Sedimentary processes and carbonate mounds in the Belgica Mound province, Porcupine Seabight, NE Atlantic

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Abstract. Carbonate mounds (up to 200 m high) formed from the accumulated remains of cold-water corals (principally *Lophelia pertusa* and *Madrepora oculata*), associated calcareous fauna and interstitial sediment are present at 500-1000 m water depths west of Ireland. Seabed mapping datasets (side-scan sonar, multibeam echosounder, sub-bottom profiler and underwater video imagery) are presented here from the Belgica Mound province on the eastern Porcupine Seabight margin. The data, integrated within a Geographic Information System (GIS), provide an environmental context to mound development. Analysis of this multidisciplinary dataset and resultant facies map highlight differing sedimentary processes (e.g., sediment wave, barchan dune, gravel lag and sand ribbon development) operating under strong northward flowing bottom currents with sandy sediment supply where the influence of mound topography on benthic current and sediment pathways is evident. Correspondingly, benthic current pathways and associated sediment transport also exert an influence on carbonate mound surface morphology and growth. Giant mounds show a transition from sediment waves that, with increasing coral colonisation, give way to banks of coral towards the mound summits. Smaller mound features (Moira Mounds) show sand entrapment as an important mound-forming process.

Keywords. Northeast Atlantic, Porcupine Seabight, carbonate mounds, sedimentary facies, side-scan sonar, sub-bottom profiler, deep-water corals

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Introduction

Deep-water corals are common along the European continental margin (e.g., Wilson 1979a; Freiwald 1998, 2002; Rogers 1999; Freiwald et al. 2002; Wheeler et al. submitted) where they are often found in close association with other organisms as part of a diverse ecosystem (Olu-Le Roy et al. 2002). In some cases the corals form reef communities (Freiwald 2002). Over time their accumulated remains, the remains of associated organisms and interstitial sediment have formed carbonate mounds (referred to as coral banks by De Mol et al. 2002). These vary in dimensions from a few metres high and tens of metres across (e.g., the Darwin Mounds; Masson et al. 2003) to giant features often greater than 100 metres tall and several kilometres across (e.g., De Mol et al. 2002; Kenyon et al. 2003; van Weering et al. 2003). The mounds take a variety of morphological forms dictated by environmental controls on growth and the morphology of the underlying substrate (Wheeler et al. submitted).

Deep-water corals and associated carbonate mounds occur in dynamic hydrological settings with high current speeds, enhanced organic particulate food delivery and reduced fine-grained sedimentation seen as important to coral vitality (Freiwald 1998). Conditions generating enhanced surface productivity, hence supplying food to underlying communities, are also important. Seabed mapping exercises have located mounds and also revealed sedimentary processes in environs of the mounds. These exercises show evidence of strong benthic currents including evidence of seabed erosion (e.g., Porcupine Bank: Wheeler et al. 2005) and sediment transport (e.g., Wheeler et al. 2000; Kozachenko et al. 2003a, b). In some cases, the lack of a rigorous benthic environment is coincident with poor to sporadic coral cover (e.g., the Hovland mounds: Huvenne et al. 2005). Results and an interpretation of seabed mapping surveys of the Belgica Mound province in the Porcupine Seabight are presented here.

The Porcupine Seabight is a north-south trending basin on the continental margin of the west coast of Ireland (Fig. 1A). Two distinct clusters of carbonate mounds (provinces) are found on the margins of this basin: the Hovland-Magellan province on the northern margin (De Mol et al. 2002; Huvenne et al. 2005; Wheeler et al. submitted) and the Belgica Mound province on the eastern margin from approximately 51.17°N to 51.60°N and from 11.60°W to 11.80°W (De Mol et al. 2002; Fig. 1A). This province is c. 45 km in length and c. 10 km wide. Mounds are distributed between the 500 and 1100 m isobaths on a part of the continental slope with an average angle of 2.7°. Some of the mounds within the Belgica province have been specifically named (e.g., the Challenger Mound, Galway Mound, Poseidon Mound, Thérèse Mound), with others ascribed a code (e.g., BEL32) and catalogued by De Mol (2002).

Seismic data from the Belgica Mounds are presented by De Mol et al. (2002) and Van Rooij et al. (2003a) who note that the initiation of mound growth was simultaneous upon a Miocene or Late Pliocene unconformity (erosional surface) respectively. The geology of contourite drifts within the province was interpreted by Van Rooij et al. (2000), Kozachenko et al. (2002) and Van Rooij et al. (2003a).

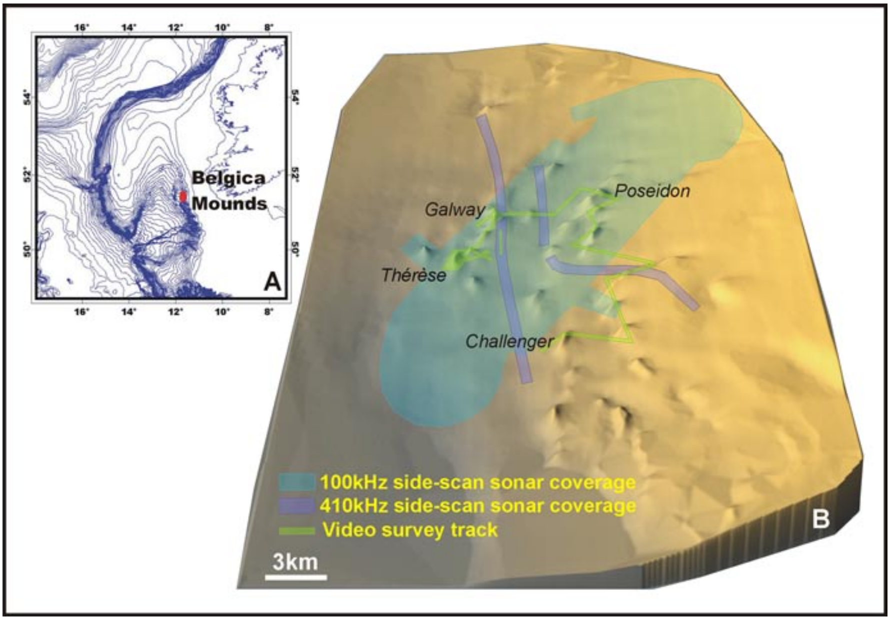

Fig. 1 **A** Location map showing the location of the Belgica Mounds study area on the regional scale, eastern Porcupine Seabight, NE Atlantic (contours from GEBCO 97); **B** Terrain model of the central part of the Belgica Mound province based on multibeam bathymetry (AWI). Transparent layers show 100 kHz and 410 kHz side-scan sonar coverage and underwater video survey track. Names of individual mounds within the province are shown

Comparison of the Belgica Mound province with other mound provinces is presented by Wheeler et al. (submitted) and Huvenne et al. (2005). Foubert et al. (2005) present an overview of ROV data collected from the province onboard RV Polarstern ARK XIX/3a cruise. This publication presents a detailed interpretation of sedimentary processes operating in the Belgica Mound province based on multidisciplinary datasets.

Materials and methods

Detailed bathymetry of the Belgica Mound province was obtained using the Hydrosweep DS-2 multibeam echosounder system operated at 15.5 kHz during RV Polarstern ANT XVII/4 cruise June 2000 (see Beyer et al. 2003 for a detailed description of the multibeam data collection and processing).

The central part of the Belgica Mound province was surveyed using a dual frequency GeoAcoustic (100 and 410 kHz) side-scan sonar in conjunction with a 3.5 kHz sub-bottom profiler onboard RRS Discovery 248 (Bett et al. 2000; Wheeler et al. 2000). Approximately 80 km^2 was mapped with the 100 kHz resolution and 6.6 km^2 with the 410 kHz resolution. Side-scan sonar swath width was 800 m at 100 kHz and 220 m at 410 kHz. The height of the side-scan fish above the seabed was controlled *via* a remotely operated electro-hydraulic winch and flown at 25 m off the seabed at 100 kHz and 10 m off the seabed at 410 kHz. To obtain optimum results, the speed of the vessel was kept at 3.5 knots. A hytech cable counter was used to calculate cable layback. The signal to the towfish was supplied by a GeoAcoustics transceiver (SS941) that was externally triggered from a CODA DA100 sonar processing system that supplied a real-time image recorded to DAT tapes. A hardcopy output of the side-scan record was also obtained directly from the GeoAcoustics transceiver using an Ultraelectronics Wideline 200 series 12 thermographic recorder with manual fixes. Navigation was supplied by the NaviPac survey software running on PC, providing the coordinate fix points and heading for the vessel from which the side-scan sonar image location was extrapolated using a layback calculation. The distance of the towfish behind the vessel was calculated using trigonometry (based on water depth, towfish height above the seabed and wire out) with error correction for inertia movements around corners and wire catenation effects. Based on this method, accuracy of image navigation is +/- 50 m.

Acquired digital side-scan sonar data were processed at the Southampton Oceanography Centre using the *PRISM* sonar software system (Le Bas and Hühnerbach 1999) and integrated within a GIS (ArcView 3.2a). Obtained side-scan sonar imagery was draped over a digital terrain model (DTM) derived from the multibeam bathymetry. Sub-bottom profiler data were unprocessed and recorded on a thermographic paper.

Geophysical imagery was ground-truthed with video imagery during RV Discovery 248 (2000) using the Seabed High Resolution Imaging Platform (SHRIMP) using a CCD colour video camera, and on RV L'Atalante (CARACOLE 2001) and RV Polarstern XIX3a (2003) (see also Foubert et al. 2005) cruises using IFREMER's VICTOR 6000 ROV. Underwater video surveys of the study area resulted in collection of ~103 hours video imagery.

A number of seabed facies were defined based on the video imagery emphasising changes in the coral population (live or dead; total or patchy coverage) on mounds and sedimentary character in off-mound areas (Table 1).

A more generalised interpretative facies map for the Belgica Mound province has been constructed based on geophysical mapping and video ground-truthing datasets. Each dataset was analysed and correlated with other relevant datasets, therefore supporting and extending the final interpretation. Multibeam bathymetry was overlaid with the 100 and 410 kHz side-scan sonar mosaic, and analysed in conjunction with 3.5 kHz sub-bottom profiler records. Sub-bottom profiler lines show the surface geomorphological features of the seabed directly underneath the side-scan sonar vehicle, hence making it easier to relate bedform distribution to the local topography. This allowed complex analysis of the side-scan sonar backscatter from a three-dimensional prospective that gave insight into the ongoing and past sedimentary processes on and near the coral mounds. Interpretation of the remotely sensed dataset was then updated in the light of ground-truthing information, which was represented by underwater video imagery. Orientation of bedforms imaged on the side-scan sonar and video imagery was interpreted in terms of current/ palaeocurrent directions, which are indicated by white arrows on the facies map

Table 1 Seabed facies classification used for the ROV VICTOR 6000 and SHRIMP video observations in the Belgica Mounds area (see also the less detailed facies scheme adopted by Huvenne et al. (2005) based on ROV video data only)

Facies Code	Facies description
1	Dense coral coverage (live and dead)
2	Dense coral coverage (mostly dead)
3	Sediment-clogged dead corals/rubble
4	Patchy mostly live corals on rippled seabed
5	Patchy mostly dead corals on rippled seabed
6	Patchy mostly dead corals on unrippled seabed
7	Dropstones (gravel and/or boulders) dominated seabed
8	Dropstones (gravel and/or boulders) – patchy distribution on unrippled seabed
9	Dropstones (gravel and/or boulders) – patchy distribution on rippled seabed
10	Rippled seabed with occasional dropstones
11	Unrippled seabed with occasional dropstones
12	Rock outcrops (?)

in Figure 2. Seven main seabed facies/types are defined: background uniform backscatter facies, sediment wave facies, barchan dune facies, gravel ridge facies, sand ribbon facies, Moira Mound facies and Belgica Mound facies. Each of these facies is described in detail.

General description of the Belgica Mounds

Multibeam echosounder data (Beyer et al. 2003) reveal that carbonate mounds in the Belgica Mound province are aligned along the slope in two parallel ridges. Some mounds rise above the seabed whereas others are buried or half buried within drift sediment. Mounds from the eastern ridge occur between water depths from 550 to 900 m. The eastern flanks of these mounds are covered by the contourite drift deposits, and therefore possess a half or, in some cases, near-total buried morphology. Mounds located at a deeper water setting, from 870 to 1030 m water depth, form the western ridge and possess an outcropping morphology with a subtle difference in slope angles between their eastern and western flanks. Slope angles of individual mounds vary from 7 to 23°, with western flanks of the mounds being generally steeper then their eastern flanks. Individual mounds are also elongated in a general north-south direction parallel to the dominant current direction implying a hydrodynamic control on preferential coral growth and interstitial sediment accumulation.

Seabed facies within the Belgica Mound province

Several interpretative facies are defined for the Belgica Mounds area and are described below. An interpretative facies map is presented in Figure 2.

Background uniform backscatter facies

Inter-mound areas especially in the eastern part of the province reveal a homogenous uniform background backscatter pattern on the side-scan sonar

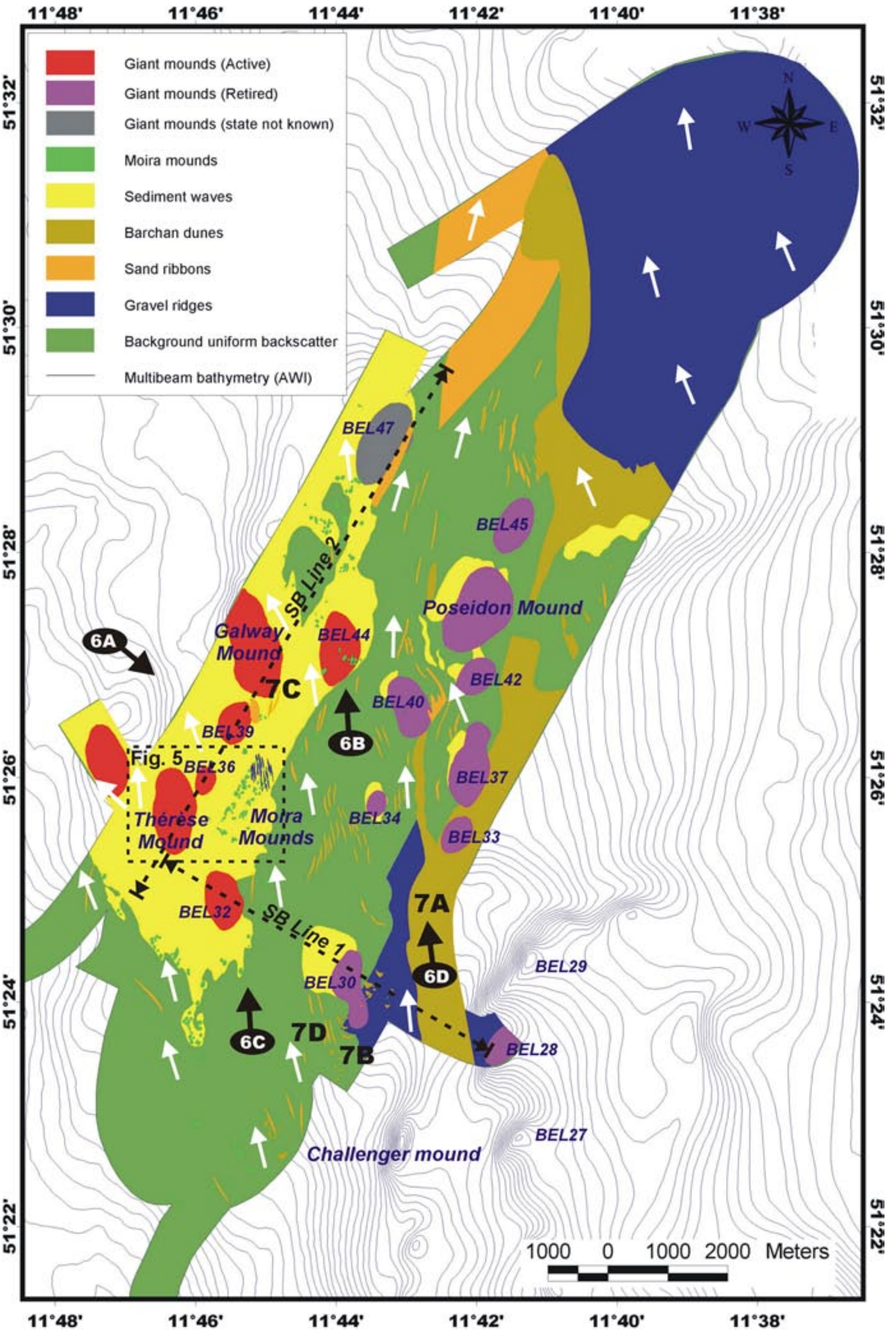

Fig. 2 Interpretation (facies) map of the Belgica Mounds area based on side-scan sonar, sub-bottom profile and video data. Dashed lines indicate the location of selected 3.5 kHz sub-bottom profiler lines (SB Line 1 and 2; see Fig. 10 for detail). A number of 3D views

imagery. This seabed facies occurs in relatively flat or gently sloping areas of the seabed, although in some cases may also characterise the flanks of carbonate mounds (e.g., the eastern flank of Poseidon Mound). Video truthing (Fig. 3) suggests that this facies is represented by smooth current swept seabed surface with patchy to dense distribution of dropstones, or, in some places, by rippled sand sheets (Fig. 8A). This facies possesses sharp boundaries with areas of sediment wave or barchan dune development and accommodates a number of sand ribbons and solitary Moira Mounds. This facies exists between the eastern and western mound areas.

Sediment wave facies

Side-scan sonar imagery shows that sediment waves are distributed throughout the mapped area, although more frequent in the western part of the province. Sediment waves shape the seabed in between mound areas and also develop on mound's flanks, indicating that mound surface morphology is strongly dictated by prevailing basal current activity. Sediment waves can be grouped in fields that possess sharp boundaries with the surrounding seabed. Boundaries between sediment wave fields are defined by differences in wave dimensions.

The orientation and size of sediment waves is dependent on hydrodynamic conditions and particle-size. Sediment wave bedforms vary in shape and size with a wavelength of 5 to 60 m and a wave height of 1 to 10 m, whilst on mound flanks they range between 10 to 15 m wavelength and 1 to 3 m height and show larger dimensions on the stoss slopes of the mounds then on their lee sides.

Most of the waves within the sediment wave fields at the lower and upper flanks of the giant mounds have been stabilised by corals and associated biocommunities, with corals growing preferentially on wave crests (Fig. 5B).

BEL44 shows a good example of a rapid transition from uniform backscatter representing rippled or current swept sand sheets to a sediment wave field at the lower flanks of the mound (Figs. 3, 6B). Due to the low topography of this mound (c. 40 m) sediment waves migrate over the mound's summit. Moira Mounds can be observed on the lower southeastern flank of this mound.

Barchan dune facies

The distribution of barchan dune forms is limited to the eastern part of the Belgica Mound province. Side-scan sonar imagery reveals an extensive barchan dune field stretched in a SSW-NNE direction along the eastern edge of the mosaicked area. This implies active sediment transport over the eastern flanks of the half buried mounds. If these features were relic (palaeofeatures) reflecting former palaeocurrent speeds, one might expect the preserved palaeomorphology for the entire area, including the gravel ridges, to be covered by rippled sands. This is not implied by the side-scan

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of the 100 kHz side-scan sonar imagery draped over the multibeam bathymetry are located (e.g., 6A; see Fig. 6). Location of 410 kHz side-scan sonar highlight images is shown (7A, 7B, 7C, 7D; see Fig. 7). Dashed box outlines the area of Thérèse and Moira Mounds that was extensively video-truthed (see Figs. 5, 8, 9 for detail). White arrows indicate directions of benthic currents derived from bedforms orientation on side-scan sonar and video imagery

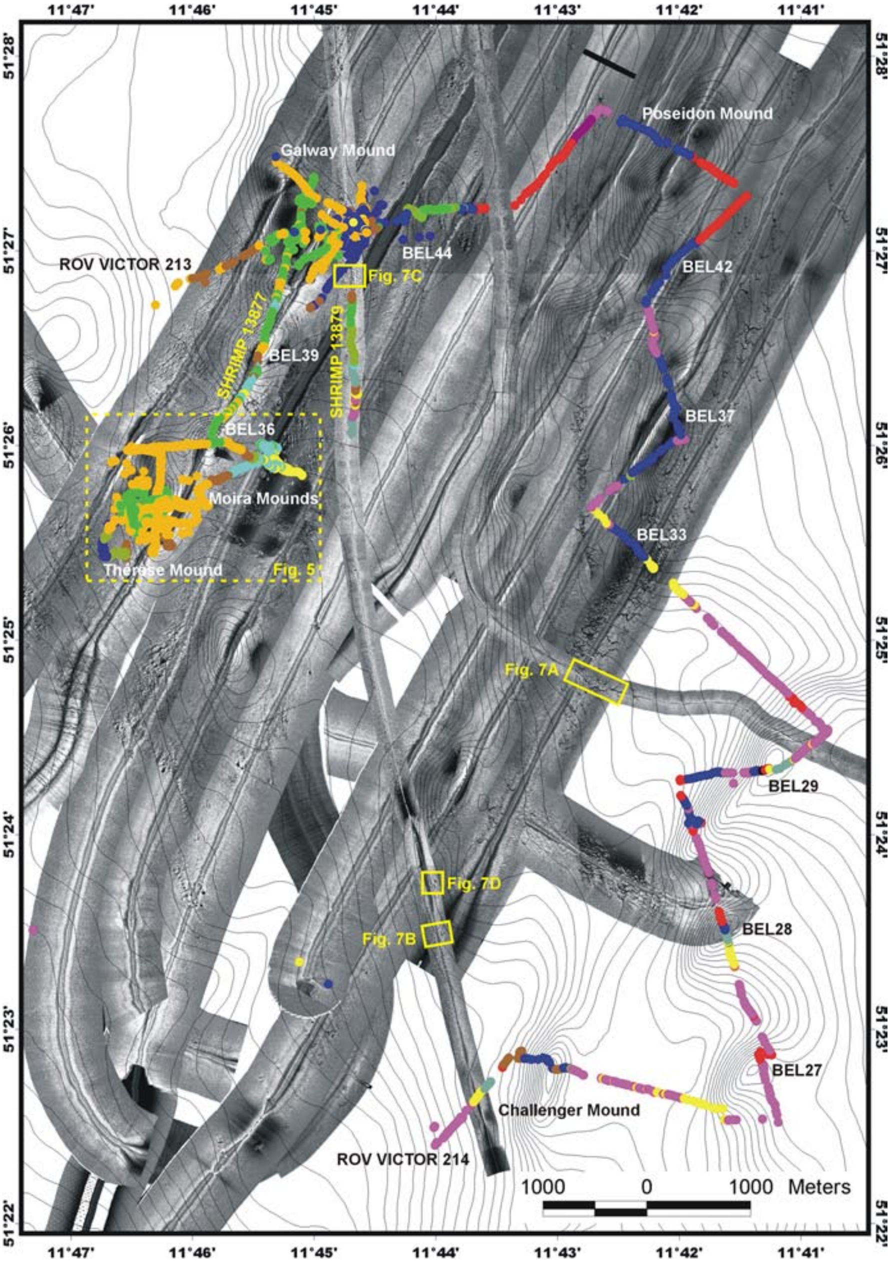


Fig. 3 This map presents facies interpretation of the video survey tracks overlaying remotely sensed imagery (100/410kHz side-scan sonar and multibeam bathymetry contours). Video data include all video surveys undertaken in the study area with ROV VICTOR 6000 and SHRIMP video systems (see Table 1 for details). Legend provided on the next page

Legend - video facies interpretation

● Dense coral coverage (live & dead)
● Dense coral coverage (mostly dead)
● Sediment clogged dead corals/rubble
● Patchy mostly live corals on rippled seabed
● Patchy mostly dead corals on rippled seabed
● Patchy mostly dead corals on unrippled seabed
● Dropstones (gravel and/or boulders) dominated seabed
● Dropstones (gravel and/or boulders) - patchy distribution on unrippled seabed
● Dropstones (gravel and/or boulders) - patchy distribution on rippled seabed
● Rippled seabed with occasional dropstones
● Unrippled seabed with occasional dropstones
● Rock outcrops(?)

Fig. 3 Legend for the facies interpretation of the underwater video survey tracks presented

sonar backscatter characteristics suggesting the peak current speeds implied by the larger scale bedforms are contemporaneous. Bedforms orientation provides evidence for strong northward flowing bottom currents. Dunes show larger dimensions at the lower stoss flanks of the mounds and decrease in sizes while migrating over the upper flanks and mound's crests (e.g., BEL33). Therefore wavelengths of observed dune forms vary from 10 to 70 m. Dunes show denser distribution in the proximity of BEL33 and become sparser to the northeast of BEL33. The main barchan dune field goes over the top of BEL33, covers the eastern flank of BEL37 and continues as far north as the southern edge of the Poseidon Mound, followed by a sharp transition to the light toned uniform backscatter. Smaller areas of barchan dunes development are observed further to the north.

A relatively narrow zone (c. 150 m) of barchan dunes runs in a south-north direction following the isobaths west of BEL33 and BEL37 to the base of BEL40 (Fig. 2). The orientation of dunes in the upper field (over BEL33 and BEL37) show a NNE sediment transport direction while in the field west of BEL37 it indicates a northern sediment transport.

A 410 kHz side-scan sonar highlight (Fig. 7A; see Fig. 2 for location) shows a zone of barchan dune development. Solitary forms are evident at the eastern edge of the field (bottom of image) whereas the centre of the field shows the bedforms combining into wavy ridges. Note that the tails of the dunes feed the centre of the dunes behind. This pattern is still evident when the dunes have coalesced into ridges. In the centre of the image, dunes migrate over a gravel ridge-dominated seabed. Gravel ridges are imaged as thinner wavy areas of dark toned backscatter (Fig. 7).

About 16 barchan dune forms migrate over the seabed directly to the east of BEL30. Wavelength varies between 30 and 70 m, with wave height reaching only a few metres. More to the east and northeast barchan dunes develop into more aggregated fields as described above (Fig. 7B).

Gravel ridge facies

Two types of gravel ridges were observed within the mosaicked area: ridges with lunate and linear crest alignment. Ridges with lunate crest alignments develop in the eastern part of the province, and in most cases coexist with superimposed barchan

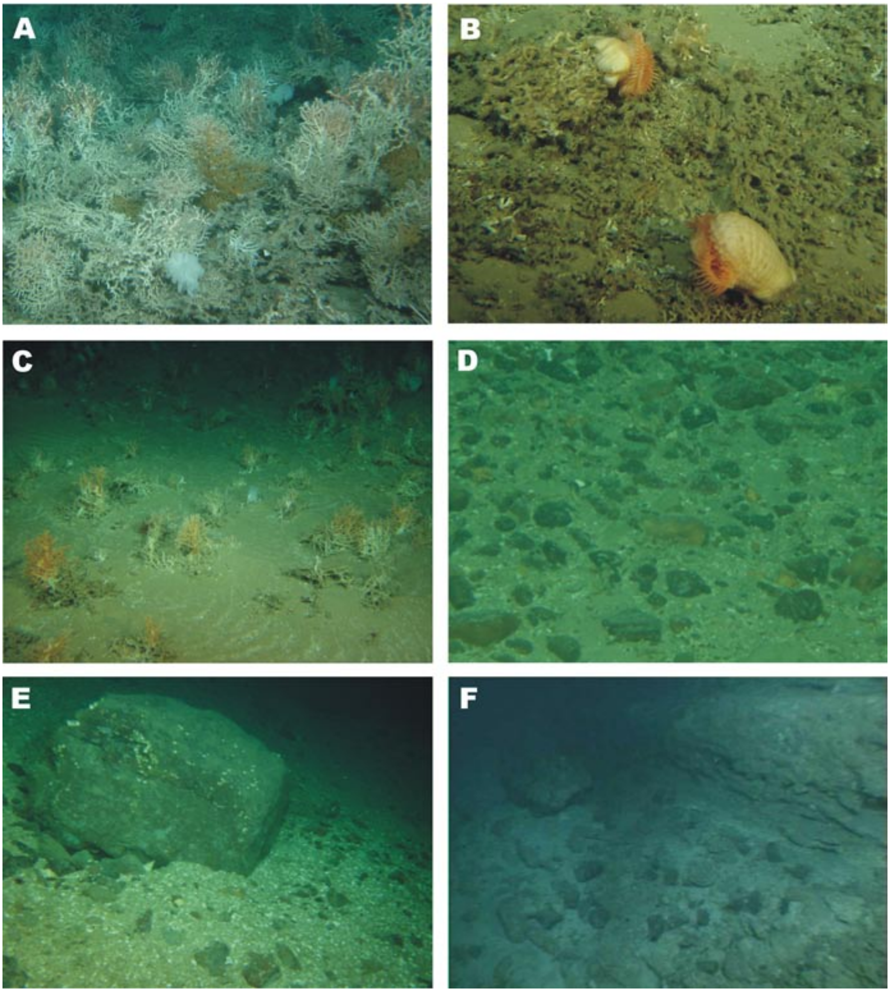


Fig. 4 Video highlights of different facies characteristic for the Belgica Mounds study area. **A** Dense coral coverage (live and dead); **B** Sediment-clogged dead corals/rubble; **C** Patchy mostly live corals on rippled seabed; **D, E** Dropstones (gravel and/or boulders) dominated seabed; **F** Hardground outcrops (All images © IFREMER)

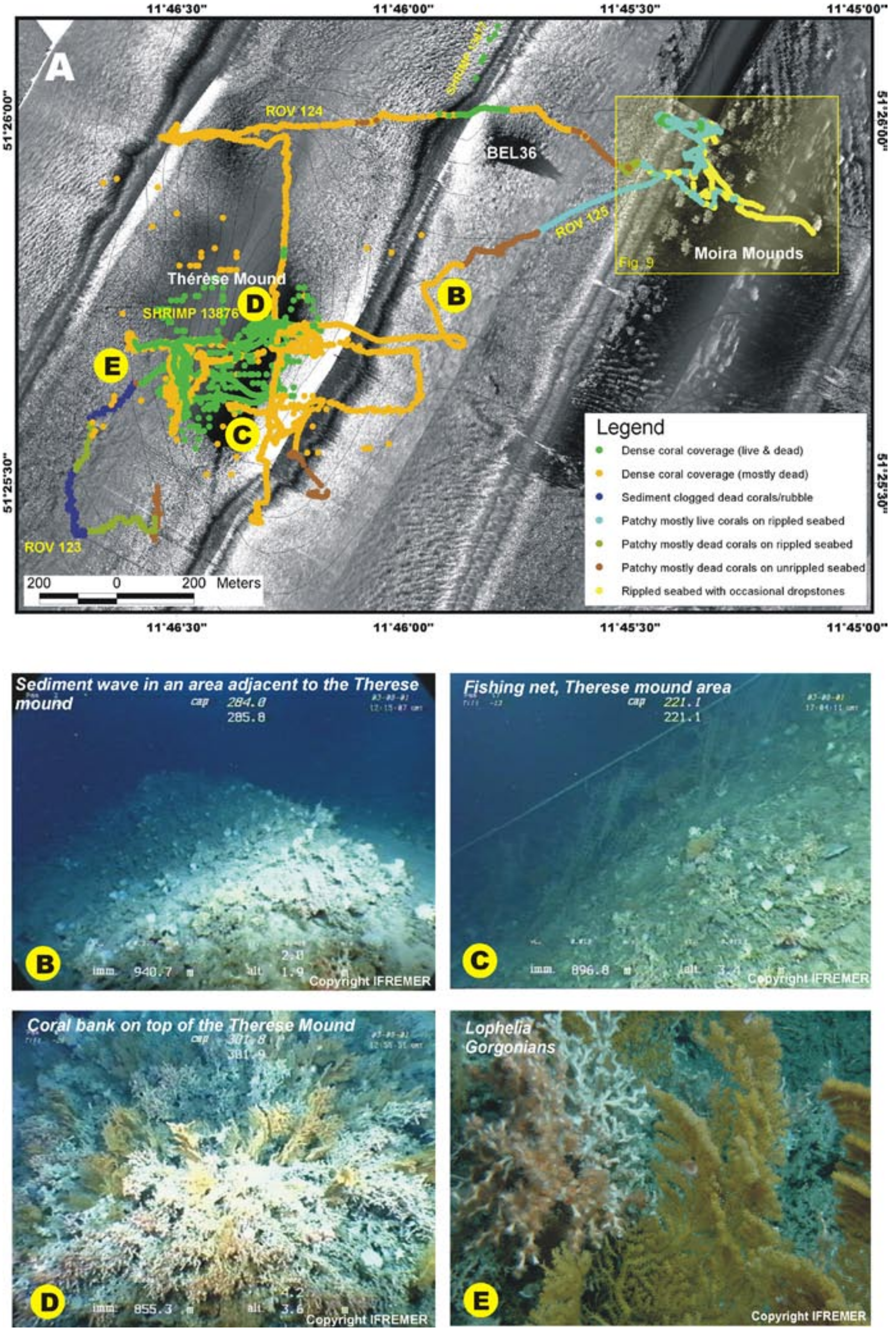
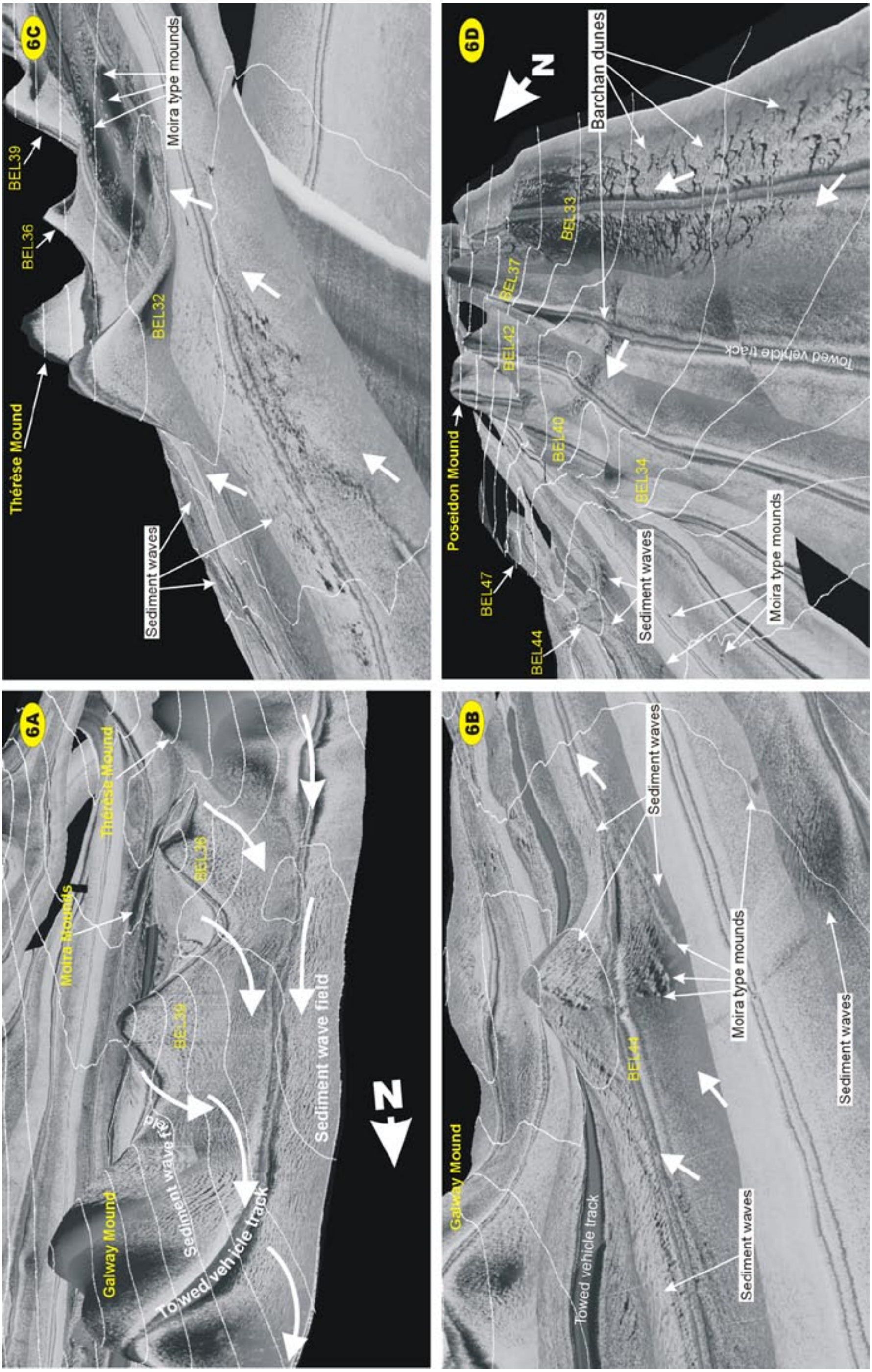


Fig. 5 A Thérèse Mound and Moira Mounds video facies interpretation overlaid over 100 kHz GeoAcoustic side-scan sonar mosaic. Analysed video data include: ROV VICTOR dives 123, 124 and 125, and SHRIMP dives 13876, 13977. See also video highlight images (**B** to **E** © IFREMER)


6A
Thérèse Mound
Moira Mounds
BEL36
BEL39
Sediment wave field
Sediment wave field
Galway Mound
Towed vehicle track
N
6B
Galway Mound
Towed vehicle track
BEL44
Sediment waves
Moira type mounds
Sediment waves
Sediment waves
6C
Thérèse Mound
BEL32
BEL36
BEL39
Moira type mounds
Sediment waves
6D
N
Barchan dunes
BEL33
BEL37
BEL42
BEL40
BEL34
Poseidon Mound
BEL47
BEL44
Sediment waves
Moira type mounds
Towed vehicle track

dune forms composed of sandy material (white backscatter on Fig. 7). Gravel ridges are represented here by sinuous crested lines. They show predominantly sinuous out of phase plan pattern with some bifurcation and have a wavelength varying between 10 and 40 m. The 410 kHz imagery implies that some sandy sediment (white backscatter) is deposited on the leeward sides of the ridges.

Ridges with linear crest alignment were observed at the northern and northwestern far ends of the Belgica Mound province. The northern part of the mosaic area shows an extensive field of sand and gravel ridges (ribbons). These ridges possess a SE-NW elongation therefore indicating currents flowing from SSE to the NNW. In parts of this zone, sand ridges are replaced by barchan or transverse dune forms indicating fluctuations in the benthic current strength. An area of apparently buried linear gravel ridges also exists in the Moira Mounds area to the east of Thérèse Mound (Figs. 2, 5A), where a series of SSE-NNW oriented features can be observed. These features are c. 10-20 m wide and distributed with an average spacing of 30 m.

Sand ribbon facies

Sand ribbons are distributed throughout the mapped area. These are relatively narrow features with straight to wavy crest alignment. They are normally elongated in the SSE-NNW direction indicating northern sediment transport direction and possess lengths from c. 150 to 900 m. Sand ribbons in the vicinity of mounds show basal currents directional change depending on the local topography. Most of sand ribbons tend to occur in groups, although 100 kHz side-scan sonar shows that solitary examples may also take place. Video truthing shows that in some places current induced sand ripples are superimposed on the body of the sand ribbons. Ripple crests show orientation perpendicular to the elongation of the sand ribbon, therefore indicating the same direction of basal current that was responsibly for formation of bedforms of both scales.

Moira Mound facies

Moira Mounds are relatively small (tens of metres across and a few metres high) coral mounds that occur in the areas between giant carbonate mounds (Fig. 6C), with some apparent examples located near BEL44 on Figure 2 and 6B. Side-scan sonar imagery indicates that the Moira Mounds preferentially occur in the areas with active hydrodynamics: on the upstream margins of sediment wave fields, and far end of gravel ridge or barchan dune dominated seabed. The facies map of the study area (Fig. 2) indicates that the majority of the Moira Mounds are located within the area of the western mounds where environmental conditions seems to be optimal for dense coral colonisation and contemporary coral growth. Most of the Moira Mounds are sub-circular in shape, showing elongation in the direction of the

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Fig. 6 **A-D** These images show a three-dimensional prospective of 100 kHz GeoAcoustic side-scan sonar mosaic of the Belgica Mounds draped over multibeam bathymetry. Location and viewpoint for each of the 3D images is shown on Fig. 2 (marked as 6A to 6D). Notice distribution and variation in bedform type and dimensions on mound flanks and between mound areas. White arrows indicate benthic current directions derived from bedforms interpretation. Thin white curves show multibeam bathymetrical contours

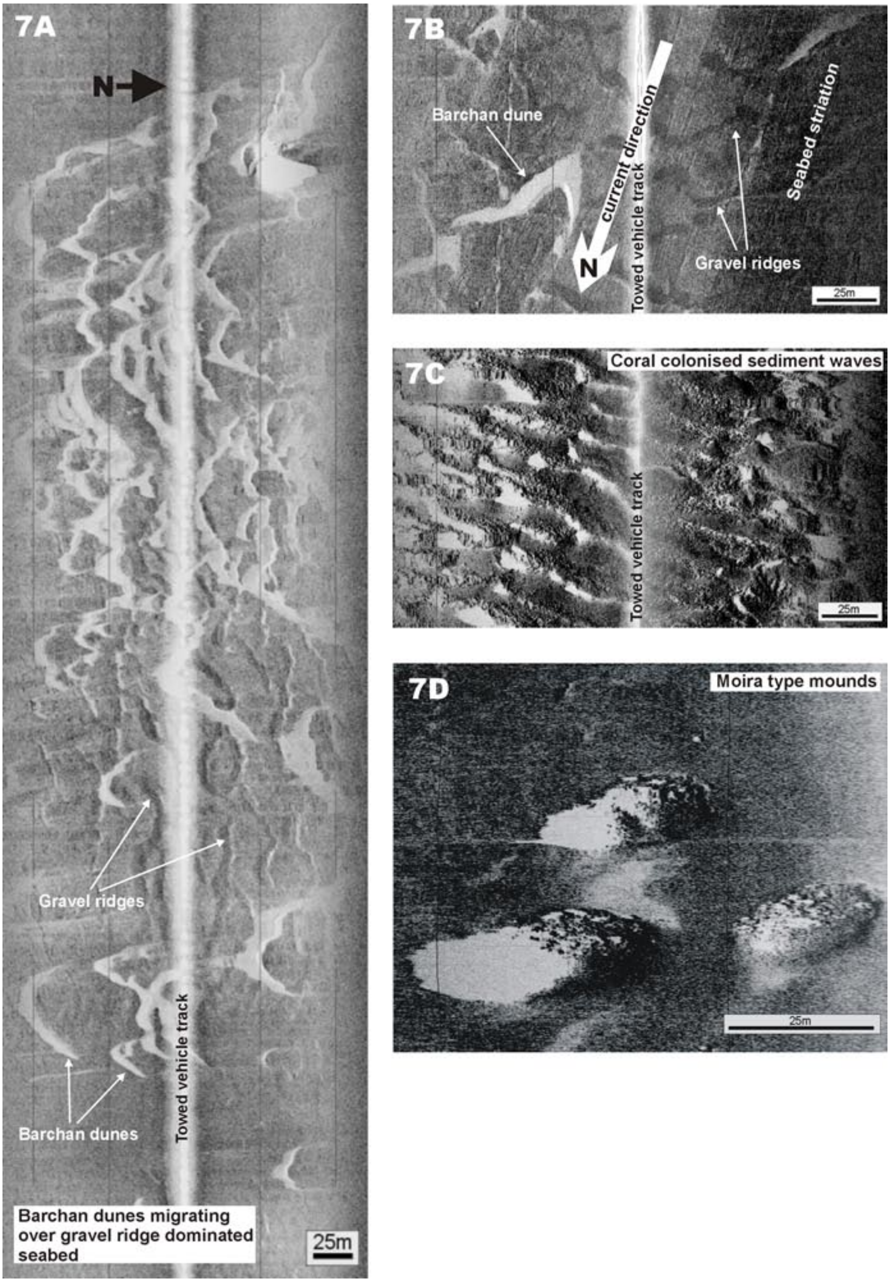

Fig. 7 410 kHz side-scan sonar highlight images. Location of images is shown on Fig. 2. **7A** This image shows a zone of barchan dune (white backscatter) development migrating over gravel ridge (black backscatter) dominated seafloor in the area between carbonate mounds. **7B** Image shows barchan dune forms composed of sandy material (white backscatter) migrating across gravel ridges (black backscatter), as well as seabed striation caused by intense current

dominant current flow. Some Moira Mounds (Figs. 3, 6B) possess long (c. 150-500 m) tail-like structures aligned in south-north direction representing down-current sediment wave trains. Moira Mounds tend to occur in groups, although solitary examples were also documented (Fig. 2). Although only a limited number of Moira Mounds was mapped with 100 and 410 kHz side-scan sonar, the survey with 30 kHz TOBI side-scan sonar (de Haas et al. 2002; Huvenne et al. 2005) showed that hundreds of Moira Mounds exist in the study area.

By using high-resolution 410 kHz side-scan sonar imagery, the acoustic signature for coral accumulations on top of the Moira Mounds was detected. Figure 7D shows three closely spaced Moira Mounds, which possess a lumpy structure with spots of high backscatter indicative of coral colonies. The mounds are sub-circular with the uppermost mound showing bimodality in form suggesting that it may have formed as a result of intergrowth between two mounds. This example exists on a gravely substrate at the edge of a gravel ridge field (Fig. 7D; see Fig. 2 for location). Video imagery shows that mounds have a slope gradient of about c. 15° (Fig. 8D).

The most studied Moira Mounds are located to the east of the Thérèse Mound (see Figs. 2, 5). This area was mapped with 100 kHz side-scan sonar and truthed with detailed ROV VICTOR 6000 video observations (Olu-Le Roy et al. 2002). These Moira Mounds occur within an area of sediment wave development that covers longitudinal gravel ridges. It is speculated here that the gravel ridges probably formed the original substrate for coral colonisation that has been subsequently buried. Wave crests within this field have an east-west orientation indicating that Moira Mound development occurs under a northerly flowing current regime. Most of the mounds show elongation with the regional current flow in the south-north direction.

Between mound areas are represented by rippled sand sheets with occasional small dropstones and, in places, patchy live coral cover. In some areas, current ripples are superimposed on larger scale current-induced bedforms (low angle sand waves). Current ripples also shape the surface morphology of the sediment infilling coral framework on mound flanks and summits. Occurrence of the Moira Mounds in the areas of rippled sand sheets development within the sediment wave fields implies benthic current strength of approximately 60 cm sec^{-1} (Southard and Boguchwal 1990).

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velocities. **7C** This image shows that the surface morphology of the lower flanks of the carbonate mounds is strongly controlled by sediment waves. High backscatter spots on the surface of the waves are caused by coral and associated bioaccumulations. White backscatter represents acoustic shadows cast by wave crests. This image is from the southeastern flank of the Galway Mound. **7D** Three closely spaced Moira type mounds are imaged in the area between giant carbonate mounds. Moira Mounds possess a lumpy structure with spots of high backscatter indicative of coral colonisation. This example exists on a gravely substrate at the edge of a gravel ridge field. Areas of white backscatter represent acoustic shadows, implying that mounds are sufficiently elevated above the surrounding seabed

Belgica Mound facies

Geophysical observations

The location of the giant mounds (and hence the giant mound seabed facies) is

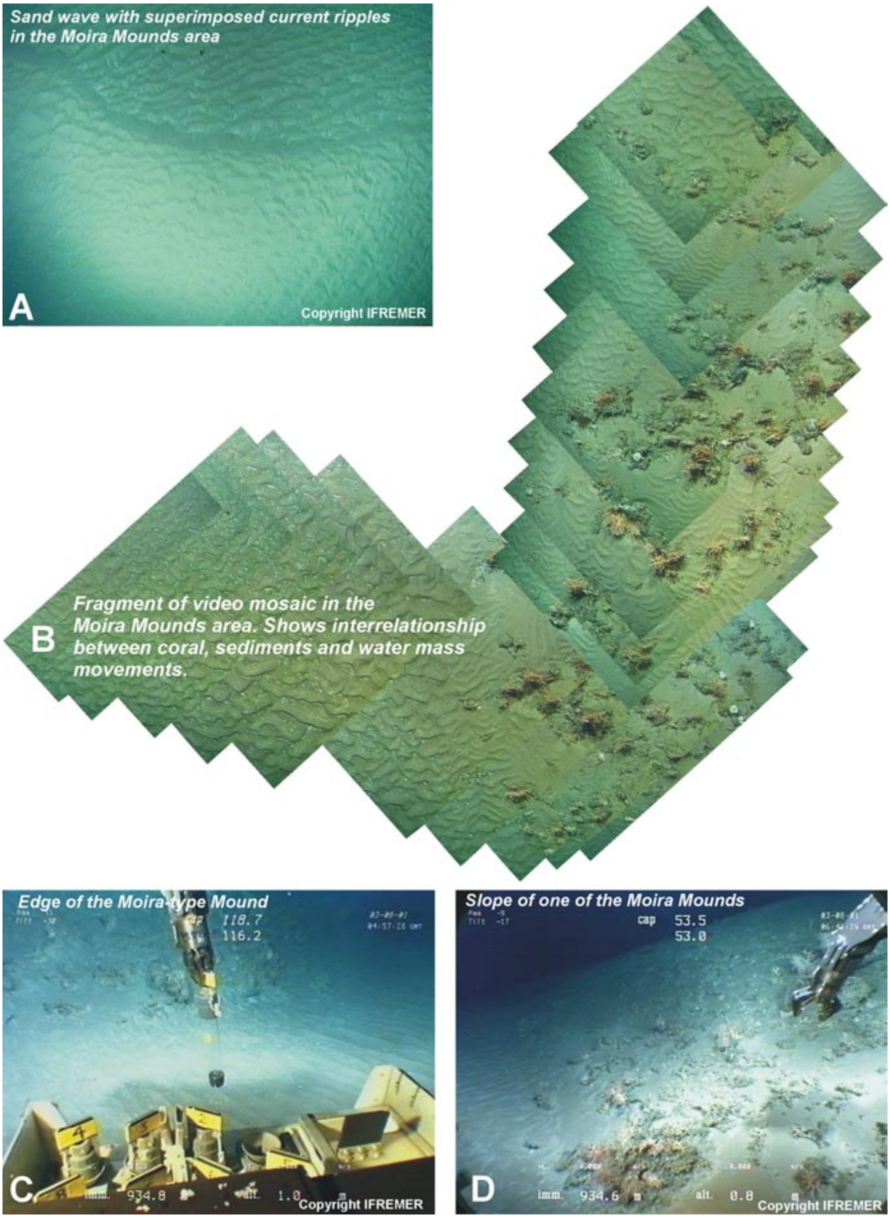

Fig. 8A-D Fragment of video mosaic in the Moira Mounds area and video highlights. (All images © IFREMER)

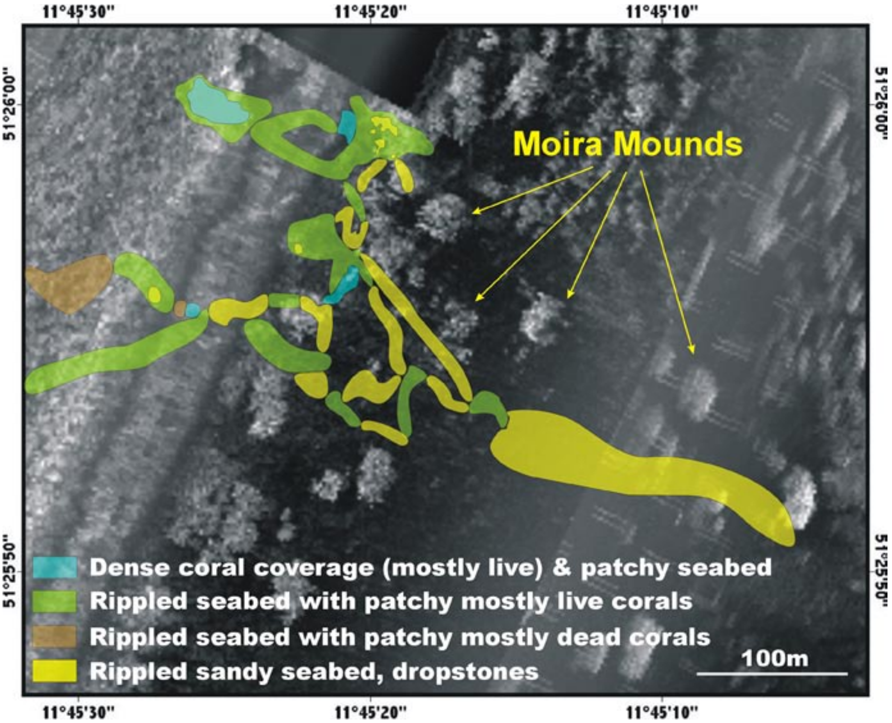

Fig. 9 Moira Mounds video facies interpretation (ROV VICTOR 6000 dives 124 and 125) overlaid over 100 kHz GeoAcoustic side-scan sonar mosaic

best documented from the multibeam and sub-bottom profiler data. Furthermore, sub-bottom profiler records interpreted together with the available ground-truthing information allows a distinction between active and retired mounds to be made (see also ROV-based conclusions in Foubert et al. 2005). This interpretation was based on the nature of the seabed reflector. Sub-bottom profiler records show two types of seabed reflectors of the mound's surface: a solid seabed reflector with the same characteristics as the surrounding seabed and a diffuse reflector. Video and sampling surveys of several mounds suggest that a diffuse reflector occurs where mounds are topped with exposed coral framework (see below). In most cases this will imply the coexistence of both dead and live coral populations. Mounds possessing a solid seabed reflector normally show no evidence of coral life and are dominated by coral rubble or sediment clogged dead coral framework. In this way, the 3.5 kHz sub-bottom profiler record provides a rough estimate of mound cover and coral ecosystem "health". Table 2 lists all mounds imaged on the 3.5 kHz sub-bottom profiler in the central Belgica Mound province, and summarises where available ground-truthing information on particular mounds. Ground-truthing information has been collected for 9 mounds imaged on the sub-bottom profiler that has been extrapolated to mounds that were imaged on the sub-bottom profiler only (Table 2).

Table 2 Summary of ground-truthing information for Belgica Mounds imaged on 3.5 kHz sub-bottom profiler lines

List of mounds imaged on 3.5kHz sub-bottom profiler lines	Seabed reflector type on 3.5kHz profiler	Ground-truthing information	Mound type (active/retired)
Thérèse Mound (BEL35)	Diffuse	Dense coral coverage (live and dead) *Video data*: ROV VICTOR dives 123, 124, 125; SHRIMP 13876#1; *Box core samples*: PS64/271-2, PS64/271-1, PS64/271-3, 13881#1, 13881#2, 13881#3, 13874#1, 13874#2, 13874#3	Active
Galway Mound (BEL43)	Diffuse	Dense coral coverage (live and dead) *Video data*: ROV VICTOR dives 213, 214 *Box core samples*: PS64/254-1, PS64/254-2, PS64/254-3, PS64/257-2	Active
BEL36	Diffuse	Dense (live and dead) coral coverage on the mound's summit *Video data*: ROV VICTOR dive 124, SRIMP13877#1	Active
BEL39	Diffuse	Dense (live and dead) coral coverage on the mound's summit *Video data*: SRIMP13877#1	Active
BEL32	Diffuse	Coral framework *Box core samples*: see Van Rooij et al. 2003b	Active
BEL38	Diffuse	n/a	Active (?)
BEL44	Not crossed at the summit, but shows diffuse reflector on the western flank	Dense (live and dead) coral coverage on the mound's summit *Video data*: ROV VICTOR dive 214	Active

Table 2 continued

List of mounds imaged on 3.5kHz sub-bottom profiler lines	**Seabed reflector type on 3.5kHz profiler**	**Ground-truthing information**	**Mound type (active/retired)**
BEL29	Solid	Mound's summit is dominated by unrippled seabed with patchy dropstones; with sediment clogged dead corals/coral rubble on the western flank of the mound *Video data*: ROV VICTOR dive 214	Retired
BEL33	Solid	Sediment clogged dead corals/coral rubble *Video data*: ROV VICTOR dive 214	Retired
BEL37	Solid	Sediment clogged dead corals/coral rubble *Video data*: ROV VICTOR dive 214	Retired
Poseidon Mound (BEL41)	Solid	Sediment clogged dead corals/coral rubble on the western flank, and dropstones dominated seabed on the eastern flank *Video data*: ROV VICTOR dive 214 *Box core samples*: PS64/276-2, PS64/276-3	Retired
BEL30	Solid	n/a	Retired (?)
BEL34	Solid	n/a	Retired (?)
BEL40	Solid	n/a	Retired (?)
BEL42	Solid	n/a	Retired (?)
BEL45	Solid	n/a	Retired (?)

Side-scan sonar data provide details of the surface morphology of the upper and lower flanks of the mounds. Side-scan sonar imagery reveals that mound morphology is strongly dictated by prevailing basal current activity. Most of the outcropping mounds of the western mound belt are largely covered in sediment waves. The type and size of bedforms changes depending on the local topography related to mound proximity and position up the flanks of the mounds (Fig. 6). 410 kHz side-scan sonar data revealed sediment waves with coral accumulations (Fig. 7C). Mounds of the eastern mound belt possess a half buried morphology due to onlap of the contourite drift deposits. Drifting sediments are superimposed on the eastern flanks of the mounds in the form of barchan dunes, which in some cases (e.g., BEL33 on Fig. 6D) migrate over the mound summits.

Table 2 and the facies map of the study area (Fig. 2) clearly show that at present mounds of the eastern belt of the province are retired (purple facies) and mounds of the western belt are active (red facies) in terms of the vitality of the coral cover and hence mound growth. The two most representative 3.5kHz sub-bottom profiles are indicated by the dashed lines on the facies map (Fig. 2) and presented with some interpretations on Figure 10.

Line 1 (Figs. 2, 10) images two carbonate mounds (BEL30 and BEL32) and contourite drift, which, on the sub-bottom profiler data, appear as a well-stratified

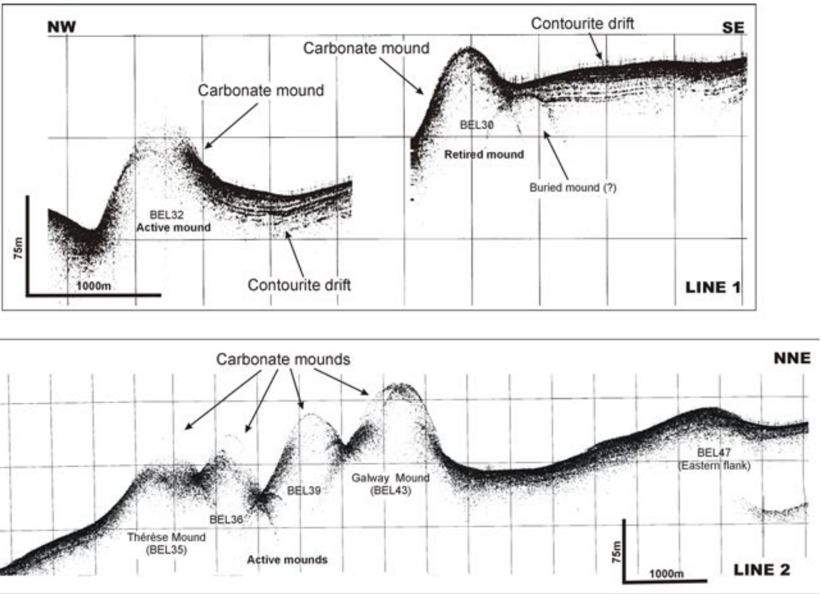

Fig. 10 3.5kHz sub-bottom profiler lines. Location of profiles is shown on Fig. 2. LINE 1: images two carbonate mounds (BEL30 and BEL32) and contourite drift sequences that are characteristic for the study area. Solid seabed reflector of BEL30 suggests that this mound is retired at present, while diffuse reflector of BEL32 suggests that this mound is active. LINE 2 shows few active mounds of the western mound belt including Thérèse and Galway Mounds

sediment succession. The south-eastern flank of BEL30 is partly covered by this drift, another carbonate mound immediately to the east of BEL30 has been totally buried by this drift and the area between BEL30 and BEL32 is filled with the contourite drift deposits with sediments onlapping on the south-eastern slope of BEL32. This mound is bounded from northwest by a seabed depression (gully) between BEL32 and Thérèse Mound. The first mound on this line (BEL30) possess a solid seabed reflector, while BEL32 shows a diffuse seabed reflector, which implies that BEL30 is retired, and BEL32 is active at present (see Table 2).

Line 2 (Figs. 2, 10) images the westernmost mounds of the Belgica province including the eastern flank of BEL47, an interval of gently sloping seabed and four outcropping carbonate mounds: Galway Mound, BEL39, BEL36 and Thérèse Mound. Each mound is nearly symmetrical in a NNE-SSW direction, showing highly diffuse seabed reflectors especially at their summits. Groundtruthing reveals these mounds are heavily colonised by corals (see Table 2) and represent the best examples of active mounds within the province.

Video observations

Eight mounds were video ground-truthed within the eastern area of the province, which can be characterised as a “retired” mound belt, as all mounds here show a lack of live coral cover. The mounds’ flanks and summits are mostly composed of sediment-clogged dead coral frameworks or coral rubble. A general description of video transects across these mounds is presented below paying particular attention to evidence for sediment transport (see Figs. 3, 4). Video facies descriptions are also summarised by Foubert et al. (2005).

The Challenger Mound is characterised by sediment clogged dead coral and coral rubble facies. No living framework-building corals were observed on this mound although gorgonians and sponges were found growing on dead corals on the flanks and summit of the mound. At the lower eastern flank, patchy dead corals and coral rubble clogged within rippled sand sheet were encountered. The orientation of ripples indicates active sediment transport to the NNW, which implies that currents follow around the contours of the lower flank of the mound.

Lower southwestern flank of BEL27 also showed rippled sands. The orientation of ripple crests indicates that currents are flowing to the NNE, following the topographical contours of the lower western flank of the mound. The orientation of comet and scour marks at the lower southern flank of the mound shows westerly-directed currents implying that regional northerly flowing contour currents are being deflected and intensified to the west by the mound’s topography. The northern upper flank of BEL27 shows a dense dropstones distribution, implying further active seabed erosion on this side of the mound also.

The southern flank of BEL28 also shows rippled sands migrating in the form of low relief sediment waves over a current swept seafloor typified by a coarser gravel lag. The orientation of the current-induced ripples superimposed on sediment waves and the orientation of comet marks behind dropstones in between wave areas indicates south-westerly flowing currents. The summit and flanks of this mound are represented by background uniform backscatter on 100 kHz side-scan sonar.

Video truthing suggests that the upper southern flank of BEL28 is represented by muddy bioturbated seabed, with the summit of this mound (c. 690 m water depth) possessing sediment-clogged dead coral cover. No live framework-building corals were observed on this mound although gorgonians and antipatharians growing on dead coral framework and dropstones were present. Video imagery shows the presence of dropstones on the mound's summit embedded within sediment-clogged coral cover implying strong seabed erosion by bottom currents. This may be one of the reasons for the mound's retirement.

Lower southwestern flank of BEL29 shows a dropstone dominated seabed. Areas between dropstones are filled with carbonate-rich sediment probably composed of broken shells and coral rubble. The western flank of BEL29 shows sediment-clogged dead coral cover. Mid-slope areas contain a c. 200 m area with patchy dropstones that are embedded within coarse-grained carbonate rich sediment suggesting erosion and reworking of a pre-existed coral cover. Extensive hardgrounds are exposed on the upper western flank of BEL29 suggesting strong seabed erosion and exposure of the lithified internal mound sediment. Erosive currents may account for an absence of coral settlement in this area. The possible hardground outcrop is followed for c. 40 m to the east by very dense distribution of boulder size dropstones. Rippled sands drape dropstone-dominated seabed at the summit of the mound. Orientation of the ripple crests and current induced features surrounding exposed dropstones suggests northerly currents flowing over the mound's summit. A similar situation develops at the upper eastern flank of the mound.

To the northeast of the BEL29 summit, the dive track crosses the 410 kHz side-scan sonar line. The light toned uniform backscatter on the side-scan sonar imagery with apparent boulder and ridge-like structures is represented on the video imagery with relatively flat muddy bioturbated seabed with patchy distribution of boulder size material.

Video imagery of the lower southeastern flank of BEL33 shows active sediment transport in the form of transverse and barchan sand dunes in accordance with 100 kHz side-scan sonar data. The summit and western flank of the mound demonstrate dead sediment clogged corals and coral rubble cover. This mound does not reveal any framework-building corals only shows epifauna (e.g., actinians) that uses dead coral framework as an attachment substrate.

Flanks of BEL37 also show dead sediment-clogged coral coverage. The southern flank of BEL37 shows no evidences of live corals or epifauna. The northern upper and mid flank of the mound demonstrates the abundance of soft corals (e.g., gorgonians). BEL42 at its flanks and summit shows patchy to dense dead coral cover, which corresponds to background uniform backscatter on 100 kHz side-scan sonar (Fig. 3). In some areas this is more reminiscent of the coral rubble facies. Both corals and coral rubble are sediment clogged and show patchy growth of gorgonians.

The Poseidon Mound is the biggest mound of the eastern mound belt, the eastern flank of which is covered in coarse gravel lag. The summit and the western flank of the mound show dense, mostly dead, coral cover. However, very sparse live *Madrepora* *oculata* is found growing on the mound's summit. Mostly dead coral framework supports the growth of epifauna (e.g., antipatharians, sponges, anemones). Video imagery of the lower western flank of Poseidon Mound confirms 100 kHz side-scan sonar interpretation that sediment waves are colonised by corals although corals are mostly dead at present. Coral preferentially grow on the sediment wave crests with the very limited growth in wave troughs. It is plausible to assume that these sediment waves are not active at present, as they have been stabilised by coral growth.

In contrast to the eastern mounds, western mounds in the Belgica Mound province showing dense coral coverage with a large percentage of live colonies of *Lophelia pertusa* and *Madrepora oculata* on their summits. Lower flanks of the mounds show mostly dead coral cover with the sediment clogged corals and coral rubble at mound's basements (see also Foubert et al. 2005).

Mapping of the Thérèse Mound (Figs. 3, 5), suggests that the surface morphological details of this mound show distinct relationships to sediment waves that have become colonised and stabilised by coral and associated communities (Fig. 5B). On the lower flanks of the mounds, corals colonise the crests of sediment waves with limited growth in the troughs, therefore taking advantage of stronger current and nutrient flux. Coral density increases up the mounds (Fig. 5C) until sediment waves become fully stabilised and corals continue to grow into coral banks (Fig. 5D). Coral population is mainly represented by *Lophelia pertusa* and *Madrepora oculata*. Coral growth supports extensive epifauna (e.g., sponges, gorgonians; Fig. 5E), and a wide range of benthic organisms, as well as deep-sea fishes (Olu-Le Roy et al. 2000).

The observations from the Thérèse Mound are also typical for most active mounds of the western mounds in the Belgica Mound province (including BEL36, BEL39, BEL44 and the Galway Mound). BEL36 shows dense live and dead coral coverage with patchy unrippled seabed at its lower and mid flanks. Live coral are documented on the summit of the mound. The northern slope of BEL39 shows dense live and dead coral coverage. On the top of the mound a well-developed but predominantly dead coral framework is observed that may suggest limited erosion. The southern slope is characterised by a smooth seabed with patchy dead and living coral cover.

Video imagery of the Galway Mound shows that the sediment waves imaged on 410 kHz side-scan sonar at the eastern lower flank of the mound are stabilised by coral growth (Fig. 7C). Corals are mostly dead at present, but in places show rather dense coverage. Corals show a preference for colonisation on wave crests, and are very sparse in the wave troughs and coexist with abundant population of sponges and soft corals (e.g., gorgonians and antipatharians). The seabed between the coral-colonised sediment waves show unrippled sand. The lower northeastern flank of this mound also shows dense but mostly dead coral cover whilst the upper flanks and the mound's summit show dense, mostly live coral cover. The dominant coral species on this mound are *Madrepora oculata* and *Lophelia pertusa*. Live corals grow on dead coral skeletons that also form a substrate for sponges, gorgonians and other epifaunal growth. The lower eastern flank of the mound is dominated by sediment-clogged corals and coral rubble facies. In some places, areas of sediment-clogged corals are surrounded by rippled sands whereas further a field active sand transport is in the form of rippled sand sheets and low relief sand waves.

BEL44 is the most easterly located mound of the western "active" mound belt (Fig. 2). The lower eastern flank of BEL44 shows sediment-clogged coral rubble facies with occasional dropstones (Fig. 3). This facies dominates the flank of the mound from c. 910 m to c. 900 m water depth. In places it is apparent that corals colonise previously mobile sediment wave structures. Further upslope from c. 900 to c. 860 m water depth mound's upper flanks and summit show dense mostly live coral coverage. Live corals coexist with dead corals and support epifauna of sponges, gorgonians and antipatharians. Live coral population is dominated by *Madrepora oculata*, although *Lophelia pertusa* was also observed. Rippled sands infilling the space between corals implies active sediment transport over the flanks of the mound and possibly in parts of the summit where coral coverage is not too dense.

Discussion

Seabed mapping data have been presented at varying scales of resolution. The multibeam data provide a general geomorphological prospective of the area whereas side-scan sonar and sub-bottom profiler data provide a higher resolution view on the scale of major bedforms. The interpretation of these bedforms provides information on sediment mobility, current directions and current speeds. These bedforms record peak flow events that may only be representative of extremes in the contemporary benthic environment and may, in some cases, be relict features representative of past conditions (although probably post-glacial in nature). Video data provide information on smaller bedforms often superimposed on the larger bedforms that are representative of general contemporary conditions and allow a qualification of the above premise, e.g., current ripples and sediment waves showing correspondence in current directions reveal information on current speeds during steady-state and extreme conditions. Sub-bottom profiler and video data also allow an assessment of mound "health" in relation to the vitality of the coral ecosystem and whether mounds are "active" or "retired" (*sensu* De Mol 2002; Huvenne 2003; Foubert et al. 2005). Studying all these data together allows us to draw conclusions regarding the topographic influence of mound presence on benthic sedimentary processes and the influence of benthic sedimentary processes on mound "health". Furthermore, we can also appraise the role of sediment supply and bedform-scale mound morphology on mound growth processes.

The influence of mound topography on regional sedimentation patterns

The "background uniform backscatter facies" is dominant in areas between the two main ridges of mounds and represents sedimentation unaffected by the mound presence. This is supported by the observation that on 30 kHz TOBI side-scan sonar data this seabed facies extends to the south upstream of mounds (Huvenne 2003; Huvenne et al. 2005). This facies contains rippled sands suggesting the currents are more sluggish than near the mounds and flow to the north and northwest. Active sediment transport by currents at speeds of between 0.15 and 50 cm s^{-1} (Lonsdale and Speiss 1977; Howe and Humphery 1995) is implied. Occasional dropstones are also present in this facies suggesting low, long-term sedimentation rates with periodic erosion events causing re-exposure and winnowing of the underlying glacial deposits.

The facies map also reveals a general increase in current speeds (as confirmed by resultant bedforms) related to water depth with an upslope (and southwest to northeast) transition from ripple sand (background uniform backscatter facies) to sediment waves to gravel ridges. This suggests that the eastern province (typified by retired mounds) occurs within the main area of drift sedimentation where contour currents are strongest and the western province (typified by active mounds) occurs on the margins of this contourite drift field. The implications of this are discussed below.

Set against this background trend are more localized, but in some cases extreme, variations in current speeds that can be explained as accelerations due to flow over and around the carbonate mounds that represent an obstacle to current flow. Multibeam bathymetric data reveal that these obstacles are significant being c. 1km across at their base and rising to 100 m above the seabed on average (Wheeler et al. submitted). Areas in the vicinity of carbonate mounds are generally typified by sediment waves fields (extra-local effects) suggesting that extra-local current speeds have increased from 20-50 cm s^{-1} to c. 60 cm s^{-1} (Southard and Boguchwal 1990) representing significant obstacle-related current speed accelerations. These sediment waves also possess differing morphologies reflecting subtler responses to localised hydrodynamic conditions and follow the contours of the local topography indicating that the currents both accelerate and change their directions in the proximity of giant carbonate mounds as an obstacle response. These bedforms are found at the base of carbonate mounds as well as, in some cases, across over their summits suggesting that sediment wave-carbonate mound associations are not solely related to the altitude of the carbonate mounds elevating their summits into faster flowing waters causing the higher energy bedforms found upslope.

Furthermore, the presence of barchan dune trains shows more energetic spatially restricted current acceleration passing around the carbonate mounds, e.g., Figure 6B. These bedforms suggest that locally, the topographic obstacle of the carbonate mounds cause local accelerations from c. 60 cm s^{-1} (forming sediment waves) to c. 80 cm s^{-1} (forming barchan dunes) and in excess of 150 cm s^{-1} (forming gravel ridges) (Belderson et al. 1982; Southard and Boguchwal 1990). However, it is noted that the ridges may represent either high palaeocurrent speeds (relic features) or the contemporary peak flow regime with normal lesser flow regimes characterised by non-deposition or barchan dune formation. In other areas sand ribbons are present which implies that currents with the speeds up to 100 cm s^{-1} (Belderson et al. 1982). The presence of ripples superimposed on sand ribbons formed by currents flowing in the same direction as those that formed the sand ribbons suggests that sediment transport in the form of sand ribbons is an active process. Video evidence reveals ripples covering the sediment waves and barchan dunes implying that more quiescent conditions occur between these peak flow events although similar crest alignments suggest both type of bedforms are contemporaneous as they are formed by currents flowing in the same current direction.

Video evidence also shows the western flanks of “retired” carbonate mounds are typified by the presence of exposed dropstones, dead coral frameworks or hardgrounds suggesting accelerating currents inhibit sand grade sedimentation, common in off-mound areas, and may even result in a predominately erosive current regime in these exposed mounds (see also Foubert et al. 2005).

Environmental influences on mound biogeological processes

As well as mound topography having an influence on regional sedimentation patterns, sedimentary processes also have a profound influence on mound biogeological processes and may partly explain the distinction between the eastern “retired” mounds and western “active” mounds. Most of the eastern “retired” mounds are partially buried on their eastern flanks by the contourite drift sequences. As mentioned above, these mounds exist at water depths within the main zone of contourite drift sedimentation where along-slope northerly-flowing geostrophic currents are most active. Sub-bottom profiler and seismic data (De Mol et al. 2002; Van Rooij et al. 2003a) also reveal that these drifts have affecting this area since Miocene times and throughout mound growth. Contourite deposition in the area is variable reflecting changes in climate-related ocean circulation dynamics (Van Rooij et al. 2003a; Van Rooij et al. submitted) and the precise long-term relationships between mound growth and contourite accumulation is as yet unknown. Nevertheless, particle size data presented by Van Rooij et al. (submitted) note that late Holocene contourite deposition reflects relatively high current speeds (in relation to sedimentation over the last 100 ka) although sedimentation rates may be reduced (1 cm/ka). The side-scan sonar data presented confirms this through the imaging of associated high-energy bedforms.

These strong contour currents have a dual impact on coral mounds by burying their eastern flanks through the deposition of thick sediment sequences and eroding their western flanks and summits. The burial of their eastern flanks is a long-term geological process whereby mound growth rates are comparable with contourite sedimentation rates. The Holocene sedimentation rates calculated by Van Rooij et al. (2003a) are orders of magnitude lower than estimated deep-water coral growth rates (e.g., 0.4-2.5 cm yr^{-1}; Wilson 1979b; Mikkelsen et al. 1982; Freiwald et al. 1997; Mortensen and Rapp 1998) suggesting that deep-water corals, were they present, would be able to compete with contemporary contourite sedimentation. However, in some cases on geological timescales contourite sedimentation rates outstrip mound growth rates and mounds become buried (De Mol et al. 2002). In the late stages of this burial processes, sediment waves may migrate across the summits of these mounds and, in such scenarios, sedimentation rates may prove excessive for coral colonies which may become buried. In most cases, however, it appears that excessive sedimentation by contourite drifts cannot be taken as a reason for forcing mounds into retirement. In fact, there are numerous examples (see below) where active sand encroachment is tolerated by coral colonies and may even encourage mound growth.

The reasons that eastern mounds are “retired” may simply be that current speeds are too excessive for facilitate abundant growth. The exposed dead coral frameworks and dropstones suggest that excessive current inhibit sand grade sedimentation and it is speculated here may also inhibit the settlement of coral larvae preventing renewed colonisation. Additionally, the high current speeds may also break rigid coral exoskeletons once, and if, corals start to grow. Frederiksen et al. (1992) suggest that current speeds >100 ms^{-1} probably cause coral colonies to topple over.

The western part of the province shows a different scenario where most of the mounds possess a dense live coral cover. The western off-mound areas are characterised by extensive areas of rippled sands and sediment wave fields and lack the higher energy bedforms present in the eastern area (barchan dunes and gravel ridges). The deeper water location of western mounds on the margins of the main contourite drift area means that these mounds have not had to compete with high drift sedimentation rates throughout their geological history which have been outstrip by both mound and coral growth rates. Infact, currents in conjunction with moderate sediment supply and transport may play a positive role in the development of the carbonate mounds by providing basal support to coral colonies, stimulating mound growth by preventing coral colonies from toppling over (see below).

Another important factor probably influences the observed zonation within the province is the relationship to water masses properties (see White 2001, submitted). The depth interval where the western “active” mound summits occur coincides with the core of Mediterranean Outflow Water, which appears favourable to deep-water coral growth along the European continental margin (De Mol 2002; De Mol et al. 2005). The eastern “retired” mounds summits occur in shallower water, thus probably under less favourable circumstances with respect to contemporary water masses (but may also reveal tantalising insights in possible palaeo-watermass structures).

Biogeological processes, mechanisms for mound growth and mound micromorphology

Hydrodynamics and sediment transport exert a strong control on carbonate mound growth and resultant surface morphology. From a biological perspective, currents are an essential prerequisite for suspension feeders such as deep-water corals. Currents deliver organic particulate material on which the coral polyps feed: the stronger the currents, the higher the flux of food. Currents also prevent fine-grained clastic sedimentation that has a smothering effect on coral. From a biogeological perspective, excessive currents can erode the seabed and hinder coral colonisation as discussed above with respect to the eastern retired mounds. Of more interest is the role of bedload sand transport in the western active mounds where this process has a positive effect on mound growth. Two examples are discussed below to illustrate this mechanism.

Moira Mounds

The Moira Mounds are small, relatively young, deep-water coral mounds. It is speculated here that they may have initiated as late as the start of the Holocene with the rejuvenation of ocean circulation reaching comparable statures as the Holocene reefs from the Norwegian shelf. These are the only small-scale carbonate mound features found in the Porcupine Seabight and southern Rockall Trough. The Darwin Mounds in the northern Rockall Trough are comparable in size only because, unlike the Moira Mounds, they are coral-colonised fluid escape structures (Bett et al. 2000; Masson et al. 2003). Furthermore, there is no evidence of buried examples imaged on seismic data suggesting that these are probably not transient features that grow during interglacials when conditions are optimal only to become buried during glacials when conditions for coral growth deteriorate. In fact, it would appear that we are witnessing a new phase in carbonate mound development at its early stage, a phase which may eventually lead to the formation of further giant mounds after tens of thousands of years or perhaps develop into a new form of deep-water coral bioherm.

Moira Mounds represent accumulations of living and dead coral frameworks filled with sediment and show patchy to dense mostly live coral coverage on their summits. Once coral colonies gained a “footing” in these areas, coral colonies trap sand and build positive features for further coral development on the seafloor. In doing so, corals become elevated above the benthic-boundary layer gaining access to fast flowing waters (with increased nutrient flux and lower bedload sediment transport) thus stimulating further biological growth, sand entrapment and increases in mound elevation.

Side-scan sonar data reveal that the Moira Mounds occur in areas of active sand transport and often occur at the head of sediment wave trains. For instance, an interpretation-facies map of ROV video ground-truthing presented on Figure 9 shows that Moira Mounds occur in areas of active sand transport on rippled sand sheets and the upstream margins of sediment wave fields. This would suggest that not only are deep-water corals capable of tolerating sand encroachment but active sand transport may actually provide a benefit to the colonies by encouraging vertical mound growth. Video data reveal that the Moira Mounds are composed of coral frameworks and interstitial sands. Figure 8 shows a change in bedforms from off-mound lunate rippled sand to linear ripple and unrippled sand within the mounds demonstrating that currents slow down as they flow over the mounds. Coral colonies and the mounds themselves therefore form obstacles to basal currents thereby retarding bedload transport, which becomes eventually trapped at the base of the coral colonies. Sand entrapment within the coral framework strengthens the coral colonies preventing them from toppling over and allowing them to grow taller.

The side-scan sonar also reveals the importance of a suitable substrate for initial coral colonisation as a common prerequisite for Moira Mound development. The Moira Mounds to the east of the Thérèse Mound (Figs. 8, 9) occur on longitudinal gravel ridges (also imaged on multibeam data; Foubert et al. 2005) formed under previous, more energetic seabed conditions provided a suitable attachment substrate for coral growth that was also in an elevated position. Figure 7B shows another example of three Moira Mounds in an area of gravel ridges that provide a suitable substrate for colonisation.

Belgica Mound micromorphology

Active sand transport is also a consistent observation in the vicinity of the western active Belgica Mounds and it is reasonable to assume that this factor also makes a positive contribution to mound growth. The facies map (Fig. 2) shows that sediments are active in the vicinity of these mounds due to obstacle-related acceleration in benthic currents (see above). Figure 6a and 6c show that these sediment waves or comparable modified forms transgress from the off-mound areas, over mound flanks and even mound summits. Figure 7C shows a side-scan sonar image of the flank of one of the mounds showing the micromorphology of the mound is strongly reminiscent of off-mound sediment waves. However, the image also shows irregular bright backscatter spots representative of coral colonises growing on the surface of the sediment waves. Video ground-truthing confirms this hypothesis and shows a transition from off-mound mobile sediment waves, to coral colonised sediment waves to coral banks near mound summits.

In this way, it is envisaged that coral colonies on the flanks of mounds are encroached upon by sediment waves whose progress is retarded by the coral colonies that also trap the sand. In the similar way as on the Moira Mounds, the trapped sands provides support to the coral colonies allowing them to grow higher without he risk of toppling. This enhanced growth facilitates further sand entrapment thereby encouraging more grow. Overtime the sediment waves become larger and steeper, as seen in Figure 6C, with rigorous coral growth on their crests and restricted or absence coral growth in the sheltered troughs between sediment waves. This is an example of a positive feedback relationship between geological and biological growth processes. Towards mound summits the supply of sand sediment through a highly colonised mound is restricted whilst the conditions for coral growth are enhanced. We therefore see a transition from sediment waves to coral banks whereby growth is pure biological although a similar mound surface morphology is retained with corals growing preferentially in positions of higher elevation. This is an example of an inherited micromorphology (Wheeler et al. submitted).

Conclusions

Multidisciplinary seabed mapping studies based on geophysical (multibeam, 100/410 kHz side-scan sonar and 3.5 kHz sub-bottom profiler) and video surveys reveal the complexity of the environmental setting of the Belgica Mound province affected by strong northerly current flows and associated drift sedimentation. The creation of an interpretation-facies map provides information on sediment pathways and benthic current patterns that are influenced by mound topography and also influence mounds growth and morphology. Seven main seabed facies are identified and described: background uniform backscatter facies, sediment wave facies, barchan dune facies, gravel ridge facies, sand ribbon facies, Moira Mound facies and Belgica Mound facies. The data also identified "active" and "retired" mounds subdividing the mound province into two mound belts. "Retired" mounds of the eastern mound belt posses buried or a half buried morphology due to onlap of the contourite drift deposits that migrate over the mound flanks in the form of barchan dunes, and show the lack of contemporary coral life. “Active” mounds of the western mound belt show outcropping morphology with dense mostly live coral cover, with mound bases dominated by coral colonised sediment waves that, with increasing coral colonisation, give way to coral banks towards the mound summits. Small mound features (Moira Mounds) exist in areas between the giant (Belgica) mounds, and possibly represent early stage of mound development. The growth and development of Moira Mounds is strongly affected by hydrodynamics and active sand transport.

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