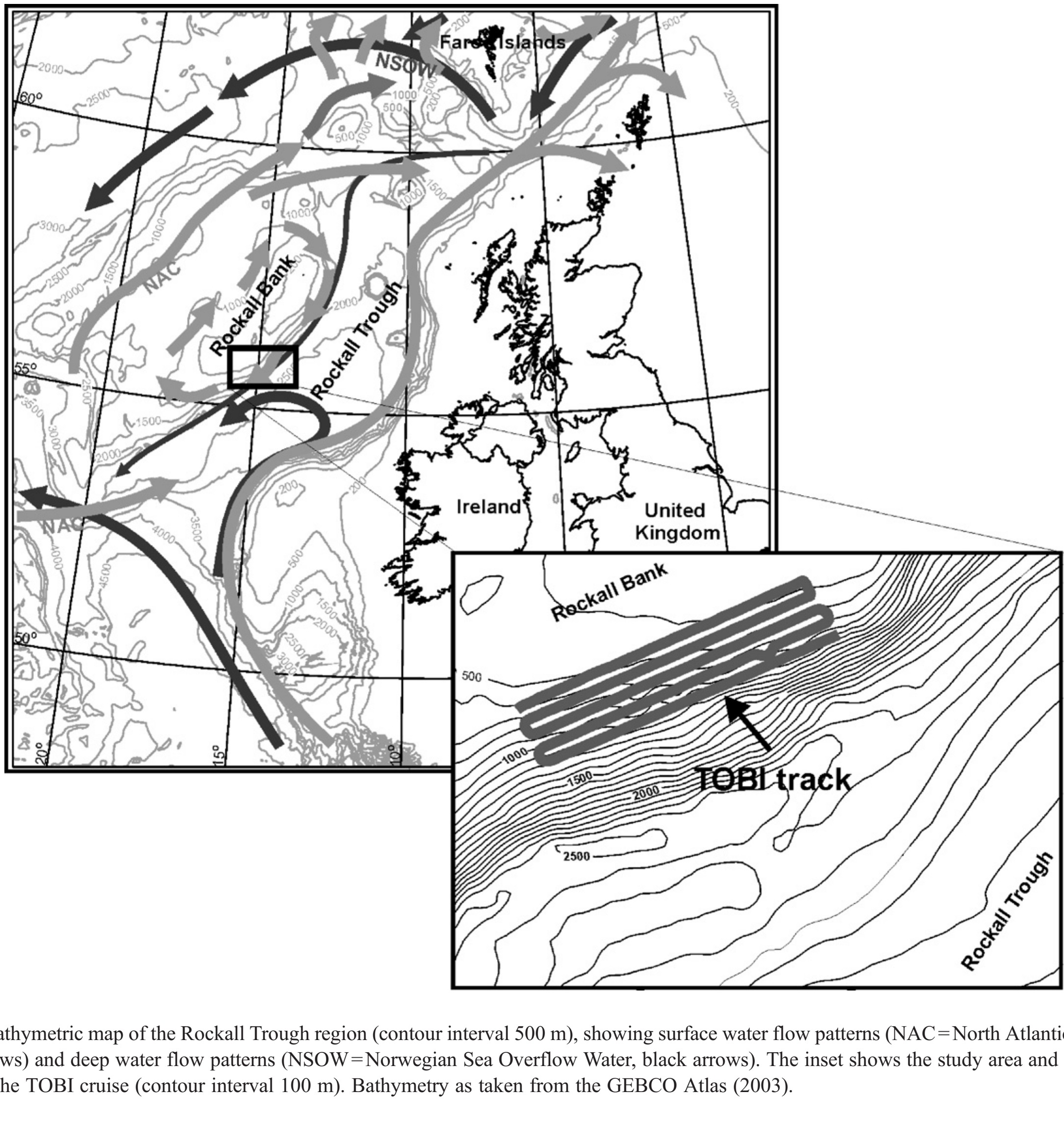

Fig. 1. Bathymetric map of the Rockall Trough region (contour interval 500 m), showing surface water flow patterns (NAC = North Atlantic Current, grey arrows) and deep water flow patterns (NSOW = Norwegian Sea Overflow Water, black arrows). The inset shows the study area and the ship's track of the TOBI cruise (contour interval 100 m). Bathymetry as taken from the GEBCO Atlas (2003).

newly recorded seismic profiles, sediment samples and underwater imagery. The area of studies has been extended considerably and covers the entire SW RT mound area, in contrast to the limited scale studies reported before (Akhmetzhanov et al., 2003; Kenyon et al., 2003; Van Weering et al., 2003a,b).

1.1. Geological setting

The Rockall Trough and Rockall Bank form part of the British and Irish continental margin (Fig. 1). This area consists of several deep basins, separated by basement ridges (O'Reilly et al., 1996; Boldreel and Andersen, 1998; Stoker et al., 2002). The Rockall Trough is a basin, which is bound to the north by the Wyville Thomson Ridge and deepens in the southwest into the Porcupine Abyssal Plain. To the west, the Rockall Trough is bounded by the shallow Rockall Bank.

Prior to the opening of the North Atlantic in the Mesozoic–early Cenozoic, extensive volcanism occurred and a thick succession of volcanic rocks formed in the region (Boldreel and Andersen, 1998; Svaerdborg, 1998). The post-break-up history of the RT and margin areas has been dominated by subsidence outpacing sedimentation. Subsidence is implied by the shut down of shelf derived sediment sources and the change to a bottom current influenced deep-sea environment (Stoker et al., 1998, 2002, 2005). During the Cenozoic, two major events affected the Northeast Atlantic margin. These events can be observed as regional unconformities on seismic profiles. Based on correlation with borehole data from the Rockall Trough, at ODP sites 610 and 980, ages have been assigned to these unconformities (Stoker et al., 2005). The youngest event, unconformity C10 (Stoker et al., 2002), is of late early Pliocene age and is considered as related to the uplift and erosion of Britain, Ireland and the Faeroe Islands. Subsequently, an erosional unconformity formed due to an increase in bottom current activity in the Rockall Trough region (Stoker et al., 2001, 2005). The Oligocene/early Miocene event, unconformity C20 (Stoker et al., 2002), marks the onset of deep-water exchange between the Arctic and North Atlantic Ocean. The present day morphology of the western margin of the Rockall Trough is mainly shaped by along slope and downslope sediment transport (Unnithan et al., 2001; Stoker et al., 2005).

1.2. Mound distribution

The mounds at the SW RT margin are arranged in elongated clusters of several kilometres long with a north–south orientation perpendicular or slightly oblique to the depth contours and occur in a narrow zone between 600 and 1000 m water depth.

A similar narrow depth range has been observed in nearby mound provinces offshore Ireland. The Belgica mound belt in the Porcupine Seabight occurs between 700 and 1000 m water depth and mounds are also oriented parallel or slightly oblique to the slope of the margin. The mounds however differ considerably in shape from those found at the SW RT Margin. Mainly single isolated mounds occur here of 1.5 km long and up to 100 m high (De Mol et al., 2002; Huvenne et al., 2002; Beyer et al., 2003; Van Rooij et al., 2003).

From the Southeast Rockall Trough (SE RT) margin mainly isolated single as well as some clustered mounds have been described, with sediment tails in the down-current direction behind the mounds (Akhmetzhanov et al., 2003; Van Weering et al., 2003b). These mounds are up to 100 m high, 1–2 km long and are mainly found at the upper slope between 650 and 900 m water depth (Van Weering et al., 2003b).

Along the Norwegian margin, coral reefs are found at shallower depths, between 250 and 500 m water depth. The Sula Ridge on the Norwegian shelf forms an asymmetrical elongated spur at 250–320 m water depth. Reefs are concentrated near the summit of the Sula Ridge escarpment (Freiwald et al., 1997; Hovland et al., 1998; Hovland and Mortensen, 1999; Hovland and Risk, 2003), have maximum lengths of ~13 km and are up to 20 m high. Coral reef mounds in fjords along the Norwegian coast are mainly found on top of topographic highs like sills or morainic ridges (Freiwald et al., 1997; Freiwald, 2002).

Along the Florida-Hatteras slope reefs show as elongated mounds parallel to the current direction (Neumann et al., 1977). Mainly single lithoherms have been found there, but also a mound cluster of 4.4 km long, 600 m wide and 150 m high locally occurs (Paull et al., 2000).

To summarise, mound provinces in the North Atlantic are related to the presence of a slope, an escarpment or ridge with the mounds mainly occurring within a confined depth range.

1.3. Mounds and corals

Mounds at the Rockall Trough margins occur as either single isolated mounds or appear as clusters (Akhmetzhanov et al., 2003; Kenyon et al., 2003; Van Weering et al., 2003b). The mounds at the Rockall Trough margins have been described as framework building reefs in which a 3D framework of coral branches acts as a trap for sediment, giving the mounds steep slope angles of on average 25° (Wilson, 1979; Freiwald et al., 1997; De Mol et al., 2002; Dorschel et al., 2005). These build-ups are considered as cold water coral mounds, because of their sediment composition (De Haas et al., 2000; De Stigter and De Haas, 2001; Dorschel et al., in press). In between the coral branches, mainly foraminiferal sand and carbonate mud is found (De Haas et al., 2000; De Mol et al., 2002; Kenyon et al., 2003). On the mounds, living and dead coral patches are found that may cause irregular internal structures on seismic profiles (Akhmetzhanov et al., 2003; Van Weering et al., 2003b).

Different hypotheses exist to explain mound formation. Hovland et al. (1994) and Henriet et al. (1998) considered that the development of mounds might be related to deep-seated faults, which would have formed conduits for seepage of hydrocarbons. In this view, the carbonate mounds at the Rockall Trough and the Porcupine Bight margins would form the final phase of a natural seep sealing process (Hovland et al., 1998). This has resulted in the present ecosystem in equilibrium with extant conditions at the seabed and overlying water column. However, no evidence for the presence of any seepage has been found on either margin of the Rockall Trough and in the Porcupine Seabight (De Mol et al., 2002; Bailey et al., 2003; Huvenne et al., 2003; Kenyon et al., 2003).

Another hypothesis is that external forcing conditions determine coral growth and mound formation. Local currents influence mound formation, creating conditions at the seabed comparable with the highly turbid environment of tropical reefs (Rogers, 1999). Corals thus benefit from flow acceleration and the interaction of seamount topography with local hydrography (Genin et al., 1986; Frederiksen et al., 1992; Huvenne et al., 2003). Currents or internal waves are considered to cause enhanced particulate organic matter concentrations in the benthic boundary layer and prevent the corals from sedimentation (Kenyon, 1987; Frederiksen et al., 1992; De Stigter et al., 2003; Kenyon et al., 2003; White, 2003; White et al., 2005).

1.4. Oceanographic setting

The Rockall Trough is a pathway for the flow of warm and saline waters to the Nordic Seas. This water is transformed in the Norwegian Greenland Seas into cold, south flowing water (Norwegian Sea Overflow Water) that enters the North Atlantic Ocean via the Denmark Strait and the Faeroe Shetland Channel (Holliday et al., 2000; New et al., 2001; New and Smythe-Wright, 2001; White et al., 2005). Two water masses are distinguished in the Rockall region that influence the mound area (Fig. 1). The upper water mass can be compared in temperature and salinity with the Eastern North Atlantic Central Water (ENAW). The ENAW water originates in the Bay of Biscay and is fed by a small branch of the North Atlantic Current (NAC) (Van Aken and Becker, 1996; Hansen and Osterhus, 2000).

Labrador Sea Water (LSW), characterised by low temperature and salinity, is found below 1200 m water depth (New and Smythe-Wright, 2001). A permanent pycnocline is observed between the warmer and saltier ENAW and the cool and fresh LSW (Holliday et al., 2000). ENAW flows clockwise around the Rockall Bank, while the LSW performs an anti-clockwise circulation in the Rockall Trough. Water masses below 1200 m depth are confined by the Wyville Tomson Ridge in the northern Rockall Trough (New and Smythe-Wright, 2001; White et al., 2005). On the Rockall Trough margins, tidal currents and internal waves have been observed. Here the highest tidal energy is found at the shelf edge, decreasing into deeper water (Dickson and McCave, 1986; Huthnance, 1986; White, 2001; White et al., 2005).

2. Methods

2.1. TOBI, sidescan sonar recording

The data used in this article have been collected during several cruises with the *R.V. Pelagia* between 1999 and 2003. During the 2002 cruise, a high-resolution deep towed TOBI sidescan sonar was deployed, providing a detailed sidescan sonar map of the SW Rockall Trough margin, which clearly showed the distribution of mounds and seabed morphology and structures in detail.

TOBI is a 30 kHz sidescan sonar with a swath range of up to 6 km. During the cruise, TOBI was towed at ~350 m above the seabed, with a constant speed of 2.4 knots. Recorded data was processed on a UNIX workstation, using PRISM (Processing Remotely sensed Imagery for Seafloor Mapping) software (Le Bas, 2002). Subsequently, the files have been imported in the image processing software Erdas to create the final images. Overlapping areas have been combined to one layer and a mosaic of all the maps was prepared, resulting in the final TOBI image. Swath bathymetry obtained from the Irish Geological Survey was used to produce 3D images of the TOBI mosaic in the Erdas program.

On the TOBI mosaic, the amount of backscatter of the seafloor is shown in different grey scales. Regions with high backscatter are depicted as light areas, while

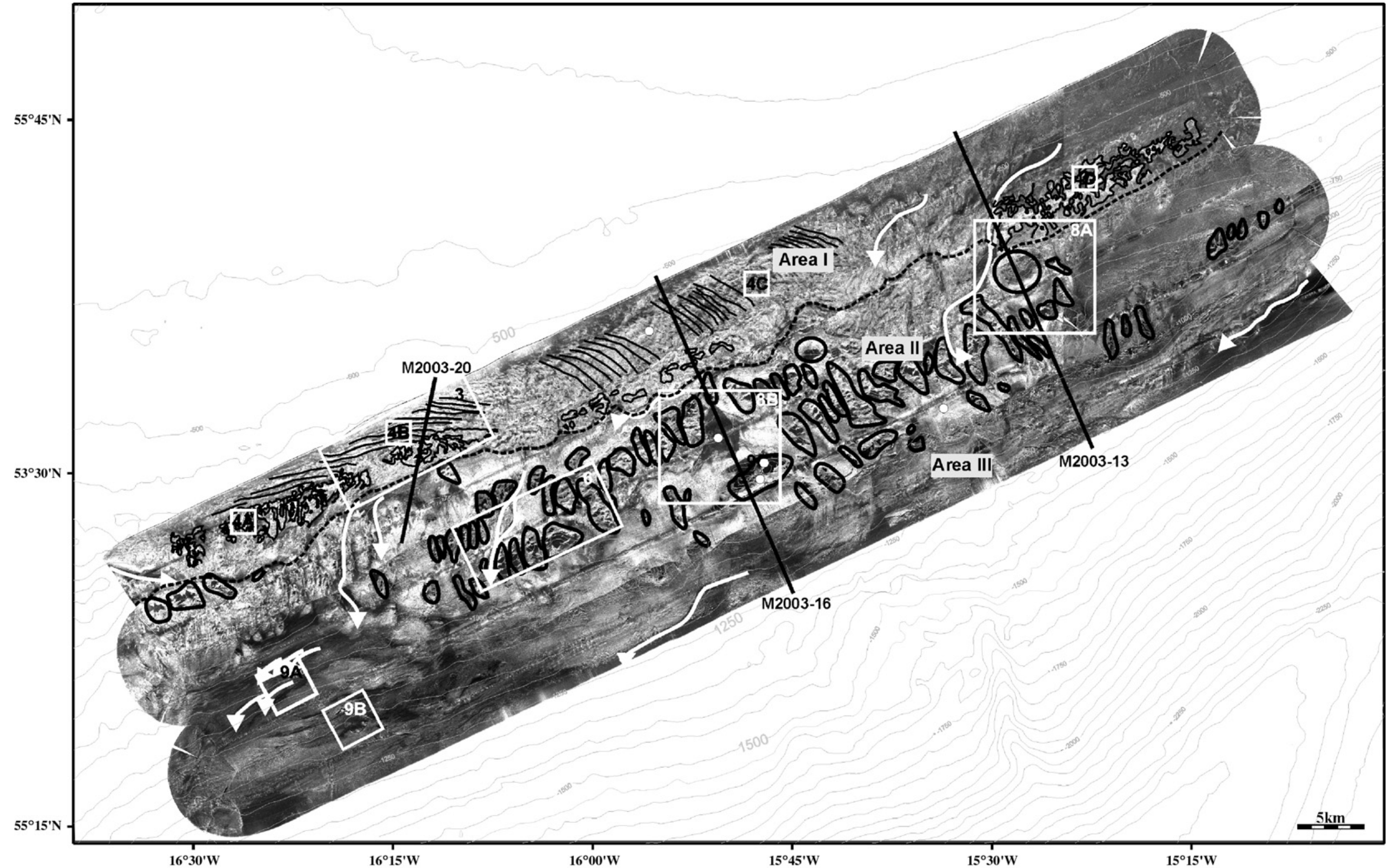

Fig. 2. Overview of the TOBI mosaic recorded at the SW Rockall Trough margin with bathymetry (contour interval 50 m). The area can be divided in three subareas. White arrows show major flow patterns. Black lines indicate the position of seismic lines, shown in Figs. 10–12. The white blocks indicate positions of (Figs. 3, 4, 6, 8 and 9), and white dots indicate photograph stations.

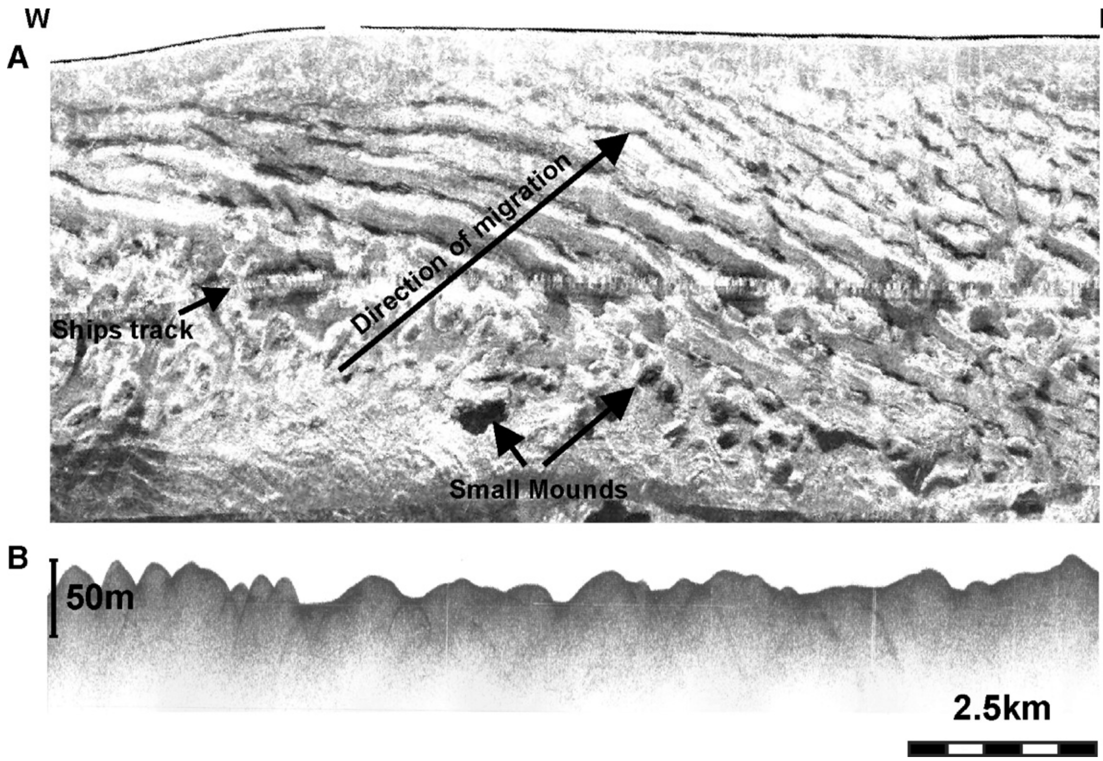

Fig. 3. (A) Enlarged part of the TOBI mosaic showing the presence of large sediment waves that are more than 10 km long having a NW–SE orientation. The leeward side of the waves is shown as high backscatter (white) areas on the TOBI image. The ripples appear to migrate in an upslope direction. Elevations with distinct shadows below the sediment waves are interpreted as small mound structures. (B) Corresponding echosounder profile along ship's track, showing symmetric and asymmetrical sediment waves up to 30 m high.

regions with low backscatter are shown in different shades of grey. Areas of zero backscatter, like shadows appear as black. The amount of backscatter depends on a variety of factors like the angle of incidence, the sediment composition and the roughness of the seafloor (Blondel and Murton, 1997).

The echosounder onboard of the *R.V. Pelagia* is an Oretech 3.5 kHz 3010 transceiver with a hull mounted transducer array. This system was used during the TOBI survey to obtain an additional overview of the bathymetry of the research area.

2.2. Seismic profiling

Seismic profiles have been recorded to study the geometry, architecture and internal structure of the mounds. During a cruise in 2003, a tuned array of 4 TI SG-I sleeve guns (10, 20 and 2×40 in.^{3}) shooting at an average pressure of 110 bars, with a shooting interval of 7 s was used as a sound source. The receiver consisted of a 6-channel Teledyne streamer, with three sections of two channels each. Seismic recording was done with a Delph Elics system; the seismic records were processed with PROMAX software. During processing, the data were stacked, deconvoluted and migrated. Interpretation of the seismic records was done by using the Kingdom Suite software.

3. Results

3.1. TOBI sidescan sonar

A total area of 100 km long and 25 km wide on the SW Rockall Trough margin with a water depth ranging from about 500 to 1200 m (Fig. 2) was mapped with the TOBI sidescan sonar. In this study area, three sub-areas with strongly different seabed characteristics can be recognised. *Area I*, in water depths of 500 and 600 m, is characterised by the presence of large sediment waves and small mounds. These sediment waves can be 10 km long and up to 30 m high. *Area II*, extending from 600 to 1000 m water depth, is characterised by elongated mound clusters and individual mounds of several kilometres long and wide and up to 380 m high. In *Area III*, directly below the mounds mainly sediment with relative low backscatter is found.

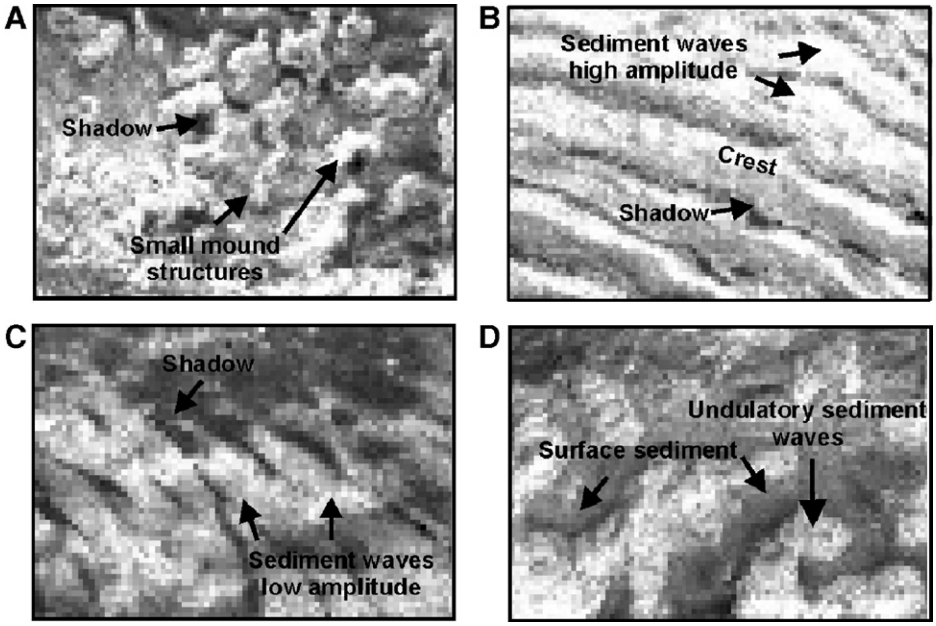

Fig. 4. Transect across different types of sediment waves from the west side to the east side of the study area, note the high backscatter of the ripples compared to the underlying sediment. (A) Shows relict wave structures, which can be interpreted as small mounds. (B) Sediment waves with a wavelength of 500 m and up to 30 m high. (C) NW–SE orientated sediment waves having maximum amplitude of 10 m. (D) Undulatory palimpsest sediment wave structures.

3.1.1. Area I, sediment waves

Giant sediment waves, remains of sediment waves and small mounds that may have evolved from sediment waves are found at the shallow upper slope of the SW RT, directly adjacent to the mounds. The sediment waves appear as zones of high backscatter that alternate with zones of low backscatter (Fig. 3A). The sediment waves extend over a length up to 15 km, have a wavelength of 500 m and an amplitude of up to 30 m. As shown on the echosounder profiles, the high backscatter zones represent the leeward side of the waves (Fig. 3B). In the western part of area I, the sediment waves have an east–west orientation (Fig. 4A,B). To the east, the orientation of the sediment waves changes to a more NW–SE direction and the amplitude of the sediment waves decreases to 10 m (Fig. 4C). The easternmost part of the area shows isolated rounded elevations of up to 20 m high that are interpreted as undulatory wave like structures. These structures are considered as palimpsest sediment waves that subsequently have been dissected and partially eroded and reshaped by bottom water currents (Fig. 4D). Sediment waves consist of coarse biogenic sand and dropstones are often found on top of the sediment waves, causing high backscatter on the TOBI mosaic (Fig. 5A).

Elevations of up to 50 m high with high backscatter observed directly downslope of the sediment wave area and north of the mound clusters are interpreted as small mounds, because of the distinct shadows of some of these elevations have on the TOBI mosaic. Below the small mounds, a ridge is observed providing a distinct boundary between areas I and II (indicated with a black line in Fig. 2).

3.1.2. Area II, carbonate mounds

Mounds and mound ridges in area II show as regions with high backscatter and have distinct shadows (Fig. 6). Mound clusters are mainly shown on the mosaic, having an elongated elliptical shape, perpendicular to the slope of the SW RT margin. Single mounds are mainly found in the eastern and western parts of the area. The mound clusters are up to 10 km long and 1–3 km wide. The top of the highest mound cluster in the area, measured both on echosounder, swath bathymetry and seismic profiles, is situated at 380 m above the seabed. All mound clusters are elongated in a downslope direction and have a NW–SE orientation, except for one mound cluster in the middle part of the area that has a more NE–SW orientation. Bottom photographs and video tracks show the presence of a dense living coral cover on top of the carbonate mounds (Fig. 5B,C). Channels separate the mound clusters, forming conduits for the downslope transport of material, as shown by areas of relatively high

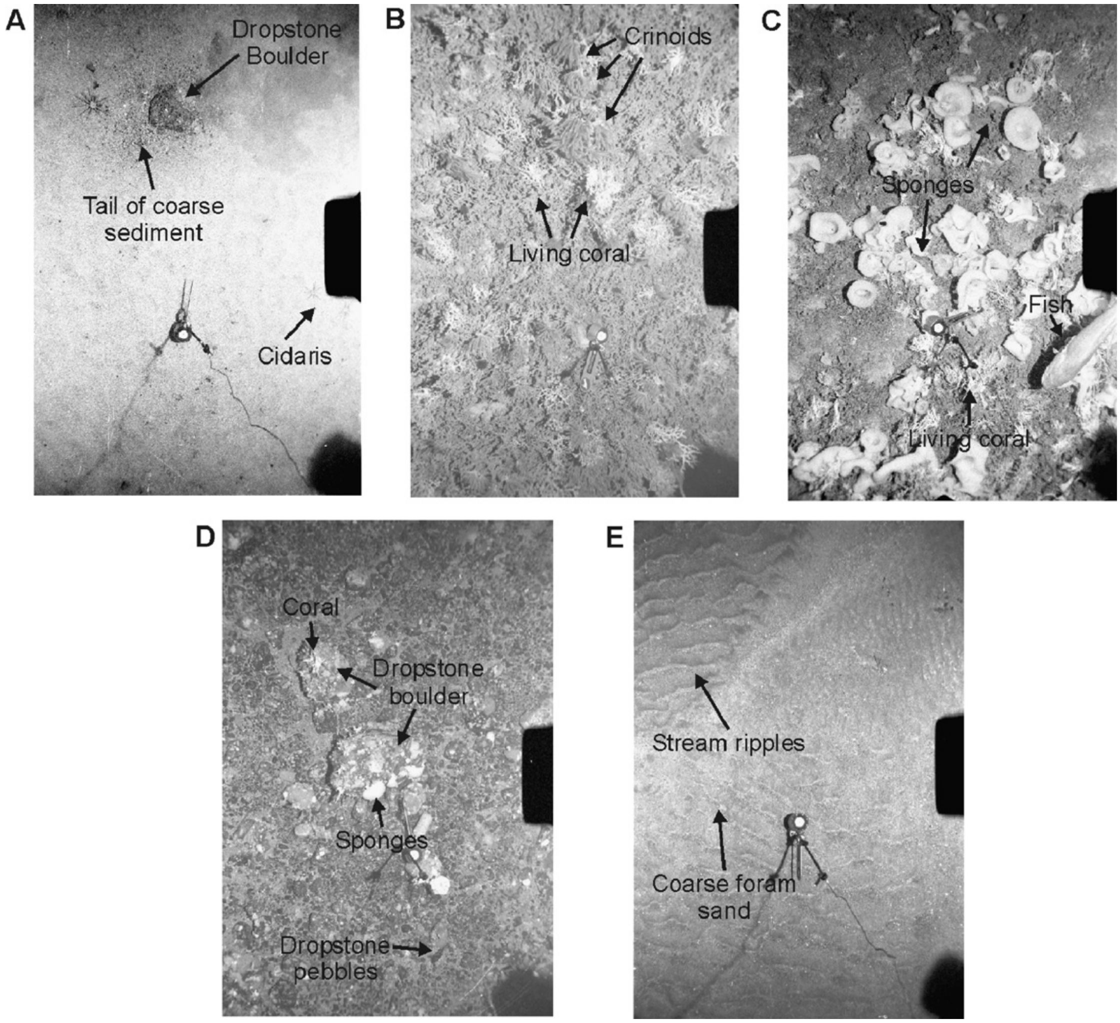

Fig. 5. Photographs taken at different locations in the study area. The compass with tail is 40 cm long. (A) Photograph of the sediment wave area (area I) showing the presence of centimeter-sized current ripples, dropstone boulders with a tail of coarse sediment and sea urchin. (B) Photograph of the top of a carbonate mound covered with a dense coral cover (~100%), where living colonies and associated organisms mainly crinoids are growing on top of coral debris. (C) Image of the flank of a carbonate mound showing patchy distribution of corals. Sponges are the most abundant species. (D) Off mound area showing the presence of dropstones (~60% coverage) with various sizes covered with single coral colonies and other sessile organisms. (E) Image of the sediment fill showing centimeter-sized current ripples.

backscatter in and at the end of the channels (Akhmetzhanov et al., 2003; Kenyon et al., 2003). Dropstones of various sizes are often observed on bottom photographs in off mound areas, causing high backscatter (Fig. 5D).

When the TOBI data are plotted on top of swath bathymetry data, the resulting 3D image clearly reflects a confined zone of mounds in the middle part of the research area with the sediment waves at the shallower upper margin (Fig. 7). All mound tops appear to reach a specific depth level below the sea surface depending on their position at the margin and mound peaks are situated between 500 and 600 m water depth. Mounds located deeper at the SW RT margin are in general higher than those at the shallower upper part of the margin. The longest mound clusters are found in the central part of the study area. The number of mounds as well as the size and height of the individual mounds decreases in the eastern and western parts of the study area.

A dome-like mound feature, with a circular shape with a diameter of about 6 km is observed in the eastern part of the area (Fig. 8A). An area with low backscatter in the middle part of the mound area shown on the echosounder profiles as a slightly elevated area is considered as a sediment fill (Fig. 8B), consisting off coarse well sorted biogenic sand with centimeter-sized current ripples (Fig. 5E).

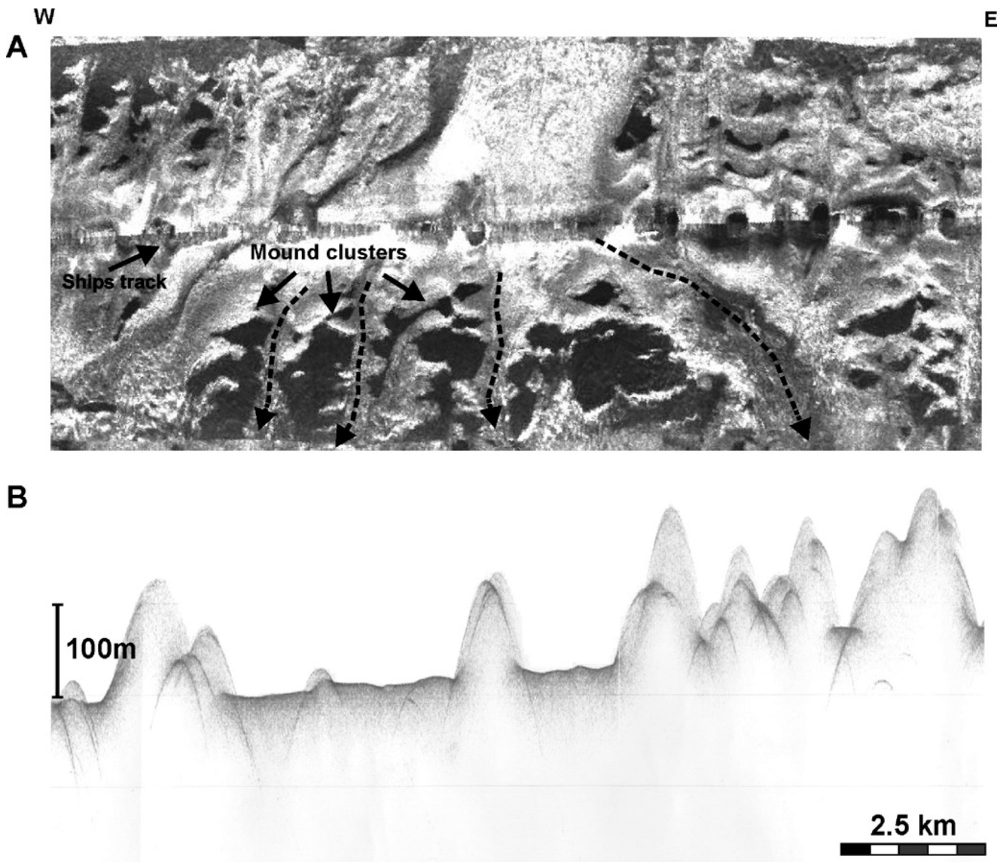

Fig. 6. (A) Enlarged part of the TOBI image showing a typical example of several mound clusters separated by channels (dotted arrows). The mounds can be recognised on the TOBI image by their strong backscatter and distinct shadows. Almost all clusters have an elongated shape with a direction perpendicular to the slope of the margin. (B) Corresponding echosounder profile recorded along ship's track, showing mound clusters separated by channels. The highest mound in the research area reaches more than 380 m above the sea bottom.

3.1.3. Area III, slumps

Below the mounds, a zone with relative low backscatter appears on the TOBI image. Typical on this part of the slope, shown by the shadows on the TOBI image and in agreement with regional seismic profiles and Gloria interpretations, is the presence of local slump and slide scars (Fig. 9A) (Unnithan et al., 2001; Van Weering et al., 2003a). In the western part of the area dark lineated structures on the seabed are observed, interpreted as ridges (Fig. 9B).

3.2. Seismic profiles

The seismic profiles collected, during cruises with *R.V. Pelagia* (De Stigter and De Haas, 2001; De Haas and Mienis, 2003), allow a further insight in the internal geometry and structure of the mounds at the SW RT margin. The mounds on the recorded seismic profiles (presented below in Figs. 10–12) mainly show highly irregular internal reflection patterns with occasionally strong discontinuous internal reflectors.

Below the mounds, two strong reflectors are defined as erosional unconformities (Van Weering et al., 2003b). The first reflector is an erosional surface interpreted as C10 by comparison of our data with other seismic profiles recorded in the RT and borehole data of nearby ODP drill sites. The sediment sequence above C10 is characterised by parallel layered reflectors that onlap onto the underlying sediment sequence and decreases in thickness in an upslope direction. In general, this reflector is found directly underneath the mounds and sediment waves.

A second strong irregular reflector has been interpreted as unconformity C20 underneath the mounds (McDonnell and Shannon, 2001; Stoker et al., 2001; Van Weering et al., 2003b). The sediment sequence in between C10 and C20 shows parallel, sometimes irregular relatively weak reflectors. An irregular acoustic

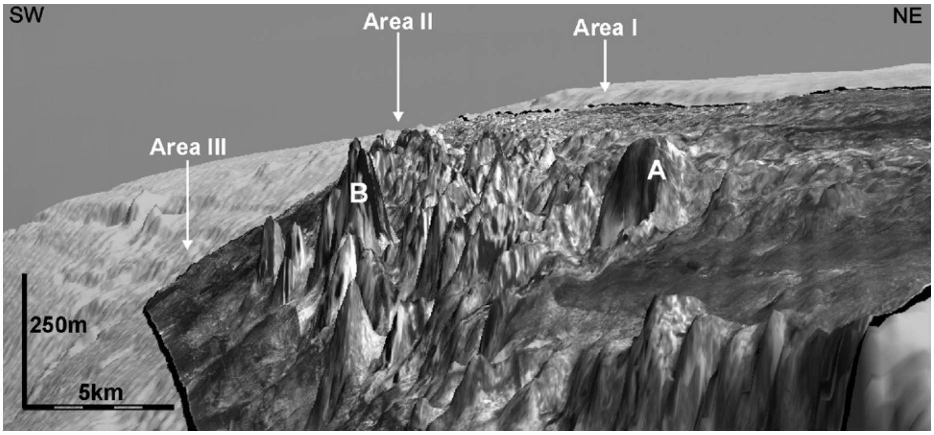

Fig. 7. 3D image of the TOBI mosaic that has been projected on top of bathymetry. The picture shows the mound area looking into a northwest direction. Three different areas are indicated. Area I, sediment waves. Area II, on the outer edges of the mound area, mainly single isolated small mounds are found, while the middle part of the mound area shows the presence of elongated mound clusters (A: circular mound structure, B: highest mound in the area). Area III, relatively flat and homogenous sediment surface. Vertical exaggeration is 25×.

basement is observed underneath the C20 sequence, which is frequently dissected by small faults.

Underneath the larger mound structures, the seismic signal is lost below and in the central part of the mounds. This is most likely caused by a velocity difference between the mound sediments and the sediment below and makes it difficult to trace reflectors over the entire margin (Bailey et al., 2003; Van Rooij et al., 2003).

Below, several seismic lines recorded perpendicular to the margin (Fig. 2) are described, showing typical features related to various stages of mound formation.

3.2.1. M2003-13

Profile M2003-13 (Figs. 2 and 10) was recorded across a near circular mound feature and across two small mound clusters lower at the slope. The circular mound differs from all other carbonate mounds and clusters, by its rounded and relatively flat shaped top shown on the TOBI image (Fig. 8A) as well as in the seismic profiles. In the middle of this feature a strong, continuous reflector is observed on top of which again some indistinct irregular reflectors are found. On the upper slope, several asymmetric sediment waves of ~10 m high form the seabed, with their upstream slope directed to the south and their steep slope to the north. On the TOBI image, these sediment waves appear as ridges having a NE–SW orientation (Fig. 4C).

The C10 reflector is well recognisable underneath the sediment waves and the small mound cluster at the lower slope, below which the reflector becomes eroded. The C20 reflector is found at the lower slope and even underneath the circular structure, implying that the upper strong reflector in this mound is the C10 reflector. The C20 reflector appears to be dissected by some small faults and shows a local elevation, interpreted as a buried mound (BM). The sediment fill at the lower flank of the circular mound is interpreted as mound debris filling an erosional moat before the formation of C10.

3.2.2. M2003-16

Line M2003-16 (Figs. 2 and 11) shows from north to south, sediment waves with relatively low relief and an irregular shape, some small mound clusters and one very high mound cluster. This large mound cluster is more than 380 m high and is the only cluster on the TOBI mosaic that is elongated in a direction perpendicular to the margin.

Within this cluster, two strong reflectors can be distinguished, similar as found in the circular mound in profile M2003-13. Consequently, the youngest strong reflector dissecting the mound is interpreted as C10. On the upper slope, this reflector almost crops out at the sediment surface, but it cannot be detected on the lower slope.

A double-layered sediment fill is found between the small mound clusters and the large mound cluster. This sediment fill appears on the sidescan sonar mosaic as a region with low backscatter (Fig. 8B). C10 seems to be eroded at the location of the sediment fill. In the sediment fill, two units can be distinguished. Unit I is the oldest sequence in the fill. Overlying unit II is interpreted as current controlled and forms a small elevation above the seafloor.

Reflector C20 is traced throughout the whole profile except underneath the large mound. Between C20 and the mound, another wedge of mound debris is present.

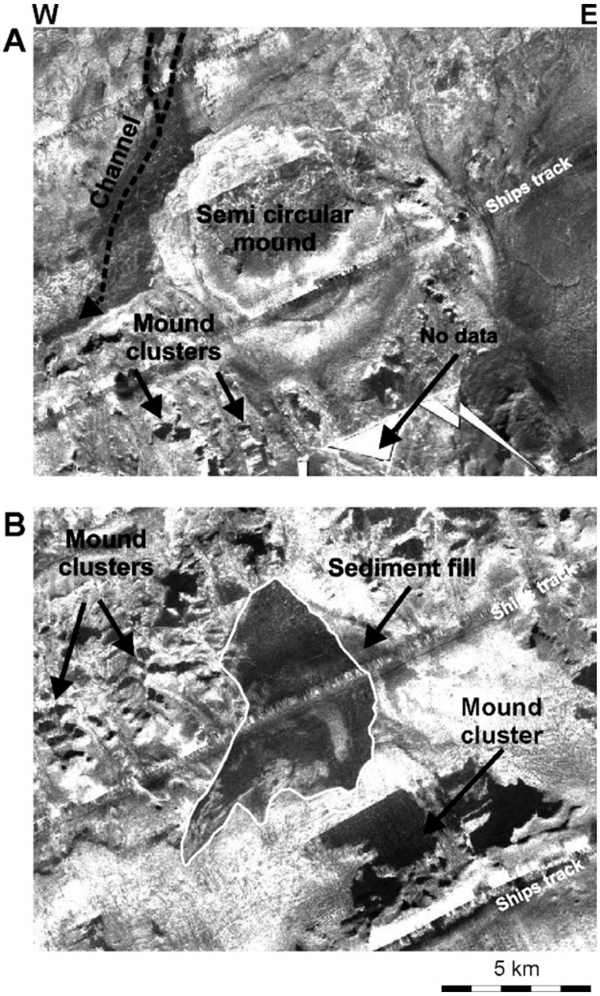

Fig. 8. (A) Enlargement of the near circular mound, which has a diameter of ∼6 km and differs in shape from all the other clustered mounds observed on the TOBI mosaic. Places with no data are shown as white blocks. (B) Sediment fill with low backscatter that shows on seismic profile M2003-16 as a slightly elevated region.

Locally, C20 shows some small faults, which do not extend into the C10 reflector. The acoustic basement is characterized by a seismic structure with high amplitude reflectors. These form a somewhat curved surface, locally dissected by small faults.

3.2.3. M2003-20

Line M2003-20 (Figs. 2 and 12) was recorded across the western sediment wave area. The sediment waves here are mainly symmetric, although locally asymmetric waves do occur with long slopes directed to the south and steeper flanks directed to the north. This indicates upslope migration of the sediment waves as is shown in profile M2003-13. The shape of the sediment waves is confirmed by the TOBI image where the southern directed long slope shows higher backscatter than the steeper northern slope (Fig. 3). More downslope some of the sediment waves change into small mounds as reflected in the presence of internal irregular and indistinct reflection patterns contrasting strongly with the distinct parallel layered reflectors characterising the sediment waves. The first strong reflector underneath the sediment waves is considered as unconformity C10, which almost crops out at the seabed more upslope. Reflector C20 is found directly underneath C10 and has been eroded by the C10 reflector in the upper part of the profile, forming a sedimentary wedge. The third strong reflector below the waves and mounds is an irregular surface with some small faults, interpreted as the acoustic basement (AB).

4. Discussion

4.1. Mound development

Mound clusters on seismic profiles show internal indistinct, discontinuous and irregular reflection patterns. We consider this chaotic seismic pattern as forced by the patchy and irregular growth of corals on the mounds and the irregular and local presence of hardgrounds. Hardgrounds likely developed mainly in glacial periods, because of absence of carbonate production and reduced sedimentation on the mounds (Van Weering et al., 2003b; Dorschel et al., 2005).

Furthermore, video observations have shown that patches of living corals alternate with dead parts (Freiwald et al., 1997; Rogers, 1999; Olu-Le Roy et al., 2002). This situation results in an irregular depositional system on the mounds in time and space (Rogers, 1999; Frank et al., 2004; Dorschel et al., in press).

Most mound clusters and isolated mounds, as well as the sediment waves on the upper slope above the mounds, have developed later than erosional unconformity C10. C10 is considered as formed by the onset of strong bottom currents in the wider Rockall Trough area (Stoker et al., 2002). The C10 reflector is present along the entire SW RT mound study area and also within the two large mounds shown on seismic lines M2003-13 and M2003-16. The circular mound structure in profile M2003-13 was described by Akhmetzhanov et al. (2003) and Kenyon et al. (2003) as a basement high and may have a volcanic origin with a coral covered top. However, this is not consistent with the presence of C20 underneath the structure.

The second strong reflector (C20, Stoker et al. (2001)) is observed in profile M2003-13 at the western side beneath the mound and in profile M2003-16 at both sides

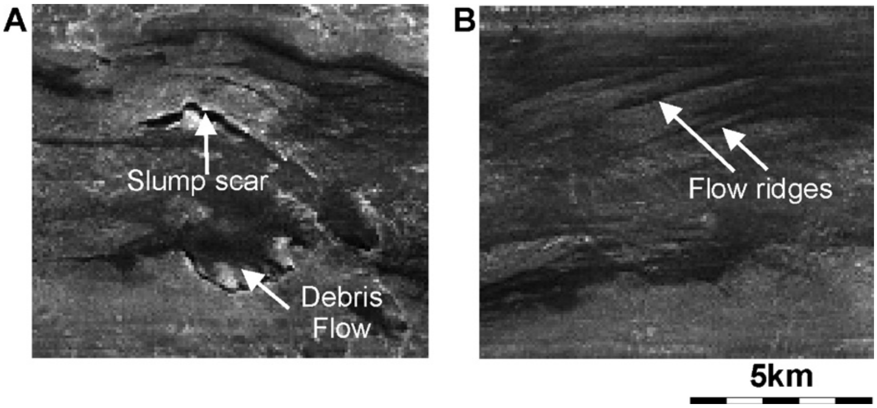

Fig. 9. Enlarged parts of the TOBI mosaic showing typical features of area III. (A) Slump scar with corresponding moat of debris. (B) Lineated stripes that have been interpreted as flow ridges, probably caused by the Eastern North Atlantic Central Water flowing in a southwest direction along Rockall Bank margin.

of the large mound suggesting that initial mound development started somewhere in the mid-Miocene. This was also indicated by Van Weering et al. (2003a,b), who suggested at least two possible stages of mound formation, the latest having a Pliocene–Holocene age, however on the basis of a less dense grid of seismic lines than presented here.

4.2. Mound growth rates

Following this interpretation, averaged growth rates were calculated from the highest mound in the area, thus reflecting the maximum growth. The highest mound in the SW RT area (profile M2003-16, Fig. 11) is 380 m high and situated at the lower slope. The sediment

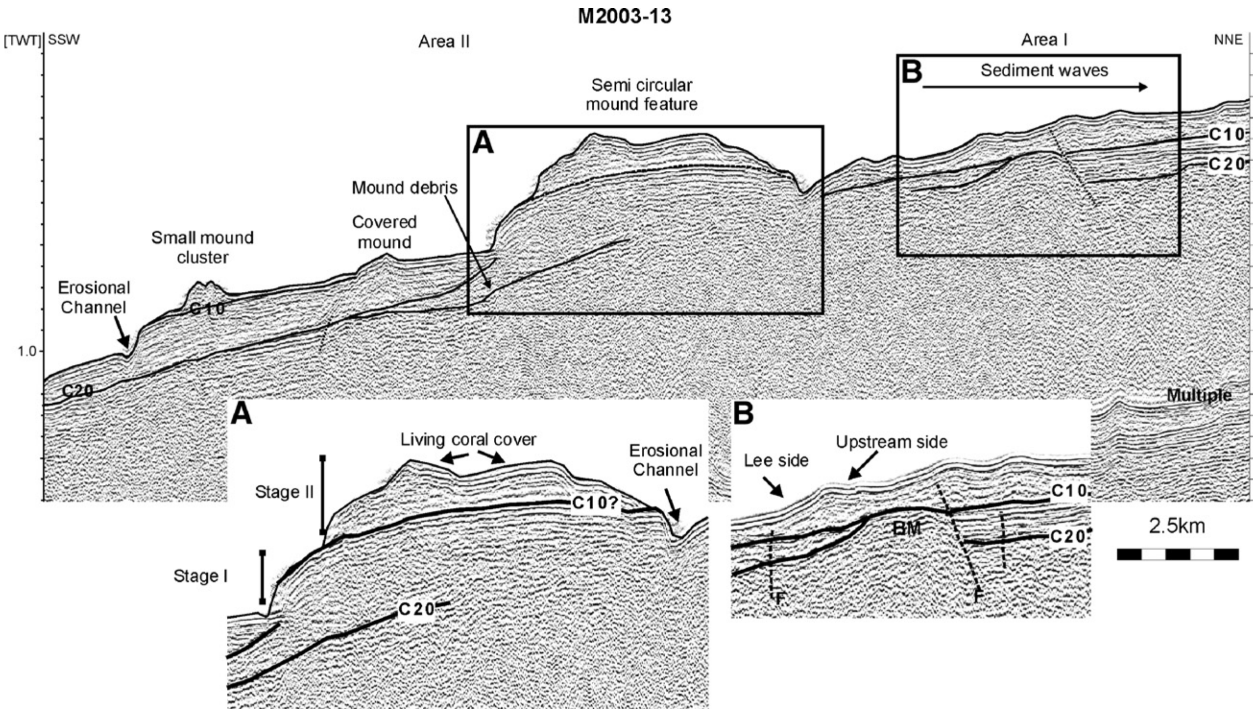

Fig. 10. Section of high-resolution profile M2003-13 (for location see Fig. 2), which shows sediment waves, a mound with a circular shape and a small mound cluster at the lower slope. Reflectors C10 and C20 are indicated. (A) Circular mound, dissected by C10. On top of C10 chaotic reflection patterns can be seen that indicates the presence of coral growth. C20 is found at the western side underneath the mound. (B) Enlargement of symmetric sediment waves and the presence of a buried mound (BM) underneath the C10 reflector. Vertical scale is in TWTT; horizontal scale is in kilometers.

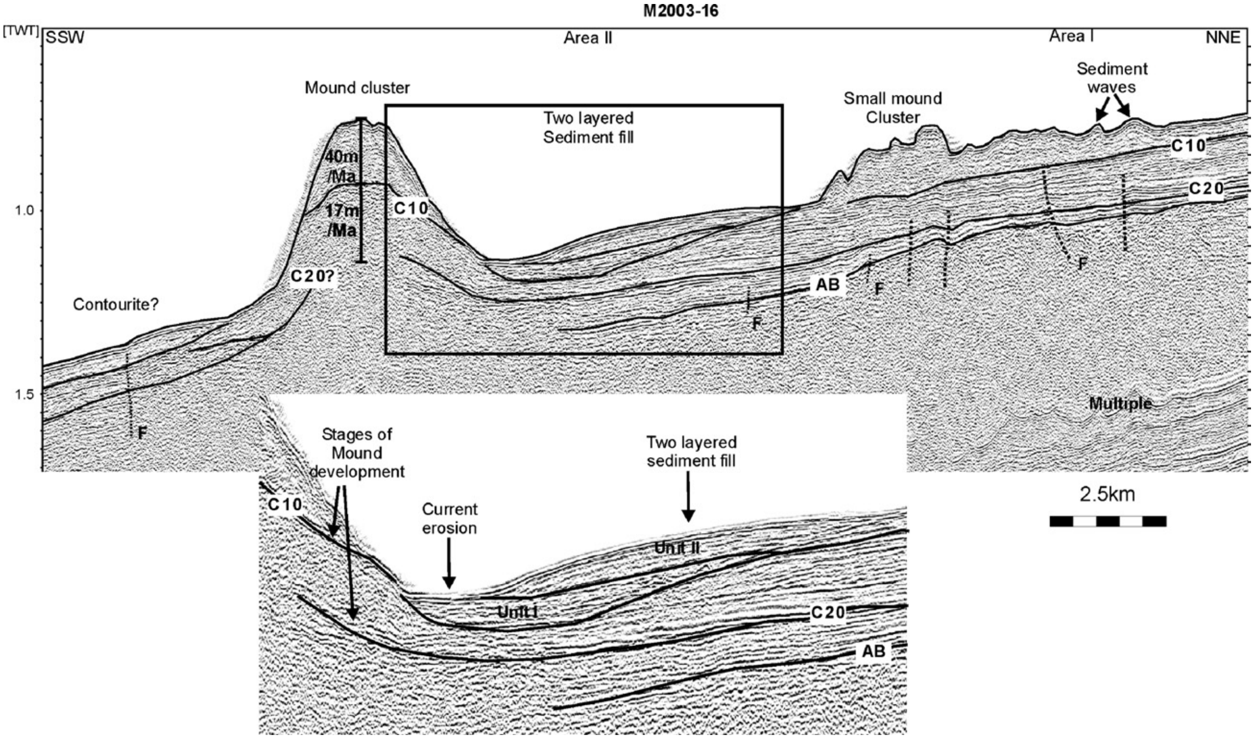

Fig. 11. Part of high-resolution profile M2003-16 (for location see Fig. 2). The profile shows sediment waves and a small mound cluster at the upper part and a high mound at the lower margin. C10, C20 and the acoustic basement are indicated. The high mound shows two strong internal reflectors correlated with C10 and C20 reflecting different stages of mound formation. Inset shows a two-layer sediment fill behind the large mound, probably current controlled (Fig. 8B). Vertical scale is in TWTT; horizontal scale is in kilometers.

package above C10, described as unit RTa (Stoker et al., 2002) has a thickness of 0.19 TWTT in the seismic profile. Calculated with a sediment sound velocity of 1.6 km/s (Stoker et al., 2002), the post-C10 growth rate (early Pliocene (4 Ma±0.5) to recent) then is 40 m/Ma, taking into account that the total duration of the glacial period is 720 ka. During glacials, coral growth is limited and no reef structure is built up. Growth of cold water coral reef systems is considered to occur preferentially in interglacial periods (Rogers, 1999; Mienert et al., 2004; Dorschel et al., 2005; Ruggeberg et al., in press). The total duration of the glacial period (720 ka) was

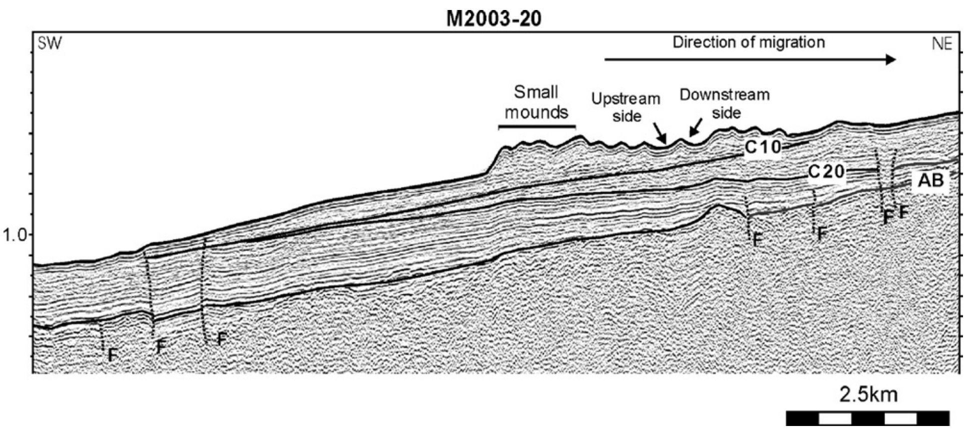

Fig. 12. Profile M2003-20 (for location see Fig. 2) is recorded in the sediment wave area, showing symmetric and asymmetric sediment waves and small carbonate mound structures. The asymmetric sediment waves have a long lee side and a short upstream side from which the direction of migration is deduced. C10, C20 and the acoustic basement are indicated. Vertical scale is in TWTT; horizontal scale is in kilometers.

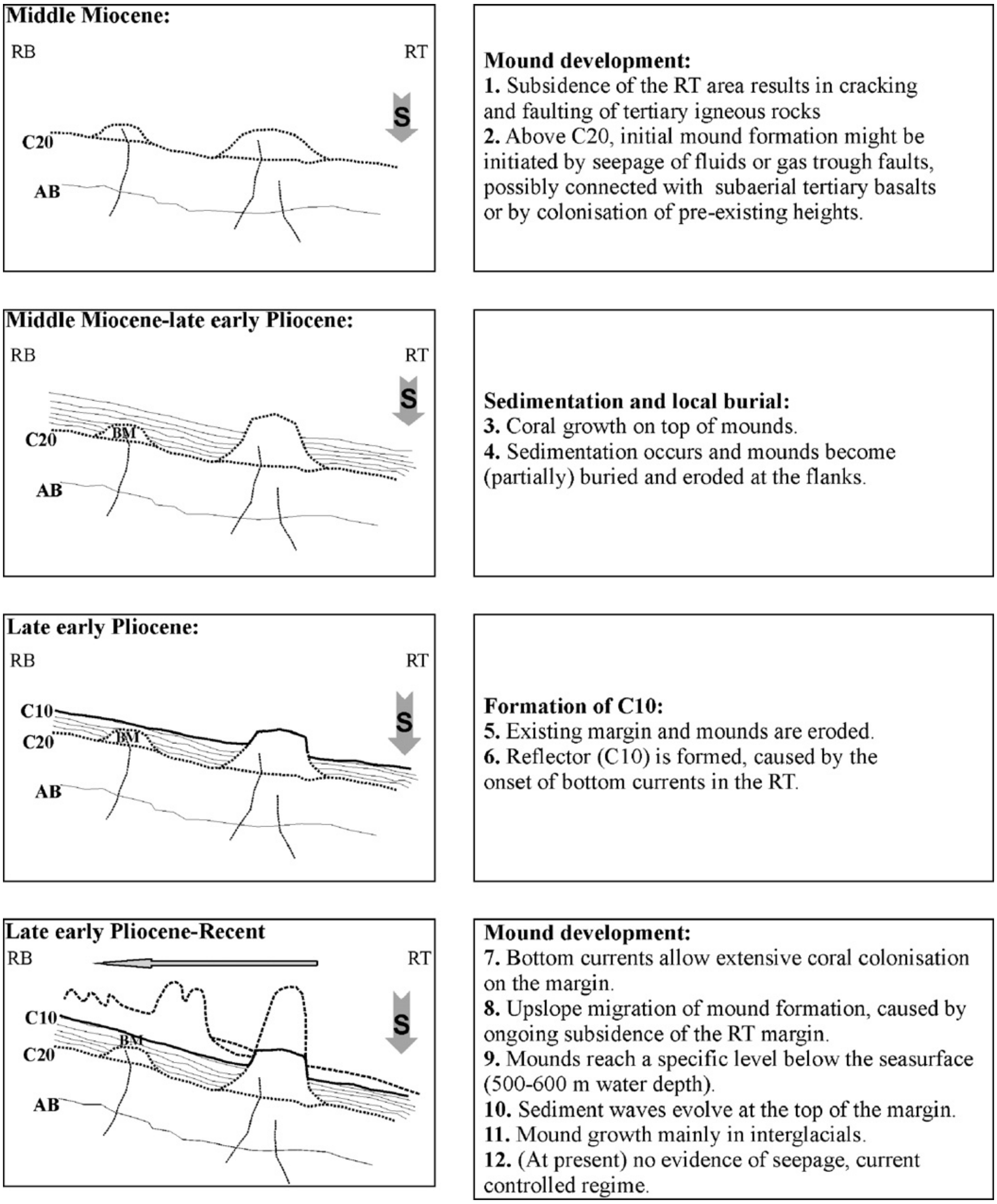

Fig. 13. Model explaining mound formation at the SW RT margin. At least two stages (post C20 and C10) of mound growth can be observed in the area. Mound growth seems to have migrated in an upslope direction after formation of C10. Arrows indicate subsidence as observed in the RT region (Praeg et al., 2005). Faults mainly occur in the acoustic basement and the C20 reflector (RB = Rockall Bank, RT = Rockall Trough).

calculated on the basis of a benthic $\delta^{18}O$ record of Lisiecki and Raymo (2005) with a threshold value of 3.5 per mil (McManus et al., 1999).

The sediment package between reflector C10 (early Pliocene, 4 Ma) and C20 (mid-Miocene, 16 Ma), is 0.25 s TWTT thick in profile M2003-16 and with a sediment sound velocity of 1.65 km/s (Stoker et al., 2001), the average growth rate of this period would be 17 m/Ma, assuming no distinct erosion or hiatus.

The acoustic basement presumably consists of igneous rocks of early Tertiary age and is dissected by small faults (Boldreel and Andersen, 1998; Kenyon et al., 2003; Van Weering et al., 2003a). Almost all faults can be traced in the AB and the C20 reflector, but are not dissecting C10. If the faults developed by cooling of underlying igneous rocks, fluid flow or gas seepage may have occurred (Boldreel and Andersen, 1998; McDonnell and Shannon, 2001). This may have initiated an early stage of mound development according to the model of Hovland et al. (1998). However, so far we have not found any evidence for the presence of seepage. On the TOBI image, no pockmarks were detected and the seismic profiles also provide no evidence of gas or fluid flow.

4.3. Mound model

On this basis, we suggest a history of mound formation, which is visualised in Fig. 13. We suggest that mound growth is initiated on top of reflector C20 either as a result of fluid flow related processes or by early colonisation of pre-existing highs and thus started somewhere in the middle Miocene. Small faults and fissures dissecting the AB and C20 could have formed conduits for seepage at this time in relation to cooling of volcanic rocks (Spencer and MacTiernan, 2001). Mounds then became buried and subsidence of the Rockall Trough region in the early Pliocene caused the onset of a bottom current dominated regime creating the regional erosional unconformity C10 (Stoker et al., 2005). The remaining highs of elevated parts or hills were subsequently recolonised and carbonate formation was resumed.

No evidence for gas seeps or fluid flow post C10 is found, neither in seismic profiles or sidescan sonar images, while isotopic measurements of corals and associated biota so far support a direct relationship with surrounding watermasses (Mikkelsen et al., 1982; Van Breukelen and Mienis, 2002; Blamart et al., 2005; Lutringer-Paquet, 2005). Coral growth and mound development possibly was then enhanced by a relatively high energetic current regime, creating favourable conditions for coral growth (Frederiksen et al., 1992; Freiwald, 1998). From this period on, currents influence the margin, creating elongated mounds, sediment waves, and provide a good substrate for coral growth and enough food for the corals to live.

The mounds on the SW RT reach a specific depth level (between 500 and 600 m) below the sea surface (Fig. 7). Mounds on the lower margin are higher than those at the upper margin and appear to be confined in their growth by the extant hydrodynamic regime, this may be related to stepwise subsidence of the NE Atlantic basins, increasing the water depths in the basins (Spencer and MacTiernan, 2001; Praeg et al., 2005). This may have resulted in an upslope migration of mound development on the RT margin. Relative shallow sites on the margin will become suitable sites for mound formation with ongoing subsidence, when they become entrained into the proper hydrodynamic regime. At present, sedimentary features like relicts of sediment waves at the upper shallower part of the margin and the presence of dropstones at the sediment surface form a preferred new substrate for mound development (Wilson, 1979; Freiwald, 1998; Rogers, 1999).

4.4. Effects of near bed hydrodynamic conditions

The presence of sediment waves, elongated mound clusters, erosional channels and local scouring as shown by the seismic reflection profiles and on the TOBI mosaic emphasises the influence of bottom currents in (re)shaping the SW Rockall Trough margin (Sherwin and Taylor, 1990; Akhmetzhanov et al., 2003; White et al., 2005).

Bottom currents are influenced by the topography of the carbonate mounds. Current measurements by landers deployed in the mound area at the SW RT margin show current velocities of occasionally above 45 cm/s on top of the mounds, directed to the southeast and southwest (De Stigter, unpublished data).

The model of Kenyon et al. (2003) implies that the development of different mound types depends on the current regime and local sedimentation rate. When the sedimentation rate is high, the mounds become almost completely buried, as has indeed been observed on seismic profiles and sonar images in the eastern Porcupine Bight, the Magellan province (De Haas et al., 2002; Beyer et al., 2003; Huvenne et al., 2003). If the sedimentation rate in the mound area is relatively low, different mound types may occur depending on the near bed current regime. If the near bed currents are high, only single mounds will form. On the other hand, a moderate current speed and the presence of food will allow extensive colonisation of corals on the margin (Kenyon et al., 2003). At present, the SW RT mounds are situated in a sediment starved area. On the outer edges of the SW RT study area, mainly small single mounds are observed. Here current speed might be a limiting factor for mound clusters to develop. At the middle slope between 600 and 900 m water depth dynamic conditions appear to support mound cluster development (Kenyon et al., 2003; Mienis et al., unpublished data). Currents will influence the shape of the mounds here as they increase in size, giving the mounds a more elongated and elliptical shape as also observed on the western margin of the Porcupine Bank (O'Reilly et al., 2003).

4.5. Sediment waves

The sediment waves at the upper SW Rockall Trough margin above the mounds have wavelengths up to

500 m, wavecrests of locally more than 10 km long and are 30 m high at the western side of the research area. The presence of sediment waves and the shaping of the carbonate mounds imply the presence of strong currents after the formation of C10 on the upper slope. We consider the sediment waves as palimpsest structures, which have changed shape due to local erosion and/or (re)deposition of sediment since the last glacial period.

In the western part of the study area, the sediment waves have an almost east–west orientation and are aligned at a low angle with the regional contours. However, the orientation and shape of the sediment waves changes in the east of the study area, where they have a NW–SE orientation, decrease in amplitude and are aligned almost perpendicular to the depth contours (Fig. 4B,C). This suggests a sediment source located in the west, assuming that sediment is transported in a NE upslope direction (Flood and Giosan, 2002; Wynn and Stow, 2002).

Upslope migration of the sediment waves is confirmed by the backscatter intensity on the TOBI mosaic and by the shape of the sediment waves (Flood, 1988). Having a long downstream side followed by a much steeper upstream flank, shown by the highest backscatter on the TOBI mosaic (Fig. 3). However, local symmetric sediment waves have formed as well at suitable interfaces with topography.

Undulatory structures of up to 20 m high in the eastern part of the research area are considered as sediment waves, which have been partly eroded by currents with variable current directions. Because of their elevation above the surrounding seabed, the remains of these sediment waves may form a firmground for the development and growth of coral colonies that subsequently evolve into small mounds (Wilson, 1979). This is illustrated in seismic profile M2003-20 (Fig. 12), which shows the presence of small mounds next to the sediment waves. A similar setting has been observed in the Porcupine Seabight with the incipient Moira mounds (Foubert et al., 2005; Huvenne et al., 2005), the Darwin mound area in the NE RT and at the Brazilian continental slope where living and dead coral patches have been found on edges of pockmarks that are made up of relatively coarse sediment (Masson et al., 2003; Sumida et al., 2004).

4.6. Sediment

The backscatter intensity of the TOBI image is clearly related to the sediment characteristics as observed in boxcores (Blondel and Murton, 1997; De Haas et al., 2002; Huvenne et al., 2002). The sediment waves in the upper part of the study area show as areas with high backscatter, which is caused by the coarse sediment that form the sediment waves. The mounds all have high backscatter, because of the presence of coral branches, coarse biogenic components and gravel in a matrix of fine sandy sediment, which was also observed at the SE RT margin (Huvenne et al., 2005). Below 1000 m water depth, contour currents likely wash out the fine particles, leaving relatively coarse homogeneous sandy sediment behind, having relatively low backscatter on the TOBI mosaic. Directly at the foot of the mound clusters and in the channels between the mounds, spots of high backscatter are present, which is interpreted as caused by the presence and concentration of coarse biogenic material, formed by coral and other carbonate debris coming from the mounds and being transported trough the channels in between the mounds. Another source of high backscatter can be the presence of dropstones fields between the mounds, deposited in the last glacial period. The sediment fill observed in seismic profile M2003-16 is shown as an area of low backscatter on the TOBI image, while the sediment consists of well sorted coarse foraminiferal sand that appears to have absorbed the acoustic beam of the TOBI.

5. Conclusions

A large number of mainly elongated mound clusters, most of which are covered with living corals on their tops, has been observed in the study area between 600 and 1000 m. The mound clusters have a size of several kilometres long and wide and individual mounds can be up to 380 m high. Two stages of mound formation are present as shown by seismic profiles, suggesting that initial mound formation started in the middle Miocene. The influence of seepage or fluid flow on initial mound formation cannot be excluded. However, at present, seepage is nowhere observed in the mound area and currents are the forcing factors shaping the SW RT margin mounds, as deduced from the elongated shape of the mounds to the SE in the direction of the main current flow and from the presence of high extensive sediment waves in the upper part of the research area. Dropstones, parts of sedimentary structures like parts of sediment waves and local elevations may form a good substrate for the settling of coral colonies and thus for the formation of carbonate mounds. The local subsidence rate and the hydrodynamic regime appear to govern the growth rates of the mounds, which reach a specific depth level below the sea surface.

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