

Benthic dynamics at the carbonate mound regions of the Porcupine Sea Bight continental margin

Martin White

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Abstract A brief review is given of some dynamical processes that influence the benthic dynamics within the carbonate mound provinces located at the Porcupine Bank/Sea Bight margin, NE Atlantic. The depth range of the mounds in this region (600–1,000 m) marks the upper boundary of the Mediterranean outflow water above which Eastern North Atlantic Water dominates. Both water masses are carried northwards by the eastern boundary slope current. In the benthic boundary layer both the action of internal waves, and other tidal period baroclinic waves, may enhance the bottom currents and add to both the residual and maximum flow strength. Both residual and maximum bottom currents vary at different mound locations, with stronger currents found at Belgica (SE Porcupine Sea Bight) mound and Pelagia (NW Porcupine Bank) mound regions, whilst weakest currents are found at the Hovland and Magellan Mounds at the northern Sea Bight margin. The differences may be attributed to the presence of internal waves (Pelagia) or bottom intensified diurnal waves (Belgica). These different dynamical regimes are likely to have implications for the distribution patterns of live coral at the different locations.

Keywords Benthic dynamics · Carbonate mounds · Cold corals

Introduction

Carbonate mounds are found at several locations along the margin of the NE Atlantic between the depths of 500–1,000 m (Fig. 1). These mounds consist of a sediment filled framework composed of carbonate material, principally dead cold water coral, live specimens of which are prevalent in the NE Atlantic (e.g. Kenyon et al. 2003; van Weering et al. 2003; Freiwald 2002). The mounds vary in height from 50 to 200 m and are between 0.5 and 2 km in diameter. The principal cold water coral species found on these mounds are *Lophelia pertusa* and *Madrapora oculata*. In the Porcupine Sea Bight region, several large mound regions have been discovered (Fig. 1). These include the Belgica mounds on the eastern flank of the Sea Bight, and two set of mound clusters – the deeper Hovland and shallower Magellan mounds, on the northern flank of the Porcupine Sea Bight (de Mol et al. 2002). The Magellan mounds are buried mounds, covered in sediment drifts, whilst the Hovland and Belgica mounds include both buried and surface mounds. In addition, large carbonate mound clusters are present in two regions to the SW and NW of Porcupine Bank (van Weering et al. 2003; Kenyon et al. 2003).

There has been much speculation about the hydrographic influence on both the functioning of the deep water coral and carbonate mound ecosystem (e.g. Freiwald 2002; Roberts et al. 2003; Fredericksen et al. 1992). These studies have concentrated on the control of the distribution through such properties as water temperature and the benthic current regime. *L. pertusa* has generally been found in water, experiencing a relatively wide range of temperatures, generally between 4 and 12°C, and within a salinity range typical

M. White (✉)
Department of Earth and Ocean Sciences, NUI,
Galway, Ireland
e-mail: martin.white@nuigalway.ie

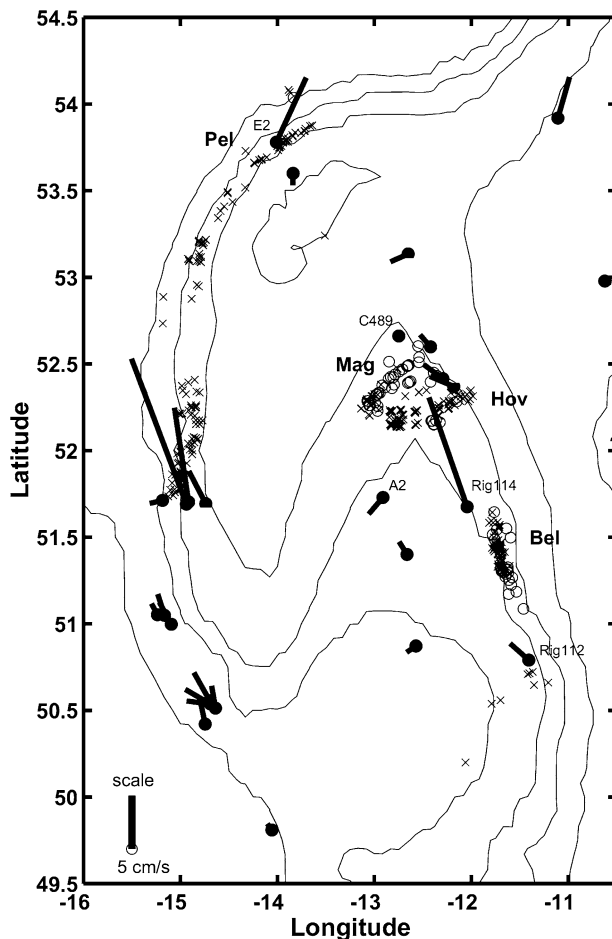


Fig. 1 Map of the Carbonate mound locations in the vicinity of the Porcupine Sea Bight and Bank. Symbols 'o' denote buried and 'x' unburied mounds, and provinces are labelled Mag-Magellan, Hov-Hovland, Bel-Belgica and Pel-Pelagia respectively. Mean near seabed current vectors, taken from historical measurements, are shown with a scale given to denote current magnitude. Locations of measurements used in later figures are labelled for reference

of several oceanic environments (Freiwald 2002). The corals are also found on hard seabed substrates. It is therefore assumed that strong currents are required to keep substrate swept clean of sediment for successful settlement and continued health of the developing live coral reefs (Frederiksen et al. 1992). In addition, the corals require a food source, and there appears to be a direct link between the regions of major concentrations of carbonate mounds and coral and high productivity levels in surface continental margin waters above (e.g. White et al. 2005).

This paper briefly discusses some of the hydrographic aspects in the Porcupine Bank/Sea Bight region that are relevant to the carbonate mounds of the region, based on previous and ongoing research work.

The paper summarises the general water mass distribution and circulation patterns, but focuses on more localised benthic physical processes that have been identified as playing an influential role in the development of the carbonate mound ecosystem.

Water masses

The Porcupine Sea Bight region lies at the continental margin of the NE Atlantic and is influenced mainly by the northward flowing Eastern North Atlantic water (ENAW) and Mediterranean outflow water (MOW), with some other influences from water masses derived from the western north Atlantic (van Aken and Becker 1996). Temperature and salinity transects across the Porcupine Sea Bight and Porcupine Bank reveal the typical water mass distribution at the depth level occupied by the carbonate mounds that were shown in Fig. 1 (Fig. 2, adapted from White et al. 1998). These transects were made in early to mid summer and a seasonal thermocline has started to develop at about 50–70 m. At the approximate latitude for the Belgica mounds (51.5°N), warm, saline water fills the upper layer down to about 600 m depth. This water mass is of ENAW origin, carried northwards adjacent to the NE Atlantic margin (Pollard et al. 1996). A significant portion of ENAW flow is carried by the Shelf Edge Current (SEC) that flows polewards along the continental margin (e.g. Pingree and LeCann 1990; Huthnance 1986). A signal of the SEC, between 200 and 400 m, can be observed along the Irish Shelf as a dipping of isotherms at the shelf edge (Fig. 2a) and a high salinity core (Fig. 2b). Between 800 and 1000 m within the Porcupine Sea Bight, a high salinity core marks the MOW, (Fig. 2b). In the Porcupine Sea Bight, the MOW occupies the whole of basin between 800 and 1,000 m depth. Fig. 2a also shows that the upper level of MOW is associated with the permanent thermocline and that the depth of the thermocline matches the mean water depth where carbonate mounds are found. MOW is also present west of the Porcupine Bank, but its signal rapidly diminishes north of 53°N and it is thought that MOW re-circulates west of the bank (e.g. New et al. 2001).

Over the Porcupine Bank itself, a cold dome of water is apparent in the temperature transects at both latitudes (Fig. 2a, c). This is a common feature of the Porcupine Bank and has been observed on several occasions (e.g. White et al. 1998). White et al. (2005) have suggested that these dome features are formed by deep winter mixing over the bank, which occurs down

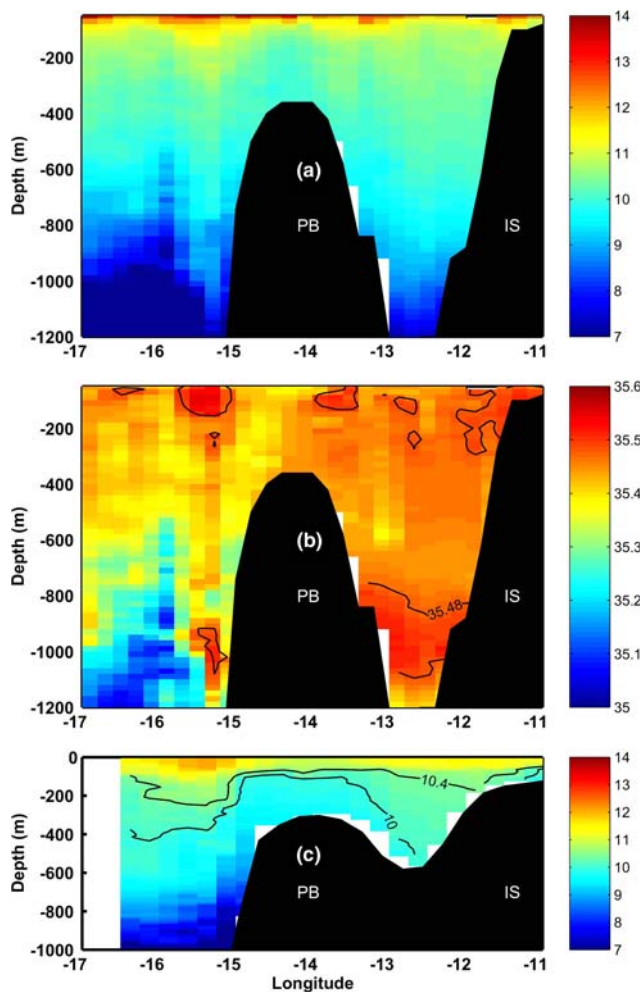


Fig. 2 Transect of **a** temperature and **b** salinity across the Porcupine Sea Bight and Bank at 51.5°N in June 2002, taken from Mohn et al. (2002) and White et al. (1998), and **c** temperature transect at 52.5°N in May 1995. A colorscale for all plots is shown on the *right* and the salinity 35.48 contour in **b** and 10/10.4°C contour in **c** shown for clarity. The Irish Shelf (*IS*) and Porcupine Bank (*PB*) are also indicated

to 600–800 m depth in this region (van Aken and Becker, 1996). In addition, doming of the isotherms can be helped by Taylor Column dynamics over the bank (White et al. 1998). The feature is persistent and may last for many months, and was measured from March to July in the particular year (1994) when the profiles shown in Fig. 2 were made.

Circulation and near seabed processes

Circulation and currents

Mean residual circulation near the seabed, as measured directly from historical current meter records, is highlighted in Fig. 1. The predominant circulation

along the continental margin of the NW European shelf is directed polewards (Huthnance 1986). In the Porcupine Sea Bight itself, the flow is essentially cyclonic with poleward flow along the Irish Shelf at the eastern Sea Bight margin (e.g. Pingree and Le Cann 1989, 1990). Mean residual bottom flows of between 2 and 5 cm s⁻¹ have been measured (Fig. 1), although much stronger currents, up to 10 cm s⁻¹, have been measured west of Porcupine Bank and at one location in 1,000 m water depth at the northern end of the Belgica province (Rig114, Pingree and Le Cann 1990). At the northern margin of the Sea Bight, the deeper portion of the seabed between the Irish Shelf and Porcupine Bank has a maximum depth of ~300 m, so that the flow along the margin below that depth has to re-circulate in the vicinity of the Hovland and Magellan mound provinces. Flow in the upper 300 m can pass into the Rockall Trough at the Malin Shelf edge where a strong full depth poleward slope current is re-established (e.g. White and Bowyer 1997). Poleward flow along both the western Porcupine Bank and Irish Shelf form two branches of the NE Atlantic slope current (Huthnance 1986), although continuity in the upper layer flow between the two branches is open to question (Raine et al. 2002).

The low frequency character of the benthic currents at various locations within the Sea Bight is highlighted in Fig. 3. At the deeper site in the NW Porcupine Sea Bight below the mound depths (A2, 1,220 m depth, Fig. 3a), mean daily currents are generally weak, between 2–10 cm s⁻¹ and directed southwest. Significant mesoscale variability is apparent in the record. At shallower depths in the Magellan/Hovland region (C489, Fig. 3b) where a very small mean flow has been observed (Fig. 1), mean daily currents may measure up to 10 cm s⁻¹ but again, large mesoscale variability is present in the currents. This character is similar at other locations in the northern Sea Bight and perhaps reflects the presence of a barrier to the deeper portion (> 3,000 m) of the slope current flow in the northern Sea Bight. Conversely, at Rig114 at the northern end of the Belgica mounds (Fig. 3c), currents are strongly polarised in the along-slope direction and directed poleward. To the south of the Belgica mounds, measurements made concurrently with Rig114 (Rig112, Fig. 3d), daily mean currents are smaller but with larger variability than at Rig114. Mean daily mean currents are therefore more variable. For comparison, a relatively short term observation deployed from the Pelagia mounds (NW Porcupine Bank) has shown strong benthic currents similar to the Rig114 data (daily means > 10 cm s⁻¹) present at a depth of 930 m bordering the lower depth range of the mounds.

Figure 4 provides some indication of the distribution of measured near-seabed current speeds between locations. Currents vary at different timescales related to physical processes such as tides and baroclinic motions and have peak values of importance to the benthic processes, such as sediment re-suspension. Current speeds, as illustrated by a percent current exceedance plot, show that currents along the continental margin where mounds are located are generally strong. Among the three locations within the Porcupine Sea Bight, larger currents have been measured at location Rig114 as compared to others such as c489 and Rig112. Rig112 and c489 are typical of all the other measurements from the Sea Bight region analysed here, apart from Rig114. Generally at these locations, currents exceed 15 cm s^{-1} for between 7 and 15% of the measurement period. Rig114 was the location of the stronger, more persistent mean daily currents, suggesting that the process causing these large residual

currents may also be responsible for the larger maximum instantaneous currents as well. At Rig114, currents exceed 15 cm s^{-1} for nearly 49% of the measurement time. The short term observations at 'E2' within the Pelagia mounds also indicate that the benthic currents are large in that region, comparable to the Rig114 values.

Seabed processes

Trapped waves

Measurements of bottom currents at two locations in the south (Rig112) and at the northern Belgica mounds (Rig114) have shown that mean daily and maximum currents measured at Rig112, located in the same water depth as Rig 114, are much weaker than those at Rig114. Rig112 was located along the margin where the seabed slope is steeper than those to the north.

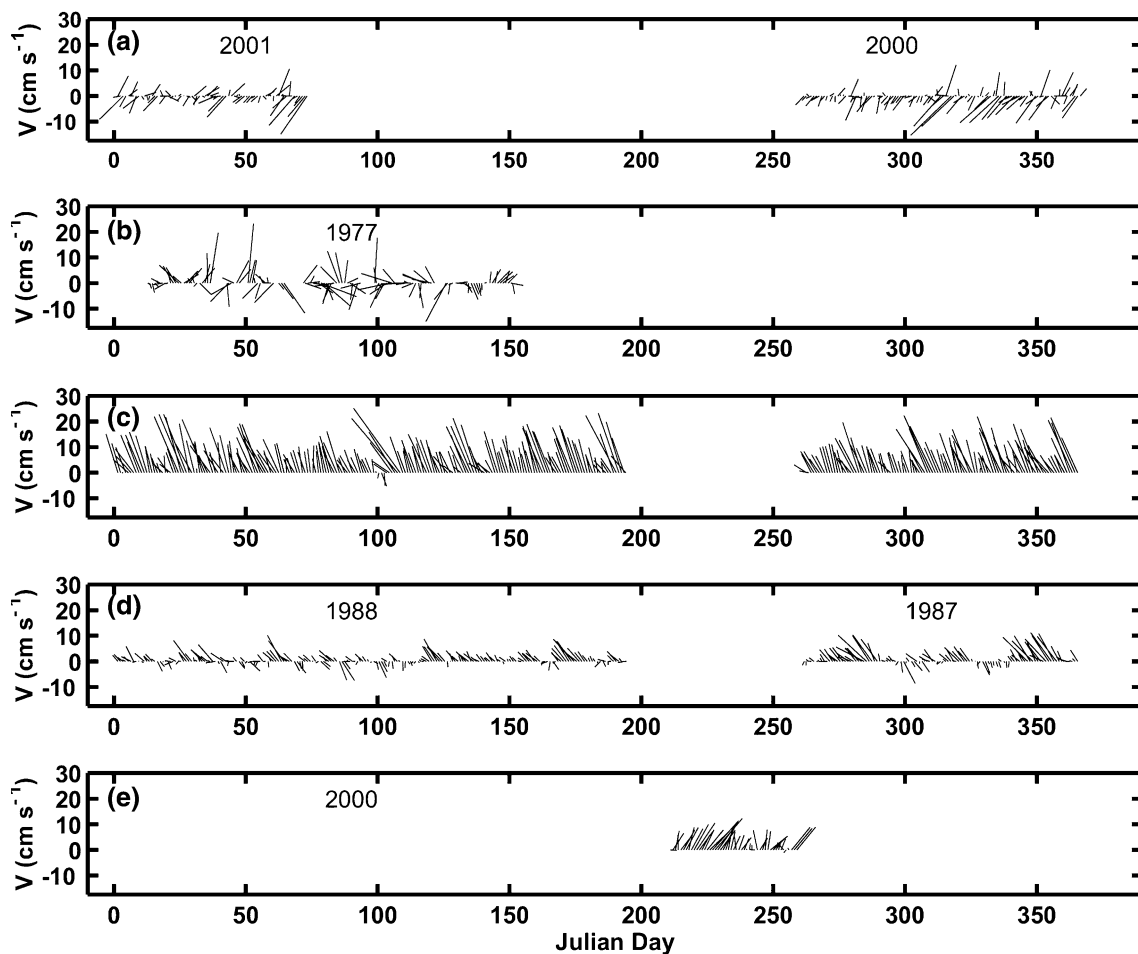


Fig. 3 Timeseries of mean daily current vectors for near seabed measurements at locations **a** A2, **b** C489, **c** Rig114, **d** Rig112 and **e** E2 as shown in Fig. 1. Data is shown for Julian Day timescale

such that timeseries that run over the end of the year have the following year's data on the correct Julian day to the left of the start date of measurements

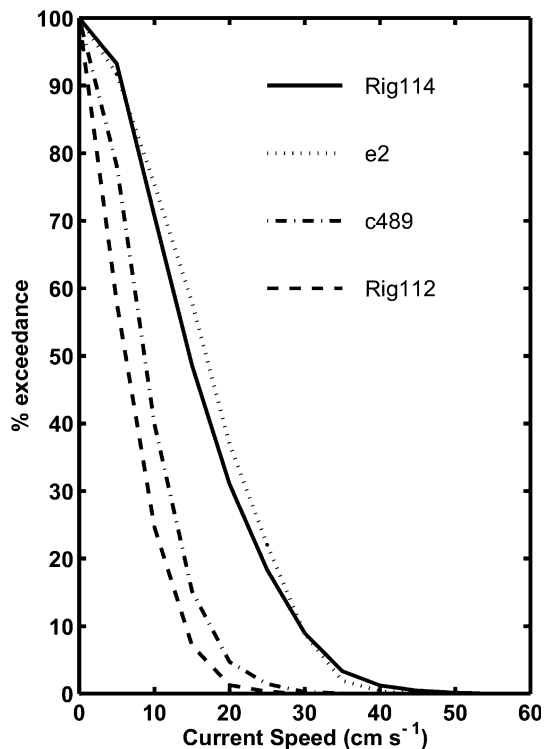


Fig. 4 Plot of % exceedance for instantaneous current speed measurements (all measurements) against current speed for measured currents shown in Fig. 3b–e

Slope currents here might be expected to have a larger mean value, therefore, due to increased topographic steering, but this is not the case. Another reason for the strong measured currents at the Belgica mound site is required. Pingree and Le Cann (1990) have indicated that the strength and persistence of the flow at Rig114 was due to baroclinic diurnal tidal modulation, with the amplitude of the diurnal tide twice that of the semi-diurnal components. Baroclinic motions at that period may be trapped against the continental slope as the wave period is greater than the inertial period ($2\pi/f$), where f is the local Coriolis parameter. Rhines (1970) has shown how these motions may be bottom intensified and Huthnance (1981) has indicated that the bottom intensification will be most likely where the value of $N\sin(\alpha)$ is a maximum. Here N is the vertical density stratification [$N^2 = (g/\rho) \times d\rho/dz$] and α is the bottom seabed slope. A resonant frequency for the trapped motion is given by $N\sin(\alpha)\sin(\theta)$, where θ is the angle of the wavenumber vector with the orientation of the continental slope.

The cross slope profile of $N\sin(\alpha)$ values for both Rig112/114 locations are given in Fig. 5, together with the minimum wave period of the intensified motion near the seabed. (i.e. for $\theta = 90^\circ$). Data were based on

the estimates of bottom slope and vertical stratification over 100 m depth intervals derived from historical CTD measurements (Fig. 2). At both locations, $N\sin(\alpha)$ values peak between 900–1,000 m, close to the thermocline depth (Fig. 5a). Values are much larger at Rig112 due to the larger seabed slope there. The maximum in $N\sin(\alpha)$ results in a minimum in the wave period for intensified motions. At Rig112, this period is about 8 h, removed from periods of major tidal forcing periods. At Rig 114 however, the minimum wave period associated with bottom trapped motions is close to 25 h, and the diurnal period tidal components. The matching of the conditions for bottom trapped motions to the diurnal period would appear, therefore, to confirm the cause of the residual and maximum currents measured at Rig114.

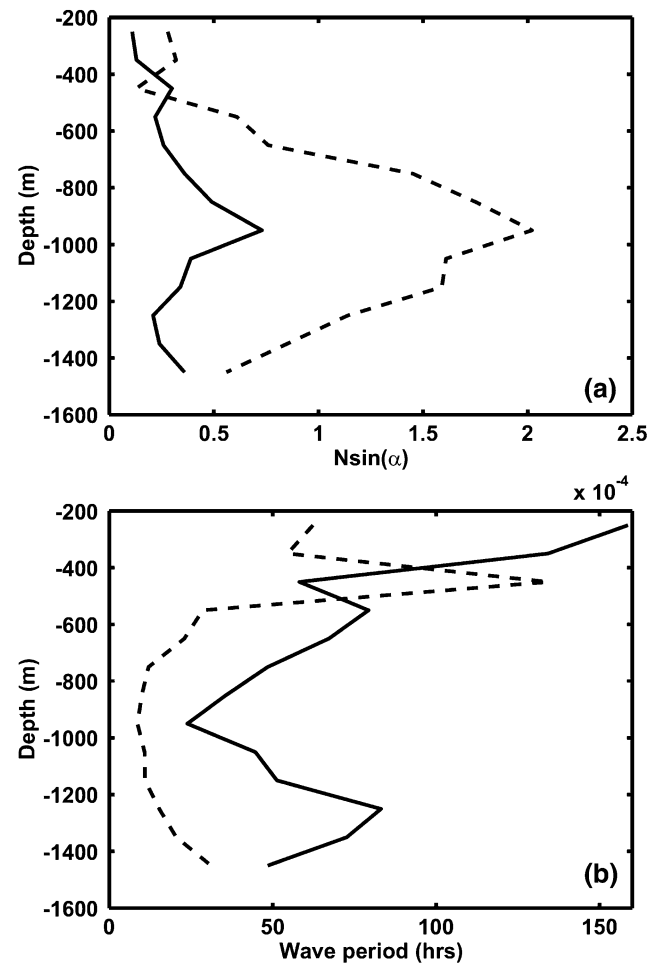


Fig. 5 Vertical profiles of **a** $\sin(\alpha)$ with depth at location (—) Rig114 and (---) Rig 112, where N is the vertical density stratification and α the bottom slope, and **b** vertical profiles with depth of the minimum wave period of bottom-trapped intensified motion associated with the profiles in **a** for the same locations

Internal waves

Internal waves are periodic oscillations in the vertical density stratification. The characteristics of internal wave group velocity propagation, e.g. the internal wave ray slope or direction of energy propagation, depend on the vertical stratification (N), wave frequency (σ), and Coriolis parameter (f). Furthermore, the interaction of these internal waves with the seabed has been suggested as a way of producing enhanced bottom currents. In particular, when the ray-slope, β , matches the bottom slope angle, α , a resonance condition may occur. At this resonant condition, enhanced generation of internal waves, together with increased bottom currents and associated shear stresses, will be expected. The resonance condition for a particular wave frequency is given by;

$$\sigma_c^2 = N^2 \sin^2(\alpha) + f^2 \cos^2(\alpha). \quad (1)$$

Figure 6 shows depth profiles of σ_c against depth, representing mean conditions for the Belgica, Pelagia and Hovland mound regions respectively. Data are based on the bathymetry shown in Fig. 1 and values of vertical stratification taken from the CTD data of Fig. 2. Note we have taken the vertical stratification from data measured in the deeper water adjacent to the slope to provide a full depth profile of N . Whilst it might be expected that the stratification in the benthic boundary layer would be smaller (than the adjacent deep water) due to boundary mixing, it was assumed that the height of the benthic boundary layer would be less, relative to the internal wave vertical wavelength. Changes in the internal wave propagation characteristics, therefore should not be significantly affected by using a mean stratification profile. Also shown is the value where waves of M_2 tidal period (the dominant period of forcing of internal waves here) are resonant with associated enhanced currents expected. For the region where σ_c is greater than the value for M_2 period internal waves, some smaller enhanced currents might also be expected if internal waves from a non-local source are present and reflecting off the seabed within this depth range. The profiles show that along the eastern Porcupine Sea Bight, resonance for M_2 period internal waves is possible, likely around 700 m depth, and this is principally determined by the bottom slope. At the Pelagia mounds, M_2 period internal waves would also be expected to generate at about 600 m. The varying nature of the slope at this location also means that a resonance condition is almost met at 950 m, close to the depth where the short term current

observations shown in Fig. 3e were made. At the Hovland site, however, the bottom slope angles are too small for resonance to occur at the M_2 period at any depth level, suggesting that interaction of internal waves with the seabed at the upper slopes of the northern Porcupine Sea Bight margin is likely not to be significant.

Discussion

Water masses

The cold-water coral dominated carbonate mounds located at the margin of the Porcupine Sea Bight are principally found between water depths 600–1,000 m. Within this depth range, the water masses within the Porcupine Bank Sea Bight are dominated principally by MOW between 800 and 1,100 m depth, and also by ENAW carried in the upper slope current at a depth level above MOW. Whilst there is a link between the depth in peak abundance of cold water coral at the level of MOW (Freiwald 2002), it would appear that the particular T-S characteristics of MOW is not a major factor in the depth distribution of coral (and hence mounds). This is because the temperature and salinity range within which coral, are found is much larger than that associated with MOW. De Mol et al. (2005) have suggested, however, a possible relationship between mounds and MOW. It was suggested that separate occurrences of MOW flow into the Porcupine Sea Bight during different geological periods have transported larvae of the deep-water corals from the Mediterranean Sea to initiate the formation of the various mound provinces in different geological times.

Benthic currents

Direct measurements of currents in the Porcupine Sea Bight are small in number, but it can be inferred that circulation along the margin of the basin is dominated by the cyclonically flowing boundary current (Figs. 1, 3). This boundary flow is driven principally by a meridional density gradient which, in turn, causes a cross slope pressure gradient and a poleward directed flow (Huthnance 1986). In the simplest terms, this current is predicted to be strongest at mid slopes and where the seabed slope is large, i.e. about 400–800 m depth, at the upper limit of the depth where mounds are located. Other factors can also force a mean poleward directed flow at the continental margin, such as the trapped diurnal waves (Huthnance 1981) and internal wave

resonance (Thorpe 1999). A large mean residual flow at the margin is important in terms of the long term sediment transport along the margin. At the northern end of the Porcupine Sea Bight the mean flows are weak which would imply that sediment can be transported to large distances only over long time scales. This might help explain the fact that the Magellan mound cluster is largely covered by drift deposits and that only the upper mound flanks of the Hovland mounds are not covered (Dorschel et al. 2005).

Strong benthic currents are associated with the presence of deep water coral (e.g. Frederiksen et al. 1990). Near seabed currents are strongly steered by the bottom topography and bottom currents are stronger along the slope than in the centre of the Sea Bight (Fig. 1). The near-seabed currents are also amplified by tidal motions or by the resonance conditions related to internal waves. Frederiksen et al. (1992) have correlated the depths of the critical wave resonance with the highest abundance of *L. pertusa* in waters around the Faeroe Islands and the submerged banks of the Rockall Trough. Internal wave influence might be expected at the Pelagia mound site at depths of ~600 and ~950 m (Fig. 6). A strong bottom slope current has been observed there at 930 m depth (Fig. 4) that may be driven by the generation of internal waves. Dickson

and McCave (1986) have suggested that internal wave resonance was responsible for the generation of intermediate nepheloid layers at about 600 m in this region, and further evidence for internal waves at this depth has also been measured here (de Stigter, personal communication). This highlights the dynamic nature of the bottom currents in this region and likely internal wave influence at the Pelagia mounds.

Rice et al. (1990) have also suggested that reflecting internal waves would cause enhanced currents along the eastern margin of the Sea Bight, but not along the northern margin of the Hovland and Magellan mounds. This is supported by Fig. 6. Rice et al. (1990) suggested the likely distribution of bottom current speed around the margin could account for the distributions of the sponge *Phoronema carpenleri*, whereby the sponge occupy the depth region below the regions of maximum predicted currents due to internal wave generation. Analysis by White (2003), however, has indicated that whilst the results do confirm the presence of large benthic currents in accordance with the predictions of Rice et al. (1990), the cause of the high currents may not be entirely due to internal waves. Current measurements at 1,000 m depth adjacent to the Belgica mounds have indicated that enhanced diurnal period baroclinic motions are present which dominate the current variability (e.g. Fig. 3c). Such motions are not uncommon along the continental slope of the NE Atlantic. White et al. (2003) have reported similar currents on the southern Rockall Bank within the carbonate mound province located there. The motions will have maximum intensification where the stratification and bottom slope are large, and the depth of the permanent thermocline is such a depth, typically 600–800 m. Most of the mounds in the Porcupine Bank/Sea Bight region lie close to the permanent thermocline depth. As a result, it would appear, therefore, that the permanent thermocline depth is influential for the depth distribution of corals through the promotion of conditions favouring stronger bottom currents at these mound depths.

It would seem likely, therefore, that the relative high currents associated with the mound provinces, and other locations where live deep-water coral is present in abundance, are a result of more than one dynamic process. The importance of an individual process probably varies geographically. For the Porcupine region, M_2 period internal wave reflection probably plays a role in generating strong currents at the Belgica and Pelagia provinces (Fig. 6). In addition, bottom intensified diurnal motions play a role within the Belgica mound province where the bottom slope reduces sufficiently to allow a trapped wave motion to occur at

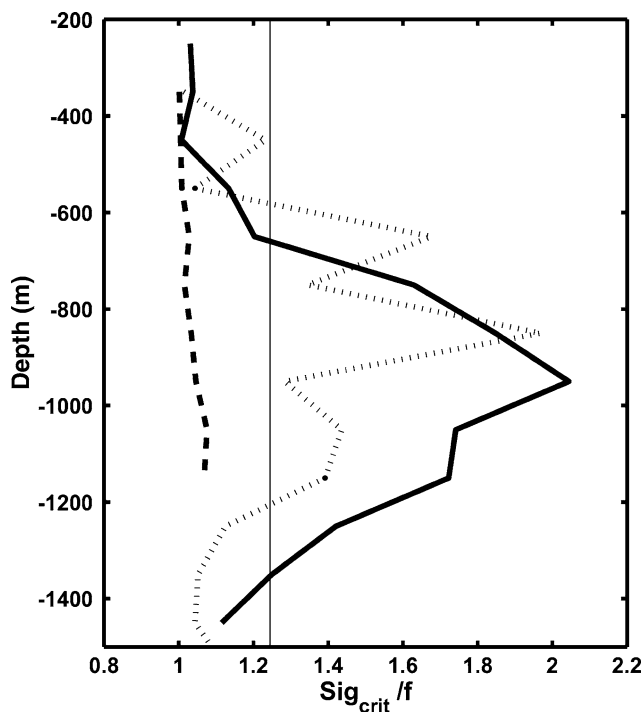


Fig. 6 Vertical profiles of critical internal wave frequency normalised by the Coriolis parameter (σ_c/f) with depth at location (—) Belgica, (—) Hovland and (...) Pelagia mound provinces. The thin vertical line indicates the mean value of σ_c/f for M_2 period internal waves for the three locations

that frequency (Fig. 5). Caution must be observed, however, as direct current measurements have not been reported from within the mound locations themselves and geological evidence suggests that all mound locations are regions where currents are certainly not weak (e.g. Huvenne et al. 2002). This includes the Hovland region where some, albeit a small amount, of live coral has been found (Dorschel et al. 2005). The mounds themselves will generate rough topography that probably induces localised strong currents and mixing that is essential for the corals to flourish. Such processes include hydraulic control over the mounds (e.g. Genin et al. 1986; Nash and Muom 2001), or the generation and subsequent breaking of small-scale internal waves by the overlying flow (Thorpe 1992).

Corals require hard substrates on which to settle, that is kept relatively clean of settling sediment. The range of current speeds within the vicinity of mounds suggest that currents are generally greater than 15 cm s^{-1} for about 10% of the time (with the exception of Rig114 as noted previously). Thomsen and Gust (2002) have suggested that 15 cm s^{-1} is a likely threshold for re-suspension of surface sediments in the region of the NE Atlantic continental margin. Currents are likely to be stronger in more localised regions such as the summits of seamounts or ridges. It seems likely, therefore, that whilst the northern Porcupine Sea Bight region, taken as a whole, may be characterised by a low flow regime that perhaps promotes large scale deposition of sediment, highly localised regions of stronger current exist around the mound that may support the development of coral colonies that form the basis of the mound structures.

Productivity

The enhanced currents generated by the different benthic dynamical processes have a secondary role in influencing the mound ecosystem, through control of the food availability. Fredericksen et al. (1990) suggested that the relationship between live coral zonation to depths of internal wave resonance was in part due to the action of the internal waves in enhancing primary production at the shelf edge and in keeping organic material transported down-slope in suspension. The large submerged banks, such as the Porcupine and Rockall Banks, are regions of enhanced productivity. White et al. (2005) have suggested how these banks may retain such productivity and promote the transportation of organic material to the mounds that are located along the deeper slopes through down-slope transport in the bottom Ekman (frictional) layer. It is the mean anticyclonic flow

around the banks that promotes this down-slope transport in the bottom boundary layer. The process would be expected for the cyclonic flow of the slope current around the Sea Bight (Fig. 1) hence providing a down-slope transport mechanism at all mound locations in the region. The mound provinces are, therefore, regions where enhanced organic material supply might be expected. Furthermore, the enhanced benthic currents close to the mound region, and around the individual mounds themselves, keep the material in suspension, thereby providing a source of organic material to the associated benthic fauna and keeping the coral on the mounds from being buried. In addition, low residual flow at the north flank of the Sea Bight does not transport the material away from the locality. This perhaps explains the difference between the somewhat dead, less dynamic nature of the Magellan/Hovland mound cluster and the more dynamic Belgica and Pelagia mounds.

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