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Hydrodynamics and cold-water coral facies distribution related to recent sedimentary processes at Galway Mound west of Ireland

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Abstract

Cold-water coral carbonate mound development is the result of complex and interactive hydrographical, biological and geological processes that can result in morphostructures several hundred meters high. The case study presented here investigates one of these large mounds – Galway Mound – in the eastern Porcupine Seabight to build an understanding of mound forming processes and the driving factors. For the first time, bottom current data have been recorded at six locations over a mound thus allowing an interpretation of the local flow field to be made. In addition to the overall flow pattern in the Porcupine Seabight, the recorded data display distinct diurnal tides. Comparison of the local flow field, coral facies distributions, current induced seabed features and grain size distributions over the Galway Mound highlights a correlation between the abundance of living corals with areas of enhanced bottom currents. However, the interplay of contour currents, tidal currents and the local topography further influences the coral facies and results in a distinct asymmetry in the coral facies distribution at Galway Mound. By baffling sediment, the corals also affect sedimentation on the mound.

Keywords: cold-water coral carbonate mound; northeast Atlantic; hydrography; current meter; coral facies; grain size spectra

1. Introduction

Large cold-water coral carbonate mounds in the Porcupine Seabight (De Mol et al., 2002), south-west of Ireland, represent some of the most impressive biotherms in intermediate water depths in the world. As their name implies, these structures are closely linked to the ahermatypic (lack of symbionts) framework building cold-water corals *Lophelia pertusa* and *Madrepora oculata* that occur in European waters from northern Norway, where they form reef-like structures on moraines, to the Gulf of Cadiz, where they grow associated with mud volcanoes and carbonate crusts, and into the Mediterranean Sea (Wilson, 1979a,b; Freiwald and Wilson, 1998; Rogers, 1999; Freiwald, 2002; Freiwald and Roberts, 2005; Taviani et al., 2005; Roberts et al., 2006). However, it is only along the eastern and western Rockall Trough margin that these coral built-ups grow up to 350 m high, so-called giant carbonate mounds (Kenyon et al.,

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2003; van Weering et al., 2003; Mienis et al., 2006; Wheeler et al., 2007), and in the Porcupine Seabight where they grow up to 190 m high (De Mol et al., 2002).

In addition to these large mounds, smaller mounds are also common. Numerous buried mounds have also been reported on seismic profiles from the northern Porcupine Seabight (Huvenne et al., 2007; Huvenne et al., 2003). So far, in total several thousand buried and exposed mounds have been mapped in Irish and UK waters including the Porcupine Seabight, Rockall Trough and Hatton Trough (e.g. Croker and O'Loughlin, 1998) ranging from a few meters high to large composite mounds (De Mol et al., 2002; Huvenne et al., 2003; Kenyon et al., 2003; Wheeler et al., 2005a,b). In the Porcupine Seabight, carbonate mounds occur in clearly defined mound provinces located between 600 and 1200 m water depth (Fig. 1).

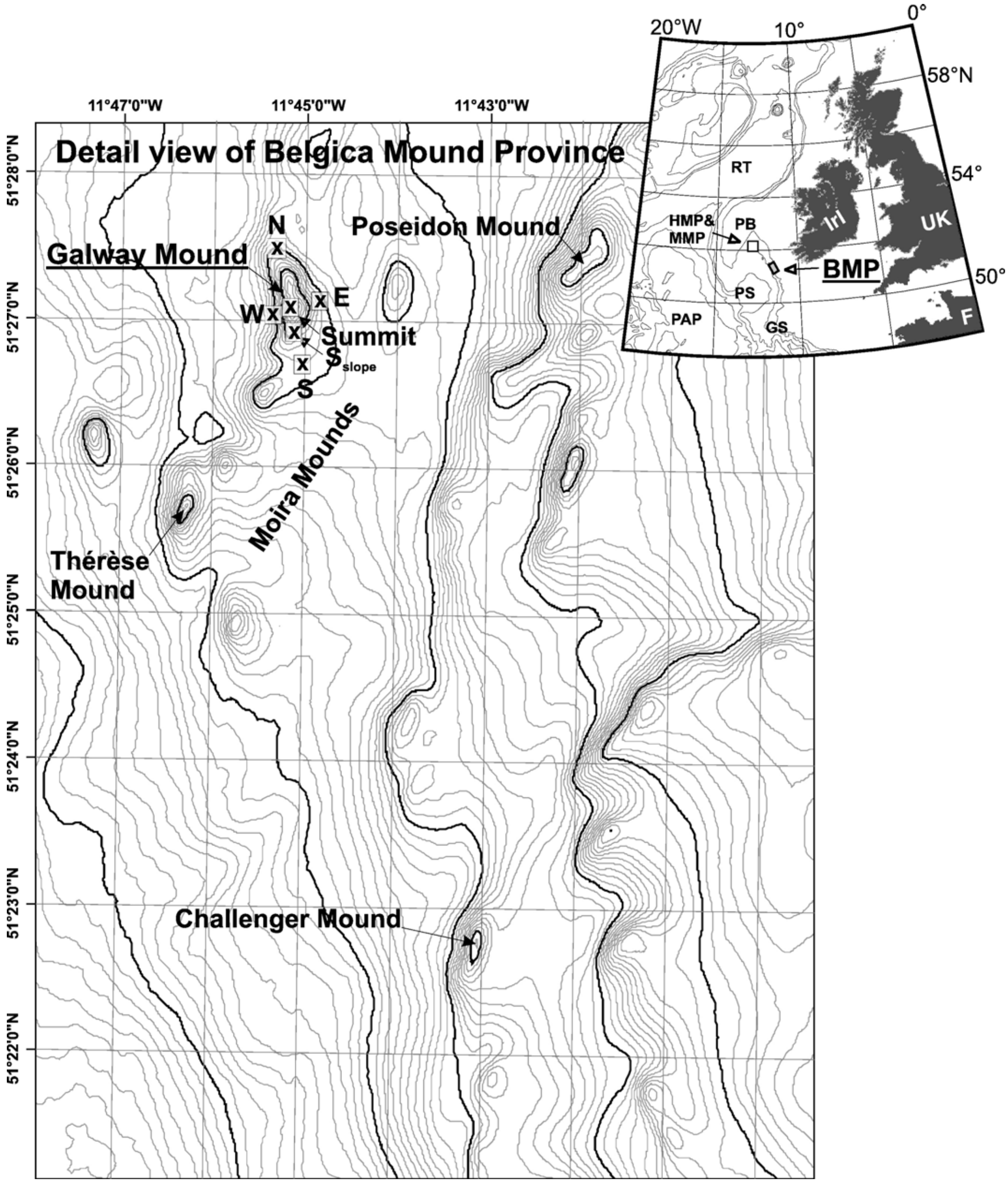

Fig. 1. Location and detailed map of the Belgica mound province (BMP) showing the locations of current meter moorings (X). RT: Rockall Trough; HMP: Hovland mound province; MMP: Magellan mound province; PB: Porcupine Bank, PS: Porcupine Seabight, GS: Goban Spur, PAP: Porcupine Abyssal Plain. Geographic data for the Belgica mound province after Beyer et al. (2003).

In the past decade, attention has been paid to mound initiation, development and the controls on mound distribution on the Irish continental slope. As a result, different mound initiation and development hypotheses have been proposed. The early hypothesis, termed the 'seepage hypothesis', initially linked the occurrence of mound provinces to the seepage of light hydrocarbon compounds (Hovland et al., 1994; Hovland and Thomsen, 1997; Henriet et al., 1998). However, detailed investigations in the Belgica mound province and other mound provinces have revealed that this association is not strictly true (e.g. Kenyon et al., 1998; Huvenne et al., 2003; van Weering et al., 2003; Wheeler et al., 2005b). This hypothesis was further weakened by the IODP expedition 307 with the RV JOIDES RESOLUTION in May 2005 (IODP 307 Expedition scientists, 2005) when complete sediment sequences were cored through Challenger Mound in the Belgica mound province (Fig. 1) and the underlying strata. No increase in hydrocarbon concentrations was found in the mound and shallow sub-mound sediments although present at much deeper levels. Instead, cold-water corals occurred throughout the whole mound succession (IODP 307 Expedition scientists, 2005; Williams et al., 2006) thus supporting an alternative hypothesis that suggests biological and environmental controls as driving factors for mound formation and development.

Recent studies indicate that carbonate mounds on the Irish continental margin more likely originate as the result of complex coupled hydrological, biological and geological processes (Freiwald, 2002; White et al., 2005). That means, wherever conditions are favourable for cold-water corals, e.g. suitable substratum, water temperature of 4–12 °C, sufficient food supply and low sediment input (Mikkelsen et al., 1982; Mortensen et al., 1995; Rogers, 1999; Freiwald, 2002; Roberts et al., 2006), cold-water corals, mainly the species *L. pertusa* and *M. oculata*, tend to form thickets. Under optimal conditions, these thickets remain in distinct locations for long periods of time growing and baffling sediments thus forming cold-water coral banks and later cold-water coral carbonate mounds. Low energy micro-environments within the coral thickets encourage sedimentation and prevent erosion. Bioerosion of dead coral skeletons also adds a significant carbonate component to the mound sediment (Dorschel et al., 2007). The loose coral frameworks become clogged with sediment and form the mound successions that have been reported from various mound provinces. Consequently, all recent studies on carbonate mound sediments have revealed that those mounds are true coral build-ups (e.g. Kenyon et al., 1998; De Mol et al., 2002; Kenyon et al., 2003; van Weering et al., 2003; Noë et al., 2005; Rüggeberg et al., 2005; Dorschel et al., 2005; Williams et al., 2006; Dorschel et al., 2007; Foubert et al., 2007; Rüggeberg et al., 2007).

Due to the complex interaction between bottom currents and mound development, attention has recently focussed on the specific hydrodynamic conditions under which carbonate mounds flourish. The presence of contourite channels, sand sheets, sediment waves and ripples in the mound provinces, as well as scoured out moats associated with many mounds, suggest that cold-water coral carbonate mounds are closely related to enhanced current regimes during periods of development (De Mol et al., 2002; Huvenne et al., 2003; van Rooij et al., 2003; De Mol et al., 2005; Dorschel et al., 2005; Wheeler et al., 2005b).

To unravel the complex interactions that control contemporary mound development and to identify the factors and processes that have recently shaped the mounds, this study investigates the hydrographical, biological and sedimentological factors at a key site (Galway Mound in the Belgica mound province) in the Porcupine Seabight. It focuses particularly on the local flow field over the Galway Mound and correlates it to coral facies distributions and surface sediment distributions.

1.1. Setting

The Galway Mound (51°27′5″N/011°45′9″W) is part of the Belgica mound province, located on the eastern margin of the Porcupine Seabight, west of Ireland (Fig. 1). The Porcupine Seabight is a tongue-shaped embayment in the Irish continental margin, closed at three sides and opening towards the southwest into the Porcupine Abyssal Plain. Within the Porcupine Seabight, mounds occur in three distinct provinces. The Hovland mound province, a province of mounds with only sparse coral coverage, is located in the northern Porcupine Seabight (Dorschel et al., 2005; Huvenne et al., 2005; Dorschel et al., 2007). The Magellan Mounds, a province of several hundred small (less ~50 m from base to top) mainly buried mounds, is located next to the Hovland Mounds in the southeast (Henriet et al., 1998; Huvenne et al., 2003; Huvenne et al., 2005). The Belgica mound province, of which the investigated Galway Mound is part of, is located at the eastern slope of the Porcupine Seabight. The Belgica mound province extends approximately 30 km parallel to the Irish shelf between 51°10′N and 51°35′N. Two continental slope parallel mound chains can be distinguished.

The shallower, eastern mound chain at approximately 650 m water depth (wd) is characterised by the sparse occurrence of live corals and erosive features such as hard grounds. The deeper mound chain at approximately 950 m wd is comprised of mounds densely overgrown by cold-water corals. These mounds, exhibiting the densest coverage of live coral, are considered 'active' and 'growing' mounds (De Mol et al., 2002, 2005; Foubert et al., 2005; Huvenne et al., 2005; Wheeler et al., 2005b). In between those two mound chains, the low relief Moira mounds and sediment wave fields are located (Foubert et al., 2005; Wheeler et al., 2005b).

Galway Mound is the most northerly mound of the deeper mound chain. It is an elongated, slightly curved, approximately north-northwest south-southeast striking feature. Its summit is at 782 m wd and elevates 160 m above the seafloor to the west and 120 m above the seafloor to the east. The exposed part of Galway Mound measures approximately 1800 m along the main axis and is approximately 1100 m across. The slope inclinations are approximately 10° for the north and south slopes, approximately 15° for the east slope and approximately 25° for the west slope. As all other mounds in the area, this mound is probably rooted on an unconformity of Mid Miocene (Williams et al., 2006) or Early Pliocene (van Rooij et al., 2003) age.

The general hydrography in Porcupine Seabight in the mound relevant depth range of 1050 to 650 m is influenced by Mediterranean Outflow Water (MOW) and Eastern North Atlantic Water (ENAW). ENAW fills the depth range down to the permanent pycnocline, at about 800 m, with MOW predominant below this depth (Rice et al., 1991). It is assumed that MOW enters the Porcupine Seabight through the gap between Porcupine Bank and Goban Spur and forms a contour current that flows cyclonically around the Porcupine Seabight (Hargreaves, 1984; Rice et al., 1991; Van Aken and Becker, 1996; New and Smythe-Wright, 2001). Near the seabed, this current may be supplemented by poleward flowing residual currents generated by tidal rectification processes (Pingree and LeCann, 1990; White et al., 2007). Current induced seabed features such as ripples, sand waves and sediment drifts may be a result of such enhanced energetic environments (van Rooij et al., 2003; Wheeler et al., 2005b; White, 2007). According to CTD data from the summer of 2003 (Klages et al., 2004), measured water temperatures at Galway Mound were between 8.5 and 9.8 °C and salinities between 35.52 and 35.58 psu.

Sediment input into the Porcupine Seabight is dominantly from the Irish shelf with probable minor contributions from the Porcupine Bank (Rice et al., 1991). Prevailing sediments are mainly hemipelagic being often re-suspended and laterally transported. Dropstones commonly found in the Porcupine Seabight represent the coarsest components of Ice Rafted Detritus (IRD). Current induced features (such as moats) and sandwaves are commonly found in between the mounds (van Rooij et al., 2003; Foubert et al., 2005; Wheeler et al., 2005b, 2007). Surface samples in the depth range where carbonate mounds occur are mainly silty sands (Kozachenko, 2005; Rüggeberg et al., 2005).

2. Materials and methods

This work is based on a wide variety of data collected on three research cruises between 2000 and 2004. High resolution 100 and 410 kHz side-scan sonar data (Fig. 2) were collected during RV DISCOVERY cruise D248 (Bett et al., 2001). Video footage were obtained during cruise ARK XIX-3a with the RV POLARSTERN (Klages et al., 2004) using the remotely operated vehicle (ROV) VICTOR 6000 (IFREMER — Brest) in June 2003 and during expedition M61-3 with the RV METEOR and the ROV QUEST 4000 (MARUM—Bremen) in June 2004 (Ratmeyer et al., 2006). During the latter cruise, the surface sediment samples for grain size analysis were collected using a box corer.

Bottom currents were recorded for a period of 15 to 17 days in June 2003 using 'hs engineers S-2001' inductive current meter. Currents were recorded at 120 cm above the seafloor. The current meter moorings were located in the east, west, north and south at the foot of the mound at ~890 m wd, on the southern slope of the mound at 840 m wd and at the mound summit in 782 m wd (Table 1; Fig. 4). Current velocities were corrected for a −7.5° magnetic declination and basic statistics were calculated, including a tidal analysis using a least squares fit procedure (Figs. 3 and 4).

Based on the video footage and geo-referenced images, coral distributions were mapped and a facies classification was developed. 7 facies were identified for the Galway Mound based on coral coverage, coral preservation and seabed morphology (Fig. 4).

Seven surface samples from Galway Mound (Table 1) were analysed for their grain size spectra allowing independent hydrodynamic inferences to be made thereby providing an important check on interpretations. The analyses were performed with the Malvern Mastersizer 2000® at the University College Cork on carbonate and organic carbon free aliquots. For sample

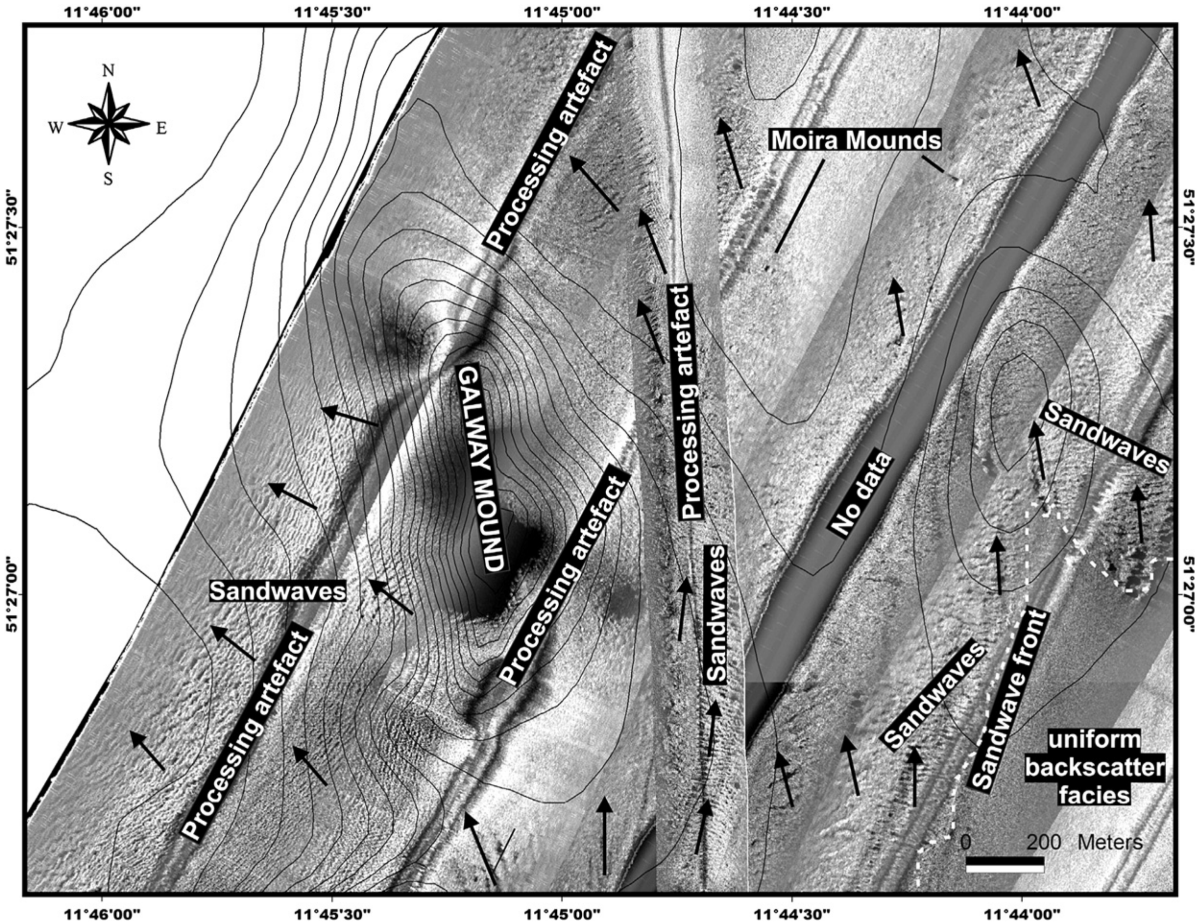

Fig. 2. 100 kHz side-scan sonar mosaic with 410 kHz overlay in the Galway Mounds area showing sandwave fields and small solitary "Moira Mounds". Black arrows show bedload transport directions interpreted from bedform asymmetry.

preparation, 1 cm^3 aliquots were treated with 10 ml of 10 % HCl and 10 ml of 10% H_2O_2.

3. Results

3.1. Side-scan sonar imagery

100 and 410 kHz side-scan sonar coverage of the Belgica Mounds (Kozachenko, 2005; Wheeler et al., 2005b) provided a regional context to current dynamics and sediment transport in the vicinity of the Galway Mound. Fig. 2 shows part of the side-scan sonar mosaic with interpretations revealing areas of seabed dominated by sandwaves and, in the southeast corner, uniform backscatter. ROV groundtruthing (Foubert et al., 2005; Kozachenko, 2005; Wheeler et al., 2005b) revealed ripples superimposed on sandwaves and coral growth (close to and on mounds). In sandwave troughs and between wave fields, rippled sand, dead coral fragments (in the immediate vicinity of the mound) with exposed dropstones were present. In the southeast corner of the area, the edge of a broad (uniform backscatter) facies was groundtruthed as rippled sands extending between the western Belgica Mound belt (including the Galway and Thérèse Mounds) and the eastern Belgica Mound belt (including the Poseidon and Challenger Mounds) (Kozachenko, 2005; Wheeler et al., 2005b).

3.2. Hydrographic data

Mean near-seabed residual currents around the Galway Mound were between 1–7 cm s^{-1} (Table 2) and, with the exception of the $South_{slope}$ mooring, directed poleward. Local bathymetric steering, however, was apparent and controlled the mean residual flow direction (Figs. 3 and 4). Progressive vector diagrams (Fig. 3) reveal that current variability was dominated by tidal fluctuations. The diurnal K_1 tide (period = 23.93 h) was the dominant tide. It was about 2× the size of the M_2 semi-diurnal tide (period 12.42 h, Table 3). The closeness of the current meters to

Table 1
Locations of current meter and surface samples

Location	Latitude (°North)	Longitude (°West)	Depth (m)	Facies
Current meter				
North	51°27,48′	011°45,32′	888	Sand lenses surrounded by dense coral cover
East	51°27.13′	011°44.83′	890	Crest of stabilised sand wave, dense living corals
Summit	51°27.09′	011°45.16′	782	Dense coral cover, living corals growing on dead corals
West	51°27.05′	011°45.35′	889	Steep slope, dense coral cover manly dead
$South_{slope}$	51°26.93′	011°45.13′	840	Sand patches, dense coral rubble, living coral
South	51°26.71′	011°45.03′	885	Slight elevation, few living corals, coral rubble
Surface samples				
GeoB9204-1	51°26.94′	011°45.16′	837	
GeoB9205-1	51°27.04′	011°45.12′	810	
GeoB9206-1	51°27.31′	011°45.12′	857	
GeoB9209-2	51°26.89′	011°45.81′	982	
GeoB9216-1	51°27.09′	011°44.81′	890	
GeoB9219-1	51°27.05′	011°45.40′	921	
GeoB9220-2	51°26.68′	011°45.04′	893	

the seabed resulted in a likely dampening of the tidal signal in the measurements, but variation in the tidal amplitudes was apparent with larger tidal amplitudes measured near the summit and to the south of Galway Mound (Table 3 Fig. 3). In general, the diurnal tides were aligned across the slope (the exception being Mooring ‘South’), whilst the semi-diurnal tides were aligned more along the slope (Table 3 Fig. 4). Current speeds were also variable at different mound locations. The maximum current speed recorded was 51 cm s^{-1} at the mound summit. Mean current speeds ranged from 16 cm s^{-1} recorded at the mound summit to 6 cm s^{-1} at the southern slope position immediately upstream of the mound in terms of the general flow pattern revealed by the measured currents (Table 2). To the east and west of the mound, mean current speeds were approximately 8 cm s^{-1} while at the mound foot in the north and south mean currents speeds were higher, 13 cm s^{-1} and 11 cm s^{-1} respectively.

Residual currents appeared heavily controlled by bathymetric steering affects. At the mound summit a mean northward flow was measured and similar poleward directed flows were apparent to the east, west and north of the summit, all essentially directed along the local isobaths. Channelling of the flow to the east of the mount might be inferred with the NE directed mean flow at the South Mooring. The lack of any real mean flow at the $South_{slope}$ mooring, immediately to the south of the main mound slope possibly indicated the presence of a stagnant region immediate upstream of the mound.

3.3. Facies distribution

ROV observations of the Galway Mound and adjacent areas were used to ascribe the following 7 facies (Fig. 4): Facies 1. dense coral coverage (mostly alive); facies 2. dense coral coverage (mostly dead); facies 3. sediment clogged dead coral framework and/or coral rubble; facies 4. patchy distribution of mostly live (or dead) coral on un-rippled seabed; facies 5. patchy distribution of mostly dead coral on rippled seabed; facies 6. sandwaves covered with corals (overgrown sandwaves); facies 7. patchy distribution of dropstones (see also Foubert et al., 2005). The facies distribution revealed a distinct asymmetry on the Galway Mound. The mound itself was covered with dense coral thickets (facies 1 and 2). Facies 1 (mostly living corals) was more common on the west flank of the mound and at the mound summit. Whereas facies 2 (mostly dead coral) occurred on the remainder of the mound. With increasing distance from the mound the facies gradually changed from sediment clogged dead coral frameworks (facies 3) to only small patches of live and dead corals (facies 4 and 5) and to overgrown sandwaves (facies 6). Overall, the coral abundance and colony size decreased away from the mound. Abundant dropstones (facies 7) were only reported from locations west of the mound (Fig. 4).

3.4. Surface sediments

Six surface samples from Galway Mound (GeoB9206-1, GeoB9219-1, GeoB9205-1, GeoB9216-1, GeoB9204-1, GeoB9220-2) and one surface sample from a reference site (GeoB9209-1) were analysed for their grain size distribution (Fig. 4). As reference, a site was selected west of Galway Mound outside of the 2 mound chains thus unaffected by the mounds but still representative of the prevailing environmental conditions at Galway

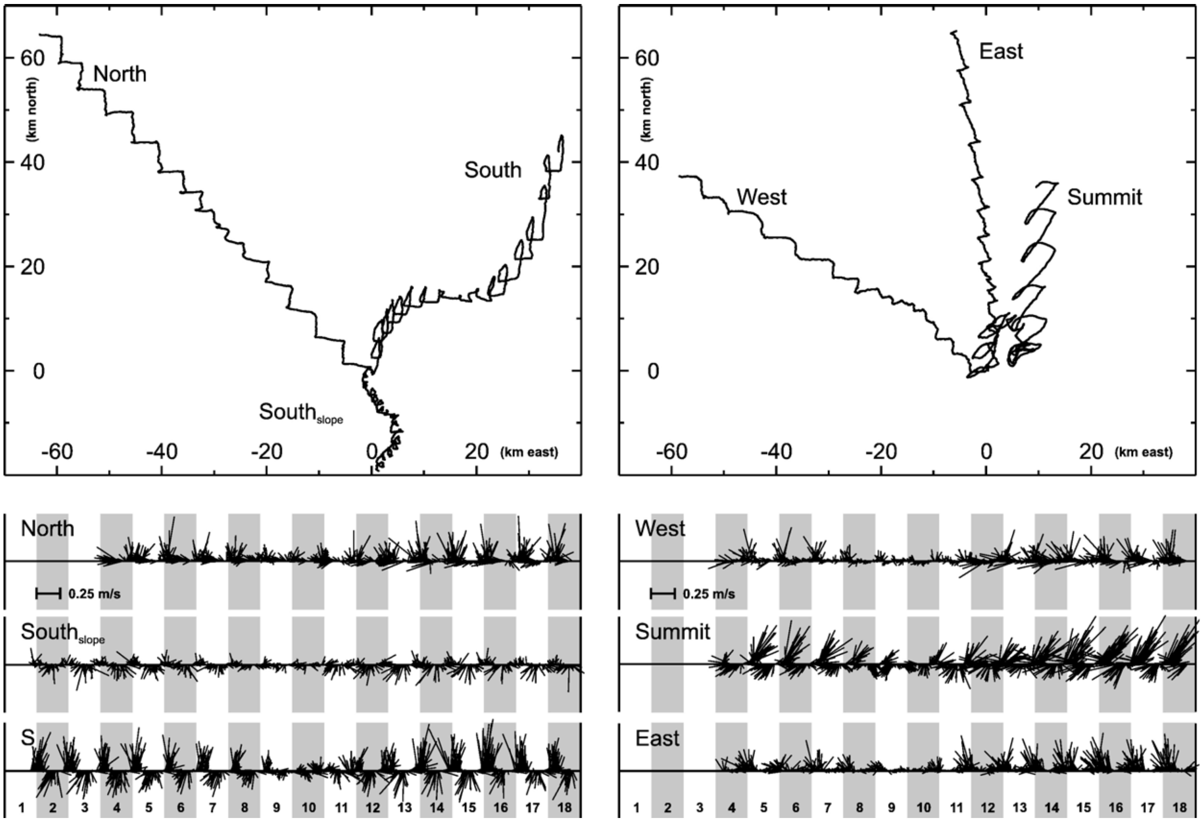

Fig. 3. Top: progressive vector plots. Bottom: current vectors plotted against time. The numbers are days in June 2003 starting with 08.06.2003. Progressive vector plots represent the hypothetical pathways of parcel of water derived by stacking the current velocity vectors of each recording multiplied by the time interval between the recordings.

Mound. The grain size spectra displayed mainly unimodal distributions with modes between 84 and 212 µm. Only the sample from the northern slope (GeoB9206-1) showed a distinct secondary mode. All spectra were strongly skewed towards finer fractions (Fig. 4). Grain size distributions from the mound sites were coarser (modes between 106 and 212 µm) compared to the reference site (mode of 84 µm). Samples from the summit (GeoB9205-1) and north (GeoB9206-1), and to a lesser extent from the south slope (GeoB9204-1) and the west (GeoB9219-1), were enriched in fine fractions compared to samples from the other sites (east: GeoB9216-1, south: GeoB9220-2 and reference: GeoB9209-2) (Fig. 4).

4. Discussion

4.1. Current dynamics and sediment transport in the vicinity of the Galway Mound

According to the side-scan sonar imagery, the vicinity of Galway Mound is marked by an acceleration of benthic currents, probably caused by the topographic obstacle of the large mound itself, creating a sandwave front beyond which sandwave trains are formed (Fig. 2). These morph into coral banks on the mound itself. Larger features mark the heads of these sandwave trains near this boundary and are interpreted as Moira Mounds (relatively small scale coral banks, Fig. 1). Isolated Moira Mounds are also imaged in the north-eastern sector of the image (Wheeler unpublished data).

Sandwave asymmetry reveal information regarding sediment transport directions from peak flow-velocity sand transport events (Wheeler et al., 2005b). East of the Galway Mound, bedload transport is to the NNW suggesting that geostrophic contour currents are the dominant mechanism for this form of sand transport. This flow appears undeflected by the relatively low topography carbonate mound west of Galway Mound although some deflection of bedload transport pathways occur around the more significant obstacle of the Galway Mound. Interestingly, to the west of the Galway Mound, sandwave asymmetry suggests bedload

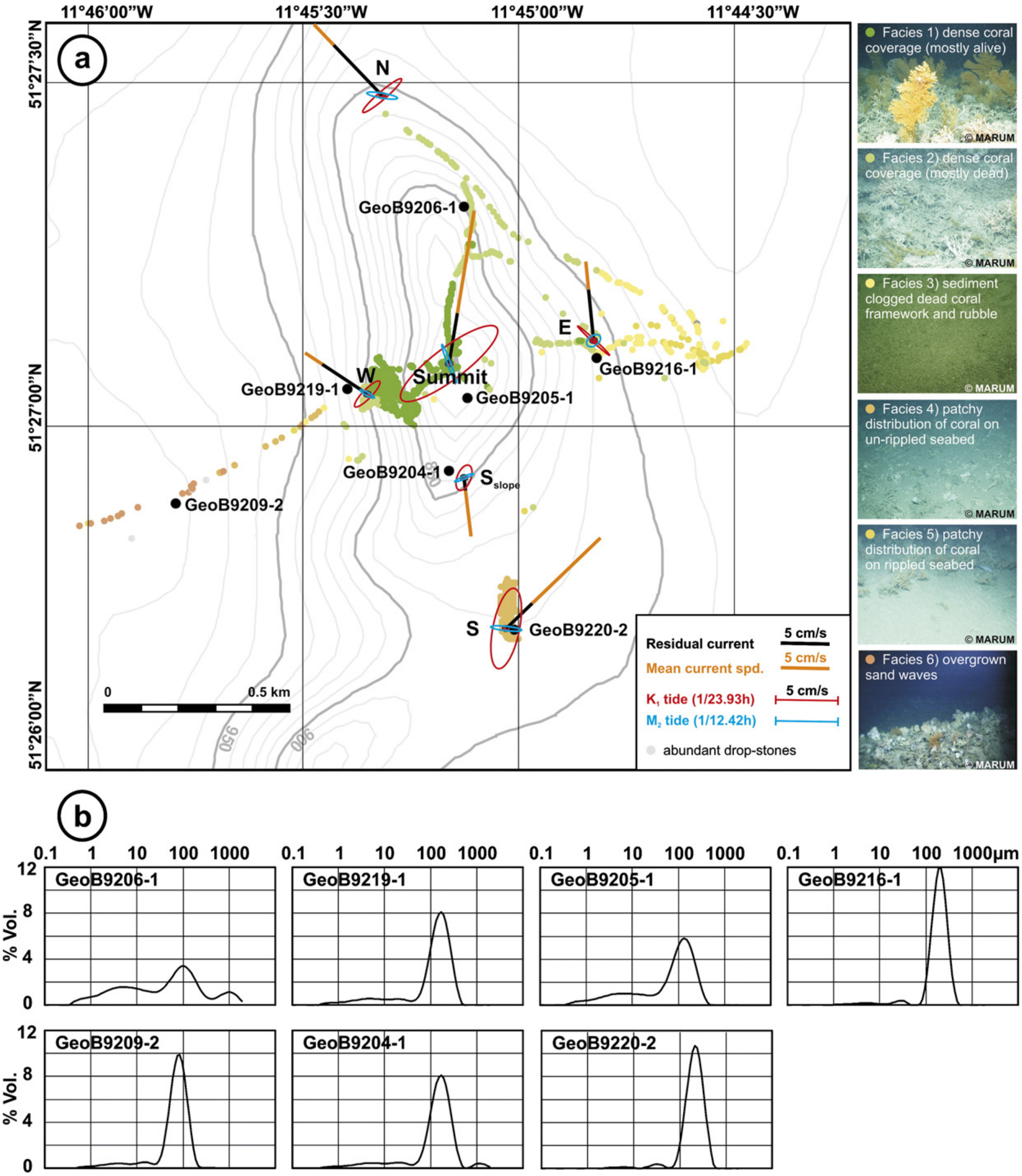

Fig. 4. a: Map showing coral facies, tidal ellipses for K_1 and M_2, mean current speeds and residual currents (for a better comparison, the current speeds are plotted from the same origin of and parallel to the residual currents). b: Grains size distribution spectra for carbonate and organic carbon free surface sediments plotted against logarithmic scaled *x*-axes.

transport in a westerly direction suggesting that peak bedload transport is influenced by tidal currents. This may represent acceleration in tidal flows through the constriction between the mounds.

The side-scan sonar mosaic (Fig. 2) is a “snapshot” of the seabed revealing the orientation of bedforms at that time. No repeat surveys of adequate resolution are available to determine the temporal dynamics of the above interpretation. It is not clear from the side-scan sonar data alone whether the bedforms are, for example, moribund features, moved by rare benthic storms or represent contemporary mobile bedforms. ROV observations suggest that sandwaves are not reversing with every tidal flow but appear "fresh" (not heavily colonised or denuded) suggesting movement during regular peak flow events.

4.2. Galway Mound flow dynamics

The general hydrographic regime at the Galway Mound is dominated by a near-seabed contour following residual current, together with tidal currents interacting with the local topography. Above the bottom boundary layer, the residual flow in the Belgica mound province is dominated by a northward flowing contour current which is part of the cyclonic circulation of intermediate water masses in the Porcupine Seabight (Hargreaves, 1984; Rice et al., 1991; White and Bowyer, 1997). Near the seabed, this current is often enhanced by the rectification of tidal motions on the slope. In particular, the eastern margin of the Porcupine Seabight is characterized by bottom enhanced, baroclinic, diurnal period tidal currents (e.g. Pingree and LeCann, 1990; White, 2007). This is due to a resonance condition of the forcing at diurnal period due to matching with the local bottom slope and vertical density stratification (White, 2007). The result of the rectification is that whilst the enhanced tidal motions are generally directed across the slope, the generated residual flow is along the slope (White et al., 2007).

This was highlighted in Fig. 4, where residual flows were directed essentially poleward along the slope, but evidence for local bathymetric steering was also apparent in the vector mean currents (Table 2). Flows appeared to be channelled through the gaps between individual mounds, particularly upslope of the Galway Mound (Fig. 4). The tidal analysis on the data (Table 3) indicated that the K_1 diurnal tidal component was largest, as might be expected with the bottom resonance condition which occurs for that period in the northern portion of the Belgica mound province for that tidal component (White et al., 2007). Maximum tidal amplitudes and current speeds (Tables 2, 3) were generally found at the summit and perhaps indicated local flow acceleration over the summit, similar to that found at seamounts and other isolated banks (e.g. Genin et al., 1986). Westward migrating sediment waves found in the facies map (Fig. 4) also demonstrated the influence of both the tidal current flows and also the long term steering of the residual flow through gaps and along local topographic features. In addition, both the small, southward-directed, residual flow and the generally low current speeds measured at the station immediately 'upstream' of Galway Mound (Table 2) may well be further evidence of topographic influence on the bottom flow. The measurements may have been located close to a stagnant region immediately upstream of the mound. ROV groundtruth photos also indicate that this current meter is located in a trough between sediment waves.

4.3. Hydrodynamic controls on coral cover density and mound growth

Corals growing on dead corals, dropstones and lithified hardgrounds, subsequently baffling sediment within coral thickets, in conjunction with the products of biological activity and biodegradation, are seen as a major process with regard to carbonate mound development (Freiwald, 2002). Furthermore, coral thickets show the tendency to grow towards prevailing bottom currents (Wilson, 1979b). The generation of low energetic environments within the coral thickets also prevents erosion during periods of enhanced bottom currents. Hence, the distribution of coral thickets controls the accumulation and preservation of mound sediments.

The ability of the corals to thrive and produce dense coral cover depends on suitable living conditions such as 1) appropriate physical conditions of the relevant water masses within the environmental tolerances of the organism, 2) availability of hard substrate to settle on (Wilson, 1979b) and 3) being sessile heterotrophs, availability of a sufficient food supply (Teichert, 1958; Stetson et al., 1962; Frederiksen et al., 1992; Mortensen et al., 1995; Freiwald, 2002). With temperatures between 10.5 and 8.5 °C and full marine salinities

Table 2
Hydrographical statistics

Location	Max spd ($cm\ s^{-1}$)	Max spd ($cm\ s^{-1}$)	Mean *U* ($cm\ s^{-1}$)	Mean *U* ($cm\ s^{-1}$)	Res. cur. ($cm\ s^{-1}$)	Dir. res. cur. (towards)
North	39.0	11.0	−5.0	5.2	7.2	NW
$South_{slope}$	27.6	6.1	0.2	−1.3	1.3	S
South	43.9	13.5	2.7	2.6	3.7	NE
West	34.5	7.7	−4.6	3.0	5.5	WNW
Summit	51.1	16.0	0.8	2.9	3.0	NNE
East	35.1	8.2	−0.5	5.2	5.3	N

Spd: current speed; U: E–W velocity component; V: N–S velocity component; Res. cur.: residual current (mean velocity); Dir. res. cur.: direction of residual current.

Table 3
Tides at Galway Mound

Location	Tide	Major axes (cm s^{-1})	Minor axes* (cm s^{-1})	Orientation (° true N)	Displacement (km)
North	K_1	8.18	1.27	49	1.1
	M_2	4.99	−0.80	100	
East	K_1	6.92	0.44	132	0.9
	M_2	2.49	−1.63	55	
Summit	K_1	17.41	5.11	53	2.4
	M_2	6.57	0.55	160	
West	K_1	5.67	1.44	44	0.8
	M_2	2.61	0.51	119	
South$_{slope}$	K_1	4.28	2.20	22	0.6
	M_2	3.26	0.43	67	
South	K_1	13.13	4.26	11	1.8
	M_2	5.00	0.71	96	

K_1 has a periodicity of 23.93 h, M_2 has a periodicity of 12.42 h, * positive = anticlockwise rotation, negative = clockwise rotation.

between 35.5 and 35.6 psu, the contemporary water masses provide the appropriate physical conditions for corals to thrive at the Galway Mound site (Rogers, 1999). Also, hard substrate in the form of coral rubble and dead coral frameworks is available. Therefore, neither of the above factors is likely to account for the variations in coral facies over the mound (especially the east–west asymmetry; Fig. 4).

Results reported here, however, show that significant variations in current intensity and flow regime occur over the mound. This variability is likely to be the main control on coral distribution and hence mound growth. Enhanced bottom currents have been reported to keep suitable settling surfaces clear from fine grained sediments, prevent corals from silting over and increasing the encounter rate of food particles (Frederiksen et al., 1992; Messing et al., 1990).

In accordance with these observations, thickets of living corals on the Galway Mound broadly coincide with areas where bottom currents speeds are enhanced. The highest density of living corals (facies 1) has been reported from the mound summit and the western slope. The summit area possesses the highest bottom current speeds and the strongest tidal signals (Fig. 4; Tables 2 and 3). This situation is similar to that reported for the coral distribution over seamounts, where the highest abundance of corals was found near the summit where flow acceleration was likely (Genin et al., 1986). In contrast to the western flank, the eastern flank of Galway Mound is characterised by mainly dead corals (facies 2). This asymmetry is most certainly caused by asymmetries in the flow field of the bottom currents.

To the east of the mound, bottom currents (the poleward flow as well as the tidal flow) are channelled in the gully between the upper and the lower mound chain and the tidal currents are oriented towards the mound (Fig. 4). On this side, sand waves in the proximity of the mound (Fig. 2) tend to migrate towards the mound possible clogging emerging/developing coral. Furthermore, the mobile sediment floor represents an unsuitable substratum for the corals.

Correspondingly, on the western flank of Galway Mound – covered by thickets of mainly living corals (facies 1, Fig. 4) – the bottom currents are not channelled and the tidal currents flow away from the mound. This possibly results in reasonable current strength, not too strong, but steered by the steep bathymetry at this side of the mound. The input of resuspended sediment is low and hence the corals do not become clogged. This observation is somehow unexpected as Wilson (1979b) described the corals tendency to grow towards the prevailing currents rather than in sheltered areas. It could be possible that at the Galway Mound the effects of sedimentation on coral facies distribution overprint the effects of the bottom currents.

4.4. The sedimentological imprint

The interplay between bottom currents and coral thicket distribution results in complex sedimentation patterns on the Galway Mound. In general, the coarser modes from the mound sites indicate enhanced winnowing compared to the reference site (Fig. 4). In addition, an increase in clay and silt content (fraction <63 μm) in the samples from areas with dense coral cover (facies 1 and 2) indicate the baffling and preservation of finer sediments within the coral thickets (Fig. 4). Well sorted sands with the coarse modes (190–210 μm) in the east and in the south of Galway Mound are the results of strong bottom currents. According to facies interpretations (Fig. 4) and side-scan sonar imagery (Fig. 2), these areas are characterised by sandwaves and ripples (facies 5 and 6).

4.5. Implications for mound development

In terms of mound development, our study supports the hypothesis of external factors being the driving mechanism for the cold-water coral carbonate mounds in the Porcupine Seabight (Freiwald, 2002; Dorschel et al., 2005). From observations at Galway Mound, the recent hydrographic conditions support coral growth at the summit area and on the western mound flank while corals on the eastern flank are mainly dead probably due to mobile sand waves caused by the channelling of the strong bottom currents intensified by diurnal period tides (White et al., 2007). If the thickets of living corals would remain in place for a considerable period time, they could compete with the sedimentation thus forming mound sediments. This would result in westward and vertical mound growth. Bioerosion of the mainly dead coral frameworks on the eastern flank could eventually lead to exposure, winnowing and erosion of the baffled sediments in these areas. The snapshot of mound development taken implies a westward migration of Galway Mound.

5. Conclusions

Galway Mound is located in an area with strong bottom currents. Sandwaves and ripples in the vicinity of the mound are indicators for recent sediment movement, winnowing and re-suspension of sediment. The flow field at Galway Mound is characterised by poleward flowing geostrophic currents and almost perpendicular tidal currents. Diurnal tides are dominant at Galway Mound.

The areas with high densities of living corals coincide with areas of enhanced bottom currents. Living corals are most abundant at the mound summit where current speed are highest and on the west flank. Within those thickets coarse sediments accumulate. Due to the sediment baffling capacity of the corals and lower energetic environments within the thickets, silts and clay deposited during slack water are protected against re-suspension.

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