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Morphology and environment of cold-water coral carbonate mounds on the NW European margin

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Abstract:

Cold-water coral carbonate mounds, owing their presence mainly to the framework building coral *Lophelia pertusa* and the activity of associated organisms, are common along the European margin with their spatial distribution allowing them to be divided into a number of mound provinces. Variation in mound attributes are explored via a series of case studies on mound provinces that have been the most intensely investigated: Belgica, Hovland, Pelagia, Logachev and Norwegian Mounds. Morphological variation between mound provinces is discussed under the premise that mound morphology is an expression of the environmental conditions under which mounds are initiated and grow. Cold-water coral carbonate mounds can be divided into those exhibiting "inherited" morphologies (where mound morphology reflects the morphology of the colonised features) and "developed" morphology (where the mounds assume their own gross morphology mainly reflecting dominant hydrodynamic controls). Finer-scale, surface morphological features mainly reflecting biological growth forms are also discussed.

Keywords: Carbonate mound - Cold-water coral - Morphology - Environmental setting - Seabed mapping

Introduction

The cold-water coral *Lophelia pertusa* (L.) is widespread along the European continental margin (*e.g.* Le Danois, 1948; Teichert, 1958; Wilson, 1979a; Zibrowius, 1980; Frederiksen *et al.*, 1992; Rogers, 1999; Freiwald *et al.*, 2002; Taviani *et al.*, 2005; Roberts *et al.*, 2006) and is often associated, although not exclusively with cold-water coral carbonate mounds. Research and ecological status reports on cold-water coral has been reviewed by Rogers (1999) and more recently in Freiwald *et al.* (2004) and Roberts *et al.* (2006) although limited attention was paid in these reviews to their geological products: cold-water coral carbonate mounds. A brief, timely review of research on European examples is presented here for a selective number of mound provinces. Cold-water coral carbonate mounds in this context refer to positive topographic features that owe their origin, partially or entirely, to the framework-building capacity of cold-water corals and have also been referred to as reefs, banks, carbonate mounds and coral build-ups (see Freiwald, 2002) .

Cold-water coral carbonate mounds vary in size and shape ranging from small, low relief ovoid features a few metres high and tens of metres across (e.g. Wilson *et al.*, 1979b; Scoffin *et al.*, 1980; Masson *et al.*, 2003; Foubert *et al.*, 2005; Wheeler *et al.*, 2005b; Wheeler *et al.*, 2005c; Lindberg *et al.*, this volume; Wheeler *et al.*, subm.), to giant mounds hundreds of metres tall and a few kilometres across (e.g. Kenyon *et al.*, 1998; De Mol *et al.*, 2002; Huvenne *et al.*, 2002; Akhmetzhanov, *et al.*, 2003; Beyer *et al.*, 2003; Huvenne et al., 2003; Kenyon *et al.*, 2003, O'Reilly *et al.*, 2003; van Weering *et al.*, 2003; O'Reilly & Readman, 2004; De Mol *et al.*, 2005; Foubert *et al.*, 2005; Wheeler *et al.*, 2005c; Huvenne *et al.*, 2005; Beyer *et al.*, this volume; De Mol *et al.*, this volume; Huvenne *et al.*, this volume; Mienis *et al.*, in press). The origin of these mounds has been related to hydrocarbon seepage (Hovland & Thomsen, 1989; Hovland, 1990; Hovland, 1992; Hovland *et al.*, 1994; Hovland & Thomsen, 1997; Henriet *et al.*, 1998; Hovland *et al.*, 1998; Henriet *et al.*, 2001; Hovland & Risk, 2003) or autogenic processes stimulated by high current speeds and food supply (Frederiksen *et al.*, 1992; Freiwald *et al.*, 1997; Mortensen *et al.*, 2001; De Mol *et al.*, 2002; Kenyon *et al.*, 2003; Duineveld *et al.*, 2004; White *et al.*, 2005). Despite these debates on mound genesis, little evidence exists for the hydrocarbon seepage model whereas recent evidence (Expedition Scientists, 2005) suggest that hydrodynamic conditions have a strong influence on mound growth and therefore resultant morphologies.

A significant increase in the extent of seabed mapping of the European continental margin in recent years has given rise to a more complete understanding of the location and variability of European cold-water coral carbonate mounds. Regional mapping exercises using low frequency side-scan sonars (10-30kHz) and deep-water multibeam systems have identified numerous mound-like features that have subsequently been confirmed as coral-colonised by video or seabed sampling (e.g. Unnithan, 2001; Masson *et al.*, 2003; Beyer *et al.*, 2003; O'Reilly *et al.*, 2003; Fosså *et al.*, 2005; Foubert *et al.*, 2005; Huvenne *et al.*, 2005; Wheeler *et al.*, 2005a; Beyer *et al.*, this volume; Huvenne *et al.*, this volume; Mienis *et al.*, in press). Furthermore, the discovery of many, often buried, cold-water coral carbonate mounds has occurred as a result of the expansion of hydrocarbon exploration activity along the European margin with cold-water coral carbonate mounds clearly revealed in seismic sections due to their topographic relief and a bright chaotic internal signature (e.g. De Mol *et al.*, 2002; Henriet *et al.*, 2003; Huvenne *et al.*, 2003; Kenyon *et al.*, 2003; van Weering *et al.*, 2003; De Mol *et al.*, 2005; Fosså *et al.*, 2005; De Mol *et al.*, this volume).

More targeted, high frequency side-scan sonar mapping surveys (100-410kHz) and ROV-mounted multibeam surveys have revealed details of gross and surface mound morphology (e.g. Kenyon *et al.*, 1998; Freiwald *et al.*, 1999; Freiwald *et al.*, 2002; Olu-Le Roy *et al.*, 2002; Akhmetzhanov *et al.*, 2003; Kenyon *et al.*, 2003; Fosså *et al.*, 2005; Foubert *et al.*, 2005; Wheeler *et al.*, 2005a; Wheeler *et al.*, 2005b; Wheeler *et al.*, 2005c; De Mol *et al*, this volume; Lindberg *et al.*, this volume). These images reveal that gross mound morphology is strongly influenced by the dominant current directions but may also be inherited from the morphology of features that provide the initial hard substrate facilitating settlement and early colonisation. Mound-surface texture may reflect either the nature of biological growth forms influenced by the sedimentary and hydrodynamic regime, or erosion.

The aim of this paper is to present an overview of morphological variation between different cold-water carbonate mounds based on extensive survey work over the past few years. This is achieved via a series of case studies where mounds are also set within their environmental context. As such, this paper presents limited new data although the timely review and synthesis is further discussed to elucidate the underlying factors controlling cold-water carbonate mound morphology from which a new mound morphological classification system is defined.

Distribution of *Lophelia pertusa*

Cold-water coral carbonate mounds become elevated above the surrounding seabed due to the framework building and sediment baffling capacity of the corals; mainly *Lophelia pertusa* and *Madrepora oculata*. *Lophelia* exists in water temperatures ranging from 4-13°C, can tolerate a range of salinity, is usually associated with oxygen minima (reflecting high concentrations of suspended organic material) and high current speeds (favourable for suspension feeding organisms). In European waters, such conditions occur down to a depth of c.1000 m (e.g. Rogers, 1999; Freiwald *et al*., 2004; Roberts *et al*., 2006).

Lophelia has a global distribution and is widespread along continental margins, seamounts and banks in intermediate and shallow water depths. Rogers (1999), Freiwald *et al*. (2004) and Roberts *et al*. (2006) present reviews of the literature on the biology of *Lophelia* and framework building cold-water corals respectively, thereby documenting published reports of occurrences worldwide. Figure 1 shows this global distribution based on a database generated by the Institute of Paleontology Erlangen, Germany, with counts of 2084 sites for *Lophelia* (live, dead, and fossil). This clearly demonstrates a concentration of *Lophelia* in the Atlantic and especially the NE Atlantic with 1816 documented occurrences (89% of known occurrences)

Figure 2 shows that *Lophelia* is fairly evenly distributed along the European margin from the Gulf of Cadiz to northern Norway although two areas of limited *Lophelia* occurrences are noted: the northern French canyon systems and the eastern Rockall margin north of the Porcupine Bank. High *Lophelia* occurrences are also noted on the banks west of Ireland/UK and on the broad Norwegian Shelf. Many of these occurrences reflect isolated colonies that may be transient in nature whereas others are associated with giant cold-water coral carbonate mounds that have probably existed for a few million years. The giant mounds occur exclusively in the Porcupine Seabight, Porcupine Bank, Rockall Bank and Hatton Bank. Figure 2 also shows the occurrences of *Lophelia* associated with coral mound provinces that have been confirmed by seabed surveys (see also White *et al.*, 2005).

Survey methodologies

A series of case studies are presented providing details from selected mound provinces. These case studies are based on a number of survey methodologies which are outlined briefly here.

Detailed bathymetric mapping of the Belgica mound province was performed using a 15.5 kHz Hydrosweep DS2 multibeam echo sounder onboard RV Polarstern with a measurement accuracy of mostly better than 1% water depth (Beyer *et al*., 2003). A complete mosaic was generated with 10% overlap of survey swathes with a grid spacing of 50 m. In addition to the depth measurements, echo amplitudes were recorded and used by Beyer *et al*. (this volume) for local seafloor classification. The bathymetry presented in the Hovland Mound province is of comparable resolution and was collected by the Geological Survey of Ireland using a Simrad EM120 instrument (see http://www.gsiseabed.ie/). Microbathymetry for the Logachev Mounds was obtained using a 200 kHz SIMRAD EM2000 mounted on the VICTOR 6000 ROV (see Klages *et al.*, 2004).

Side-scan sonar coverage for the Hovland, Pelagia and Logachev mounds was collected using the 30 kHz TOBI side-scan sonar system (Flewellen *et al*., 1993; De Haas *et al*., 2002). Additional side-scan sonar coverage in the Belgica, Pelagia and Darwin areas was also collected using a Geoacoustic dual frequency (100 and 410 kHz) high resolution side-scan sonar during RRS Discovery cruise 248 (Bett *et al*., 2001). Side-scan sonar coverage for the presented Norwegian case studies was surveyed using a Klein 595 dual frequency (100 and 500 kHz) and Ultra Electronics widescan dual frequency (100 and 310 kHz) high resolution side-scan sonars (Freiwald *et al*., 1999). Side-scan sonar data from all systems was processed using SOC’s PRISM software (Le Bas & Hühnerbach, 1999). An exception to this is the Oretech 30 kHz low frequency side-scan sonar system that was also deployed in the Hovland Mound province and processed using standard methods (Akentieva & Shashkin, 1998).

Ground-truthing of cold-water coral carbonate mounds was performed using the Jago submersible (Freiwald et al., 2002), ROV VICTOR6000 (Olu-Le Roy *et al*., 2002; Klages *et al*., 2004), towed video (Kenyon *et al*., 1998; De Bergé, 2000) and sediment samples (Swennen *et al*., 1998; De Mol *et al*., 1999; van Weering *et al*., 1999; de Haas *et al*., 2000, 2002, 2003, 2005; Freiwald *et al*., 2000, 2002b; de Stigter *et al*,. 2001; Van Rooij *et al*., 2001; De Mol, 2002;;Mienis *et al*., 2004).

Case studies from coral mound provinces

Although it is not practical here to describe the variety of all European cold-water coral carbonate mounds, examples are presented below that illustrate the degree of variation between cold-water coral carbonate mounds that have been well studied. These case studies therefore provide a review of research on these cold-water coral carbonate mounds provinces which also form the main clusters of mounds along the European margin.

Belgica Mounds, eastern Porcupine Seabight

The Belgica mound province is situated on the eastern margin of the Porcupine Seabight between 51°10'N and 51°40'N (Fig. 2) and is aligned roughly north-south. In this area, based on multibeam echosounder and sub-bottom profiling systems (Beyer *et al*., 2003), 62 mound structures have been recorded (Fig. 3) of which 35 are outcropping mounds and 27 are buried. De Mol *et al.* (2002) found further buried mounds between 51°10'N and 51°20'N on seismic profiles making the total mound distribution extending 55km along the Porcupine Seabight margin.

The mounds occur in a depth range in between 700 and 1000m and are bordered to the west (downslope limit) by a wide, north-south oriented channel (Fig. 3). The Belgica Mound province, and in particular its northern part, is pervaded by shallow south-west trending downslope channels which feed into the north-south channel (Van Rooij *et al*., 2003; Huvenne *et al*., 2005). These channels appear to be mostly relic at present. Mound distribution shows an alignment parallel to the continental margin with most structures forming single mound occurrences although they are often connected by sediment drift bodies and therefore appear as apparent clusters. As well as single mounds, some mounds coalesce at their bases (Henriet *et al*., 2003; De Mol *et al*., this volume).

Mound shape (see Fig. 4) varies from conical forms to elongated, ellipsoidal ridge-forms. Ridge-form orientation is at a slight angle with respect to the mound alignment and shows mainly a NNE - SSW orientation. Many mounds on the slope have an exposed steep western flank that is at about 20^o compared to the average slope of the margin at *c*.5^o. The eastern, upslope-side of the mounds is often buried by sediments which leads to a terrace-like margin morphology. Depressions, up to 50 m deep, often occur on the steep downslope side of some mounds and are probably a result of strong bottom currents around some mounds (Van Rooij *et al*., 2003).

High resolution side-scan sonar imagery in inter-mound areas reveals numerous features indicative of high benthic current strengths including barchan dunes, seabed striations, comet marks, gravel ridges and sediment waves (Wheeler *et al*., 2005c). The sediment waves have large wavelengths of 20 m - 25 m (De Mol *et al*., 2002) and reaching up to 100 m (Beyer *et al*., 2003).

The surface morphology of the mounds is also dominated by waveforms although video footage reveals that these, especially near mound summits, are coral banks mimicking off-mound sediment wave morphologies (Fig. 5). At the base of some mounds, a transition from non-coral colonised sediment waves to coral banks exists.

Also, in the vicinity of large cold-water coral carbonate mounds, small mounds (Moira Mounds) exist (Fig. 6) and could represent an early stage of the mound development (Foubert *et al*., 2005; Wheeler *et al*., 2005c).

Geological studies highlighting changing palaeoenvironmental conditions and mound growth histories show strongly punctuated sedimentation histories (Van Rooij *et al*., this volume).

Hovland Mounds, northern Porcupine Seabight

The Hovland Mound province is located in the north of the Porcupine Seabight, between 52°06’ / 52°22’N and 12°52’ / 12°05’W (Fig. 2). In this area, the bathymetric contours curve around the head of the Seabight and water depths range from 500 to 1000 m. Slopes dip generally south- to south-westwards, with an angle of approximately 0.5°, which is reduced to 0.2° just north(west) of the Hovland mounds (Magellan province). Further upslope to the north, Slyne Ridge connects the Porcupine Bank with the main Irish shelf.

The seafloor in the Hovland Mounds area is cut by 6 depressions or blind channels, generally running north-south (except for one which bends towards the north-west: Fig. 7). They are between 10 and 17 km long and 70 to 150 m deep compared to the surrounding seafloor. Hovland *et al.* (1994) attributed them to bottom current erosion or to the escape of pore water or gases through the seafloor although De Mol (2002), based on detailed seismic study of the Hovland Mounds, suggested they were caused by current scouring by a northerly directed current.

Most of the Hovland Mounds (especially the larger ones), are associated with these channels: they are located along their flanks or at their heads. Increased current speeds and turbulence, caused by the presence of the mounds, may well have helped in the scouring and deepening of the depressions. The most western channel may even have been formed through the merging of several moats (scouring depressions created around the mounds).

The general seabed in the Hovland Mound province is of a uniform backscatter as imaged on the TOBI side-scan sonar mosaic (Huvenne *et al*., 2005). There is no evidence for bedforms such as ripples or sandwaves, and the backscatter intensity on the side-scan records is very homogeneous, although it seems to increase a little towards the north (Fig. 7a). Core descriptions of the area (Kenyon *et al*., 1998) identify these sediments as ‘bioturbated foraminiferal marls or silts’ with Dorschel *et al*. (2005: this volume), Rüggeberg, *et al* (2005) .and Rüggeberg, *et al*. (this volume) showing significant hiatuses in mound sequences. The overall environment of the Hovland Mounds at present is low energy with evidence of former higher energy conditions in the form of scoured moats and depressions. Image texture analysis of details of the OreTech side-scan sonar data indicated fundamental differences between the acoustic response of the mound flanks, the moats and background sediments (Huvenne *et al*., 2002).

Eleven large and 15 smaller surface mounds could be recognised on the TOBI side-scan sonar mosaic of the Hovland Mound province (Huvenne *et al*., 2005). Hovland *et al*. (1994) counted 31 surface mounds, but this included some structures which are now classified in the Magellan Mound province (Huvenne *et al*., this volume). De Mol (2002) found only 14 surface mounds on seismic data, but he may have counted close-by mounds as one structure if their sub-seafloor expression on the seismic records indicated a common base.

Most of the Hovland Mounds are grouped in 2 clusters: one towards the centre of the northern Seabight (Fig. 7) and one a little more on the northeastern flank. As stated above, most of the mounds are placed close to one of the depressions, which in the central group cause a strikingly rectangular cluster shape of c. 23 x 16km.

Several mounds have an elongated shape, with lengths varying from 1700 to 3200 or even 5000 m, and widths of 450 to 1200 m. Most of them are sharp ridges with several summits, others consist of multiple mound structures and some small mounds are lined up, as if they represent half-buried mound ridges. Some of the ridges are forked, with spurs extending in different directions. The overall directions of the ridges or lined-up mounds vary greatly (Fig. 7b). There are 4 mounds with a general east-west elongation, although 3 of them have a rather sinusoidal shape and one has several spurs directed to the north. Two mounds are elongated WNW-ESE, and one set of small mounds is lined up in a north-south direction. The largest mound in the central cluster (often referred to as the ‘Propeller Mound’: De Mol, 2002; Dorschel *et al*., 2005; Dorschel *et al*., this volume; Rüggeberg, *et al*., 2005; Rüggeberg, *et al*., this volume) consists of a north-south trending ridge, forking towards the north into ENE and WNW-ward pointing branches. The western branch then connects to another long ENE directed ridge. The ridges are generally not parallel to the depressions but are located at the heads of the blind channels.

Pelagia Mounds, northwest Porcupine Bank

Numerous steep-sided, giant cold-water coral carbonate mounds have been identified on the northwest Porcupine Bank (Kenyon *et al*., 1998; Akhmetzhanov *et al*., 2003; Kenyon *et al*., 2003; van Weering *et al*., 2003; Wheeler *et al*., 2005a) and are collectively known as the Pelagia Mounds (Fig. 2). These mounds exist between 500 and 1200m water depth in an area on the Bank subjected to fast northerly flowing waters. The mounds occur downslope of a significant zone of iceberg ploughmarks and upslope of submarine canyons and slope failures (Fig. 8) (de Haas *et al*., 2002). A further cluster of giant carbonate mounds exists further south around the head of a major canyon system (Porcupine Bank Canyon Mounds) with smaller mounds also identified even further to the south (Grehan *et al*., 2006). Video observations of the seafloor (Olu-Le Roy *et al*., 2002; Wheeler *et al*., 2005a) and sediment samples (Kenyon *et al*., 2003; Klages *et al*., 2004) reveal a seabed typified by a thin cover of mobile rippled sands and areas of exhumed dropstones and hardgrounds (some of which have become colonised by corals).

Within the Pelagia Mound province, a number of scarp-features are identified on seismic lines and TOBI side-scan sonar data that have a slight topographic rise upslope and a steep scarp-face downslope. Cold-water coral carbonate mounds are often, although not exclusively, found on top of these scarps (Fig. 9). The scarps run sub-parallel to the isobaths and their shape and downslope acoustic facies suggests that these are not associated with slope failures but may represent either the edges of erosional scours where low-angle bedding is exposed, or fault scarps associated with underlying boundary faults. In support of the former, comparable (although much smaller scale) erosional exposures of consolidated sediment exposures have been identified in this area from ROV footage (Olu–Le Roy *et al.*, 2002; Wheeler *et al.*, 2005a) and also previously imaged on high-resolution side-scan sonar records (Akhmetzhanov *et al.*, 2003). These exposed consolidated sediments have become coral colonised (Fig. 10). In support of the latter, industrial seismic data suggests a correlation between Rockall Trough boundary faults and the scarps (Croker *et al.*, 2002) that would support the gas-seep hypothesis for mound formation (Hovland *et al.*, 1994), although disputed by Wheeler *et al.* (2005a).

The cold-water coral carbonate mounds in the Pelagia Mound province are giant mounds being predominantly 100 to >300m across and ranging in height up to *c*.250m. At present, coral colonisation is mainly restricted to their summits. They occur both as isolated features and in association with the scarps. Mound shape ranges from ovoid, to ridge-shaped running sub-parallel to the isobaths, to complex forms. Some of the mounds, especially those occurring as groups, are also surrounded by zones of high backscatter seabed suggesting either coral rubble/live coral spreading off of the mounds or a coarse gravely substrate in the mound vicinity due to high benthic current speeds (Fig. 11). A few mounds also show low backscatter moats.

The giant mound cluster is aligned perpendicular to the slope although in other instances, there is a clear tendency for along-slope mound alignment. This alignment usually occurs either on the slope parallel scarp features (Fig. 11) or, in one instance, along the crest of a slope parallel topographic spur at the head of a canyon system (Fig. 8).

Logachev Mounds, eastern Rockall Bank

The Logachev Mounds exist on the southern eastern Rockall Bank between 500 and 1200m water depth (Fig. 2) and form a complex arrangement of coalescing mound clusters that are aligned both up- and downslope. Mienis *et al.* (in press) discusses these mounds in detail. A sediment wave field exists upslope of the mounds with wavelengths of up to 500m long and individual waves being traced for several kilometres. Downslope of the Logachev Mounds is a 5 km wide area of very low backscatter revealing slope parallel flow features and slide escarpments.

The Logachev Mounds possess diameters in the order of hundreds of metres to a few kilometres. Mound clusters are predominantly aligned north-south (downslope), east-west (along-slope) aligned mound clusters are also present (Fig. 12). Seismic evidence suggests that the north-south mound clusters were initiated earlier than the east-west mound clusters (van Weering *et al.*, 2003).

In between the mound clusters, narrow and elongated areas of low backscatter are present running downslope although occasionally these structures run along slope. The structures are interpreted as valleys in between the mounds acting as channels through which (tidal) currents are funnelled. Boxcores from these areas usually retrieve only pebbles and boulders (e.g. De Haas *et al.*, 2000). Video observations (Olu-Le Roy *et al.*, 2002) from these areas show a largely sediment starved environment with evidence of scour.

High resolution multibeam and video data (Olu-Le Roy *et al.*, 2002) reveals a terraced morphology to the mounds with the fronts of the terraces colonised by live coral and the backs of terrace characterised by exposed dead coral skeletons. Interstitial sediment between the coral frameworks is minimal (Fig. 13).

Norwegian mounds

The northernmost occurrences of *Lophelia* exist in Scandinavian waters from the Swedish Kosterfjord area (Jonsson et al., 2004: Wisshak *et al.*, 2005) to the southwestern Barents Sea at 71° northern latitude (Freiwald *et al.*, 1997: Lindberg & Mienert, 2005). Through intense seabed mapping efforts and collated reports by fishermen, more than 1000 geographically referenced *Lophelia* locations are now known (Fosså *et al.*, 2002; Fosså *et al.*, 2005). Corals are most abundant on the continental shelf specifically along the upper slope of the continental margin and along many flanks of the deep mid-shelf troughs in the bathymetric range of 200 to 400 m water depth (Fig. 2). Fjord systems which lack a shallow sill near the entrance, thus permitting the episodic intrusion of oceanic water through estuarine circulation patterns, provide another suitable environmental setting for *Lophelia* reefs and patches as shallow as 38m water depth have been found (Dons, 1944; Freiwald *et al.*, 1997; Fosså *et al.*, 2000).

During the Neogene glaciations the waning and waxing glaciers repeatedly reached the shelf and occasionally also the shelf-break in certain areas of the Norwegian Shelf (Vorren *et al*., 1983). These glaciogenic processes caused erosion but also deposition of a sequence of moraines onto the shelf. During the final postglacial collapse of the Fennoscandian ice shield, drifting icebergs frequently grounded thereby producing ploughmarks and flutes (Lien, 1983), or released scattered ice-rafted debris in the form of dropstones on the seabed. These marine Pleistocene glaciogenic processes provided a broad array of suitable hard substrata for the arriving *Planula* larvae of *Lophelia* during the climatic amelioration. Typical coral-rich grounds are elevated moraines and boulder levees of ploughmarks (Freiwald *et al*., 1999). Oldest radiocarbon dates obtained from *Lophelia* skeletons from various sites off mid and southern Norway cluster around 8,700 to 8,600 years BP for the Early Holocene coral colonisation (Mikkelsen *et al*., 1982, Rokoengen & Østmo, 1985, Hovland *et al*., 1998). Since then the framework-constructing potential of *Lophelia* has resulted in the formation of impressively large build-ups, commonly called coral banks, bioherms, or reefs (Teichert, 1958; Mortensen *et al*., 1995; Mortensen *et al*., 2001; Freiwald, 2002).

Despite the large number of *Lophelia* occurrences known in Scandiavian waters, only a few sites have been analysed in great detail. One of the best known study sites is the Sula Reef Complex (SRC) at 64° northern latitude (Hovland *et al*., 1998, Mortensen *et al*., 1995, 2001; Freiwald *et al*., 2002). The SRC stretches over 14km in lateral extension along a spur – the Sula Ridge. The ridge forms a northeastward continuation of the Frøyabank and is underlain by a tilted Paleocene sandstone unit. A thin cover of Late Pleistocene moraine deposits was left behind after the last glacier advance onto the shelf. During the deglaciation grounding icebergs carved out both the morainic deposits and parts of the Paleocene sandstone unit. Especially on the shallowest parts of the ridge, the incised furrows of the iceberg ploughmarks are flanked by boulder-rich levees which exert an important control of the present day general outline of the SRC (Freiwald *et al*., 1999). Individual *Lophelia* build-ups can be grouped into morphological categories (Mortensen *et al*., 2001; Freiwald *et al*., 2002). Build-ups with a height less than 10m are often single-peaked and possess a circular outline measuring 20 to 70m across (Fig. 14a). The larger build-ups are elongated and multi-peaked with heights between >10 to 25m indicating that these may originate from coalescing neighbouring reefs (Fig. 14b). The lateral extension is variable, ranging from 200 to 1000m with a width of 40 to 120m near the base. Both *Lophelia* reef shape groups show the same basic arrangement of sedimentary facies and biological habitats. Two major sedimentary facies characterise the off-reef environments: the bioturbated silty sand facies and the sponge-rich boulder ground facies. The reef-associated facies generally provide a consistent lateral sequence from the distal and deeper lying base to the proximal reef top (Fig. 14c): (1) Pebbly sand facies, (2) Coral rubble facies, (3) Sediment-clogged coral framework facies, (4) Exposed dead coral framework facies, and (5) Living coral framework facies. Regardless of direction or the degree of current exposition, no evident variation of the facies sequence was documented during the ground-truthing operation (Freiwald *et al*., 2002).

High-frequency (>100 kHz) side-scan sonar records yield characteristic backscatter features that provide valuable information for the recognition and identification of *Lophelia* occurrences on the seabed specifically for Scandinavian waters. The geographical restriction is related to the distinct colony shape of *Lophelia* that differs strongly from *Lophelia* colonies found elsewhere along the northwestern European continental margin. A living coral framework viewed with a side-scan sonar resembles a giant cauliflower (Figs. 14a & b; Freiwald *et al*., 1999). Ground-truthing with a manned submersible proved that this feature originates from individual hemispheroidal coral colonies measuring up to 1.5m in thickness and up to 2m in diameter. Ideally, this type of a *Lophelia* colony has a circular outline. Occasionally larger hemispheroidal coral colonies were observed. These huge colonies start to collapse from the central inner core predominantly due to the bioerosional effect of boring sponges. This characteristic feature (“Wilson-Ring”) is detectable on the sonographs and was predicted to occur during the ontogenetic evolution from a single polyp to a mature colony stage by Wilson (1979b).

Further studies by Mortensen *et al*. (2001) and Fosså *et al*, (2005) on *Lophelia* distributional patterns in a wider geographical context on the Norwegian Shelf yield evidence that coral reefs preferably occur close to breaks and escarpments but much less on the level bottom. In fjords, moraine sills with their turbulent hydrodynamic regime seem to provide nourishing conditions for coral growth as has been demonstrated for the Stjernsund Reef at 70° northern latitude (Fig. 15). *Lophelia* reefs occur in areas with high densities of pockmarks but also in areas where no pockmarks were found. Hydrocarbon seepage as a nutritional agent may stimulate the entire food web as suggested by Hovland *et al*. (1997) (see discussion in Freiwald *et al*., 2002), as long as hydrocarbon emissions are not too strong to kill the oxygen-demanding communities.

Discussion

Cold-water coral carbonate mound development

The process of mound development has been investigated by several authors and the principle aspects of this process are outlined below. The framework building capacity of *Lophelia* enables it to grow upwards into the water column. In doing so, *Lophelia* can feed in faster flowing waters, thus increasing food flux, and isolating itself from detrimental bedload and heavy particle suspended load transport associated with the benthic boundary layer, whilst still benefiting from fine organic suspended sediment flux. However, due to the effects of bioeroders and hydrodynamics, colonies eventually keel over and provide an elevated platform for new growth. Vertical mound growth is also assisted by sedimentation around colonies that provides structural support to the colonies provided that coral colony growth rates are in excess of on-mound sedimentation rates. Once mounds reach a certain height they become isolated from bedload transport and mound growth style changes. For *Lophelia* a more suitable habitat is therefore created with an increase in organic particle supply due to faster flowing waters and higher organic:lithic suspended sedimentation ratios.

Despite the commonality of this process, the above case studies highlight the degree of variability that exists in the resultant morphology of cold-water coral carbonate mounds that vary from small scale to giant mounds, conical mounds to ridge-shaped features, and framework dominated to sediment dominated. A central tenant of this discussion is that this morphological variation is an expression of the influence of differing environmental controls (e.g. the influence of the following important environmental parameters: current dynamics, temperature, salinity, pH, organic particulate supply, vertical and bedload sediment supply) on mound growth. The morphology of mounds can therefore provide us with clues to the environment conditions once certain relationships have been defined. Although it is perhaps over-optimistic to assume that simple seabed mapping of cold-water coral carbonate mounds can unlock the complexities of environmental dynamics in mound areas (Wheeler *et al*., subm.), it is useful to make some basic observations and draw relationships that may help to explain the variety in mound morphology and explore the underlying environmental controls.

Environmental controls on cold-water coral carbonate mound distribution

As well as controlling morphology, environmental conditions also dictate, perhaps in a more fundamental way, mound distribution and occurrence. Figures 1 & 2 show that *Lophelia* and associated cold-water coral carbonate mounds are found predominantly along continental margins and seamounts at intermediate water depths. Unlike tropical scleractinians, *Lophelia* does not possess a symbiotic relationship with algae and is therefore not restricted to the photic zone. However, occasional isolated finds do occur in shelf seas and, in more northern waters (e.g. offshore Norway) exclusively on the shelf and even in fjords (Dons, 1944; Freiwald *et al*., 1997; Fosså *et al*., 2000). This distribution is an expression of the ecological tolerance of *Lophelia* particularly with respect to temperature. It is at these water depths that temperatures fall within the range of 4-13^{o}C. *Lophelia* can tolerate a range of salinity (Rodgers, 1999) (making it adaptable in fjordic settings) but as a suspension feeder, shows a preference for areas with high current speeds and high concentrations of suspended organic particulate material. It also requires a hard substrate to grow on although this may include dead coral skeletons allowing, in theory, considerable communities to grow from one isolated dropstone.

However, despite its wide distributions along the European margin, *Lophelia* is not evident in all areas where these ecological constraints are met and it only forms cold-water coral carbonate mounds in a few of these. A study of the distribution of cold-water coral carbonate mounds (Fig. 2) suggests that specific conditions are needed for their formation.

One obvious control is the need for suitable substrates for initial coral attachment that can include dropstones or, as in the Pelagia Mound area, the exposure of consolidated sediment. The absence of *Lophelia* in some areas of the margin may represent a lack of suitable substrates although many areas with suitable substrates at appropriate water depths exist where *Lophelia* is not present (*e.g*. the eastern Rockall Trough margin: see Wheeler & TTR9 Shipboard Scientific Party, 2000). Unsuitable muddy substrates exist at present in the Hovland Mound area with coral growth restricted to the summits of cold-water coral carbonate mounds where attachment is on old coral frameworks and there is no new off-mound coral growth. The muddy seabed conditions may reflect sluggish water dynamics at present and may therefore also explain the low abundance and restricted nature of living coral as present. Moats around mounds in this area suggest that vigorous currents were typical of the palaeoenvironment in this area when these mounds may have been more productive.

Two main theories have been presented that may explain why cold-water coral carbonate mounds are found in discrete provinces and are absent elsewhere. Firstly, cold-water coral carbonate mounds are linked to hydrocarbon seepage, and/or secondly specific hydrodynamic conditions exists that are optimal for *Lophelia* in specific areas. Hovland (1990) first suggested that cold-water coral carbonate mounds restricted locations are related to cold seeps where enhanced bacterial activity forms the base of a food chain supporting a diverse and abundant biological community (including *Lophelia*) and also provides conditions suitable for abundant carbonate production. Hovland *et al.* (1994) then went on to associate the Hovland Mounds with underlying faults acting as a conduit for hydrocarbon seepage. However, isotopic studies of *Lophelia* to date (*e.g.* De Mol *et al.*, 1998; Kiriakoulakis *et al.*, 2001) suggest that carbon incorporated into their skeleton is contemporary and not derived from older thermogenic sources. This suggests that mound growth is not dependent on ongoing hydrocarbon seepage. However, a lack of isotopic samples from corals from the base of cold-water coral carbonate mounds allows for the possibility that cold-water coral carbonate mounds may have been initiated by gas seepage, and once they have grown significantly, can function independently of further seepage and may, in fact cap the initial seeps (Henriet *et al.*, 2001). Preliminary results from recent drilling of the base of the Challenger Mound (Belgica Mound Province) found no evidence for thermogenic gas (Expedition Scientists, 2005). Some credibility to this theory, however, is given by coincidence of mound occurrences overlying hydrocarbon reservoirs, by hydrocarbon seepage modeling (Naeth *et al.*, this volume) that predicts seafloor hydrocarbon seepage pathways directed to the Hovland and Belgica Mounds and by the occurrenc*e of Lophelia* in sheltered environments within pockmarks in Norwegian waters (Hovland, 2005). This may also explain why these mounds reach such large proportions compared with other smaller mounds.

The second theory explaining why cold-water coral carbonate mounds are found in discrete provinces emphasises the specifics of hydrodynamics in areas that are particularly favourable to *Lophelia* growth. *Lophelia* occur in areas subjected to strong currents and prefer sites that are elevated with more prolific growth occurring on exposed flanks and summits. Additionally, *Lophelia* occurrences coincide with the Oxygen Minimum Zone in the north Atlantic (Freiwald, 1998) related to intermediate nepheloid layers containing enhanced concentrations of organic particulate material and associated with water column stratification (Kenyon *et al.*, 2003). Current dynamics on continental margins where *Lophelia* occurs include geostrophic currents often associated with internal waves that may steepen and break along the continental slope, and internal tides. It may be that the interplay between internal waves, tidal currents and the slope gradient induce conditions of near-resonance where current dynamics is at its optimum for suspension feeders (White *et al.*, 2005). The influence of current dynamics also has a major influence on gross mound morphology (see below). On a global view, *Lophelia* occurrences cluster in areas of high seasonal primary production, thus indicating a strong bentho-pelagic coupling as the major driver for carbon transfer from productive surface waters to the coral ecosystem (Guinotte *et al.*, 2006). This is also supported by biomarker analyses of coral soft tissue indicating plankton as the major food source (Kiriakoulakis et al. 2005, this volume).

Cold-water coral carbonate mound size relationships

The size of giant cold-water coral carbonate mounds may not solely be an expression of optimum conditions for growth. Their size may be more a function of longevity where recurrent favourable conditions have occurred through the Pleistocene. This situation may be aided by the fact that once formed, the mounds provide there own elevated environment more suitable for renewed coral colonisation. In this context, many of the smaller mound forms observed, e.g. Moira Mounds, Darwin Mounds and Norwegian mounds are probably younger (Early Holocene). For Norwegian mounds this is certainly true as they grow on Devensian glacial deposits.

O’Reilly et al. (2003) analyses mound size relationships for the Pelagia Mounds and, erroneously equating a published cold-water coral polyp growth rate to mound growth rates, derive an age model for mound initiation. An underestimation is achieved which is further compounded as we now know mound sequences contain many hiatuses/erosion in mound sequences (e.g. see Dorschel et al., 2005).

A similar exercise in mound size comparisons is presented here for the Belgica Mound province based on multibeam echosounder data (although not related to a growth model). The data of 35 surface mounds and 27 buried mounds were used to calculate statistics for this province (Fig. 3). Figure 16 illustrates the depth distribution of the mound bases and summits for the Belgica Mound province. The mound bases are defined as the deepest bathymetric depth of the mounds where the surface slope changes from mound flank towards general slope. The mounds are supposed to be symmetrical and shallower depths are due to partial burial at one side (mostly the eastern upslope side). The mound summits are found at the center of the mound structures indicating the shallowest depth. Summits occur in two main water depths: 850m and 700m. The mound bases show a similar depth distribution and occur mainly at 950m and 800m water depth where they possibly formed on a Late Pliocene erosion surface (Van Rooij *et al.*, 2003; Expedition Scientists, 2005). Although the mounds north of 51°30'N are more weakly aligned, they also support this depth dependent distribution. The depths of mound summits (Fig. 16a) and mound bases (Fig. 16b) correlate with an r-value of 0.93 showing a strong uniformity of mound height and position with respect to initiation and elevation in the water column. In addition, the depth distribution of the buried mound summits corresponds to the distribution of the exposed mound summits at 700m water depth. Depths of the mound bases of buried mounds are not available from bathymetry.

Exposed heights of the mounds vary between 10m and 70m (mean: 40m) on their upslope side and 40m and 160m (mean: 90m) on downslope side (Fig. 17). The mean height of the mounds is c.100m based on the depth histograms (Fig. 16a & b). The horizontal extent of the mounds is presented in Figure 18. The north-south width has a broader range than the east-west extension: varying between 400m and 2000m (mean: 860m) and 300m and 1000m (mean: 570m) respectively. However, mound size slightly decreases in the northern part of the mound province where the slope gradient is gentler (in particular north of 51°30'N).

This mound morphometric data presented here for the Belgica Mound shows that the distribution of the mound heights (downslope and upslope sides) shows a left-shifted distribution which means that smaller heights are more common compared to large heights (Fig. 17). However, this feature is more pronounced for the upslope side as a result of sedimentation. The histograms shown in Figs. 16 to 18 are useful for comparison with mound characteristics of other provinces with a similar left-shifted distribution (in this case lognormal) was reported for the largely buried Magellan mounds in the northern Porcupine Seabight (Huvenne, 2003; Huvenne et al., this volume)..

“Inherited” and “developed” mound morphological types

As well as mound location and scale, environmental factors strongly dictate mound morphology. Two types of gross mound morphological forms can be defined: “inherited” forms and “developed” forms as discussed below. Inherited forms have a strong substrate control and owe their gross morphology to the morphology of the features that have been colonised. Developed forms have grown independently of the topography at their original colonisation site and assume forms more closely in equilibrium with prevailing hydrodynamic conditions.

The tendency of *Lophelia* to grow in elevated exposed settings means that preferential sites of colonisation are often on topographic features such as morainic ridges. The Sula Ridge is a case in point where the gross morphology of the coral mound is ridge-shaped, as the name implies, growing as it does on a continuation of the morainic Frøyabank (Freiwald *et al.*, 1999). In this example, we also see a further substrate control with the boulder levees of iceberg ploughmarks offering elevated, hard substrate sites for colonisation (Fig. 14). Similarly, the gross morphology of mounds on scarps in the Pelagia Mound province reflects the geometry of the scarps with mounds extending along the crests (Fig. 9). In both instances it is the pre-existing morphology of the settlement sites that ultimately dictate gross mound morphology

Masson *et al.* (2003) suggested a fluid escape mechanism for the Darwin Mounds in the northern Rockall Trough implying that these are coral-colonised pockmarks based on a dimensional coincidence between the two features and observations of transitional partially colonised pockmarks. Masson *et al.* (2003) argue that the pockmarks were formed by the dewatering of underlying sediments, which brings suitable coarse-grained substrates to the surface in the areas where the pockmarks are colonized. This process would have no relationship to any type of hydrocarbon seepage. In this context, mound occurrence is directly controlled by the localized nature of suitable substrates with mound morphology inherited from the morphology of the pockmarks through substrate control. To the east of the Darwin Mounds, coral colonisation occurs on a seabed with a dense scattering of dropstones forming a dispersed coral cover with no tendency for mound formation (Wheeler *et al.*, subm.). Wheeler *et al.* (subm.) goes on to demonstrate a transition from inherited to more developed morphologies for the Darwin Mounds related to increasing bedload transport.

Radiocarbon dates from Norwegian cold-water coral carbonate mounds confirms these as Early Holocene (Mikkelsen *et al.*, 1982, Rokoengen & Østmo, 1985, Hovland *et al.*, 1998), whereas the age of the Darwin Mounds and Pelagia scarp mounds is speculative. However, all of these mounds are relatively small implying that the mounds are probably no older than Holocene in age and were initiated when hydrodynamic conditions and sediment supply regime altered favourably for *Lophelia.* We can therefore postulate that mound morphology of relatively young mound tends to be "inherited" simply because the mounds have not had time to develop a morphology independent of their sites of colonisation. In contrast, the giant mounds tend to have a "developed" morphology that may be an expression of their longevity. Dates for the initiation of these mounds are inferred as Pliocene (Hovland Mounds - De Mol *et al*., 2002), Miocene to Late Pliocene (Belgica Mounds - De Mol *et al*., 2002; Van Rooij *et al*., 2003) and early Tertiary to early Pliocene (Logachev Mounds - van Weering *et al*., 2003).

The gross morphology of the Belgica Mounds is clearly current aligned. The strong correlation of mound height may also suggests that the Belgica Mounds have developed an optimal elevation with all summits now stabilised within the same water mass.

In the Hovland Mound province elongated mounds and several simple elliptic or conical mounds are observed. Most of those, however, seem to occur in the eastern cluster. The elongation of the mounds, together with the occurrence of forked ridges and spurs, suggests the influence of currents on the morphology of the Hovland Mounds. As most of the spurs and forks are directed more or less north-south, this could indeed indicate a north-south directed current. A similar effect was described for the Magellan province (Huvenne *et al*., this volume).

The Hovland Mounds also show a preferred positioning around the rim of channels. This suggests that gross mound morphology has developed in response to the influence of the channels that may provide enhanced food supply from waters flushing out of them. De Mol *et al*. (2002), when providing evidence against a hydrocarbon seepage model for the Hovland Mounds, noted that mound alignment was not coincident with underlying faults.

Internal tides are also important along these marginal settings with developed mound morphologies in both the Pelagia Mounds and Logachev Mounds (Fig. 2) dominated by the influence of up- and down-slope tidal current activity. In the Logachev Mounds, mound clusters are aligned both along-slope and perpendicular to the slope. Seismic evidence (van Weering *et al*., 2003) suggests that these differently aligned clusters are of different ages. This suggests that initial mounds were aligned along-slope, due to the dominant influence of geostrophic currents, and subsequently aligned perpendicular to the slope due to a rise in the dominance of tidal currents.

Mound surface-morphology

The survey data summarised here also reveal information about the surface morphology of mounds. On the Sula Ridge (Freiwald *et al*., 1999) the surface morphology is "cauliflower shaped" (Fig. 14) revealing a surface morphology reflecting the biological growth forms of mature *Lophelia* colonies. The overall surface morphology is created by colonies distancing themselves from neighbours as closer colonies are "overshadowed" and stunned due to reduced food supply. A similar form is presented for the Moira Mounds (Fig. 6) and also for the Darwin Mounds (Wheeler *et al*., 2000; Masson *et al.*, 2003; Wheeler *et al*., subm.).

The surface morphology of the Belgica Mounds and Logachev Mounds (Olu-Le Roy *et al.*, 2002; Wheeler et al., 2005c) is dominated by ridges covered with coral growing into coral banks (Fig. 5b). These banks are non-migratory waveforms although, in the case of the Belgica Mounds, sand transport onto the banks helps to provide support for coral colonies thereby facilitating further bank vertical growth. The original holdfasts of coral colonies are probably glacial dropstones presently buried below the coral banks and Holocene sediment drift deposits.

This surface morphology is again biological controlled with growth on top of the banks benefiting from enhanced food supply while growth of those in the trough regions become "overshadowed" and stunted. The development of banks, as opposed to isolated colonies, may purely be an expression of this process occurring on a steep slope.

Conclusion

Extensive seabed mapping in recent years has enabled detailed observations and comparison of mound gross and surface morphologies between various cold-water coral carbonate mounds along the European margin. The morphology of the mounds is an expression of the environmental controls and constraints under which these mounds grew. In some cases, gross mound morphology is “inherited” from the morphology of features that were colonized because they offered suitable substrates or topographically elevated settings favourable to *Lophelia* growth. In other cases, mounds have assumed their own gross “developed” morphology that tends to be aligned with dominant hydrodynamic conditions.

Details of mound surface morphology suggest that the growth of one coral colony “shadows” the surrounding seabed restricting the growth of immediate neighbours. On low relief mounds this results in an irregular surface morphology dominated by discrete coral colonies (the cauliflower morphology of Freiwald *et al.*, 1999). On mounds with steep flanks, coral banks can be formed with similar morphologies to sediment waves. Surface morphologies are strongly dictated by biological growth forms although environmental factors, particularly sediment supply and erosion, may play a significant part.

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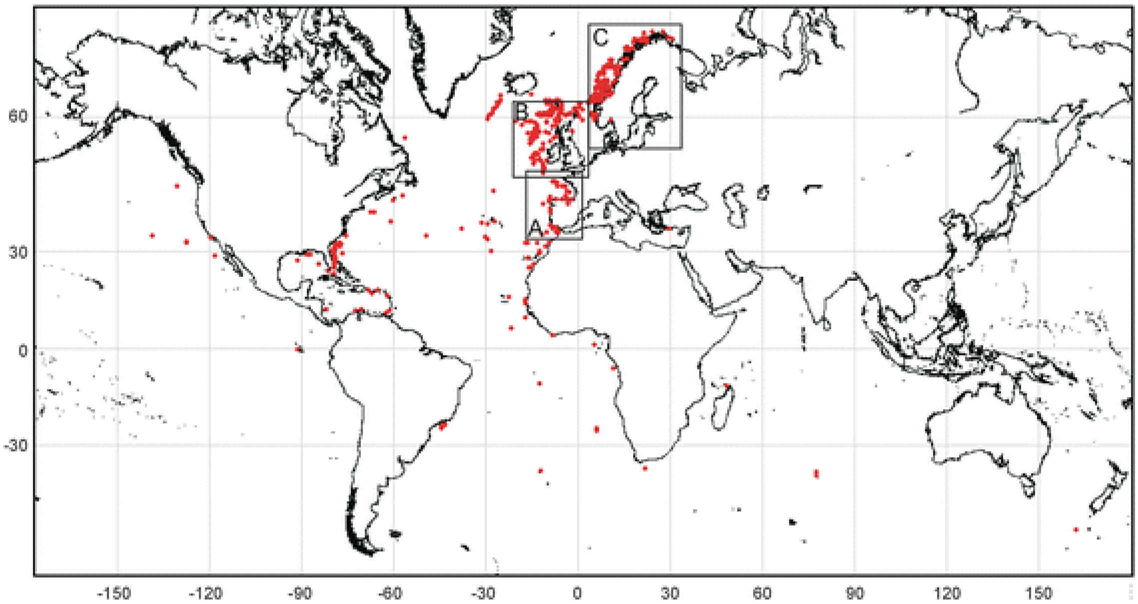

Figure 1: Global distributions of documented *Lophelia pertusa* occurrences. Boxes (A, B and C) refer to the location of highlights presented in Figure 2. Bathymetry from GEBCO.

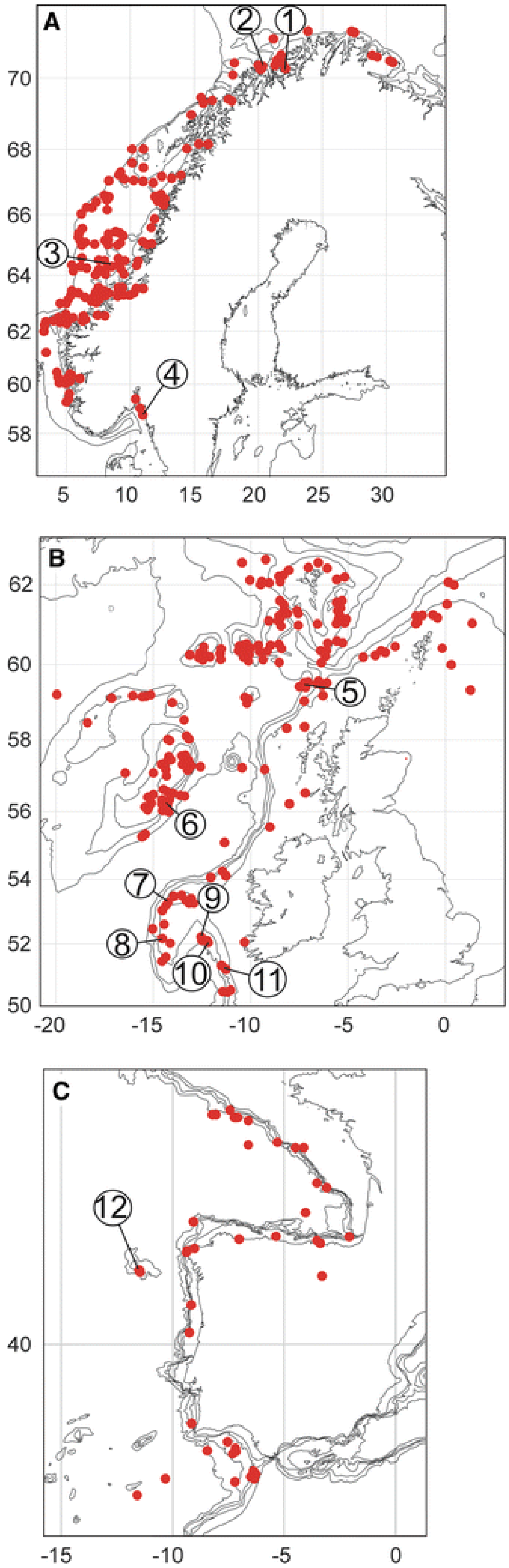

Figure 2. European distribution of documented *Lophelia pertusa* occurrences: A – Franco/Iberian Margin, B – Irish/British/Faraoese margin, and C – Swedish/Norwegian margin. See Figure 1 for location of detailed maps. Bathymetry from GEBCO. The names of confirmed coral mound (as opposed to isolated coral finds) are labelled: 1 – Stjernsund Reef, 2 – Fugløy Reefs, 3- Sula Ridge, 4 – Kosterfjord, 5 – Darwin Mounds, 6 – Logachev Mounds, 7 – Pelagia Mounds, 8 – Porcupine Bank Canyon Mounds, 9 – Magellan Mounds, 10 – Hovland Mounds, 11 – Belgica Mounds, and 12 - Galicia Bank Thickets.

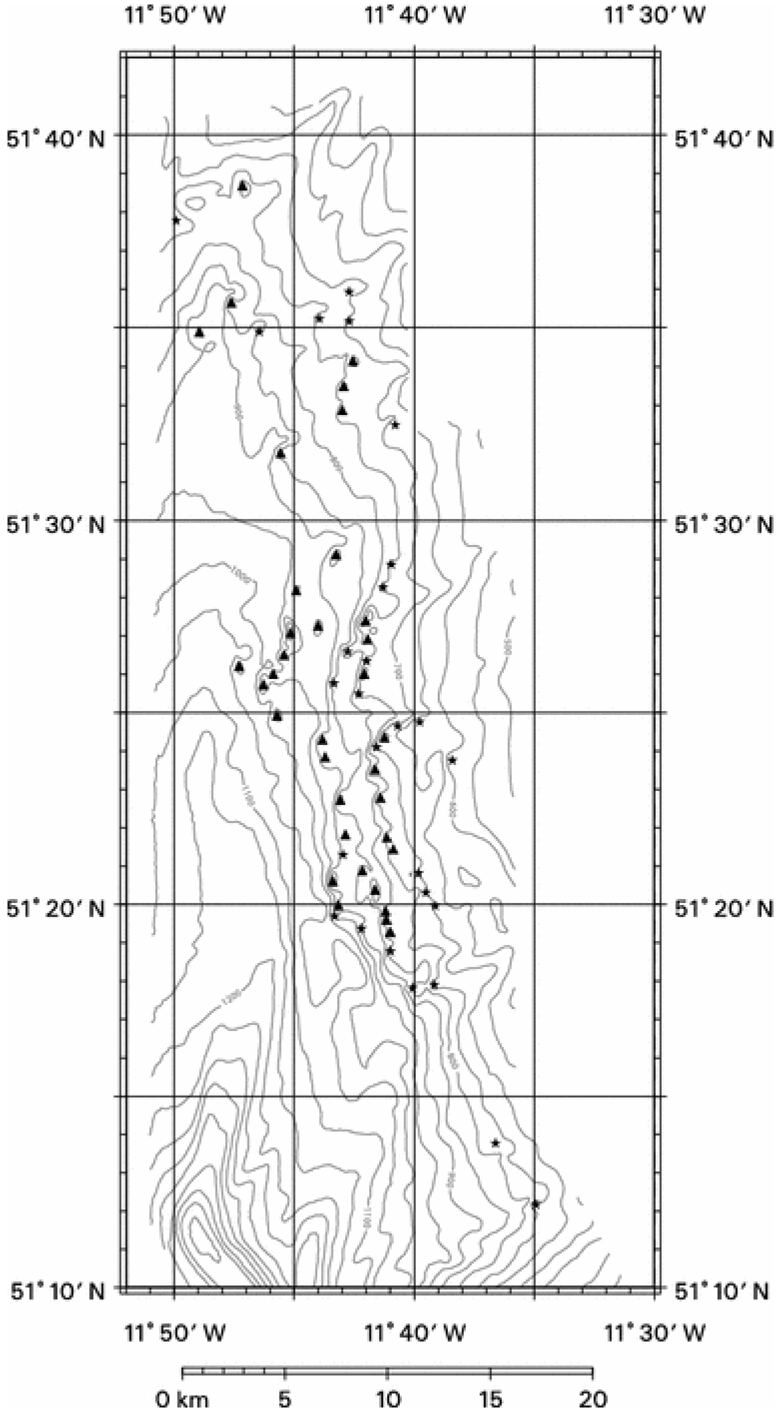

Figure 3: Mound occurrences in the Belgica Mound province. Triangles indicate outcropping mounds. Features identified as buried coral mound are indicated by asterisks. Contours are at 50m intervals (from Beyer *et al*., 2003).

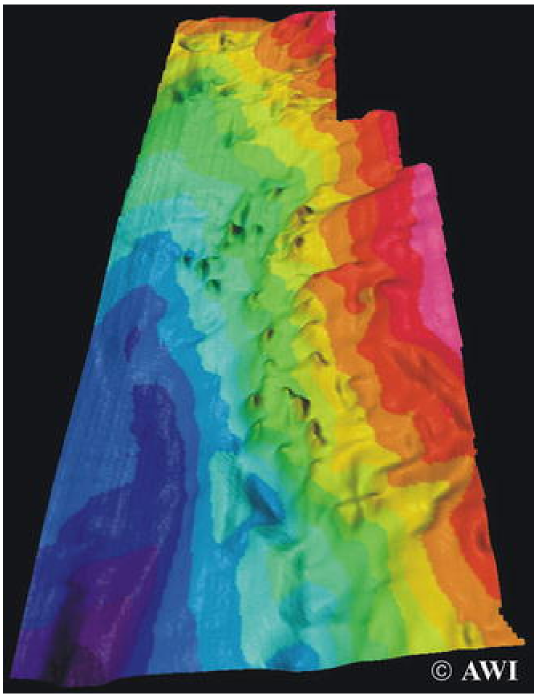

Figure 4.**V**iew of Belgica Mound province showing both conical and elongated, ellipsoidal ridge-forms. The eastern, upslope-side of the mounds is often buried by sediments which leads to a terrace-like margin morphology

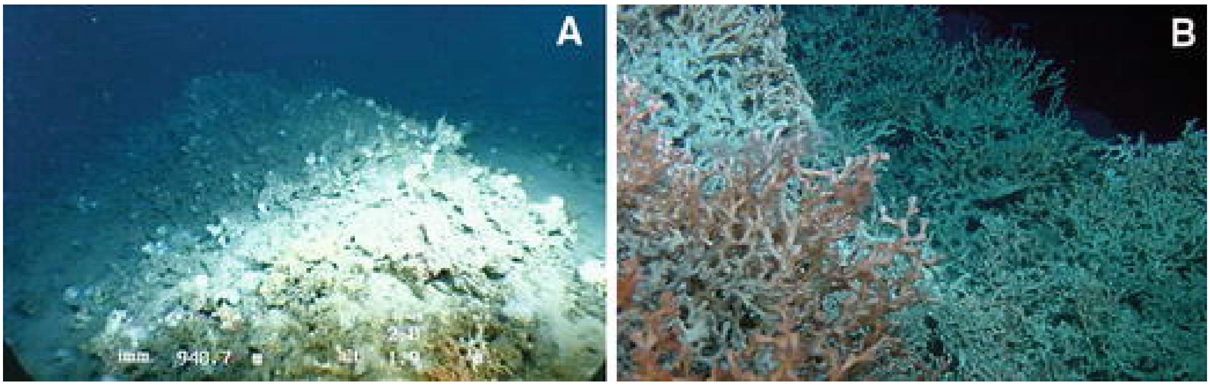

Figure 5: Video still (VICTOR ROV) showing coral banks at (a) the base of the Thérèse Mound where coral colonies trap migrating sands, and (b) the summit of the Thérèse Mound where waveforms are purely biological constructions.

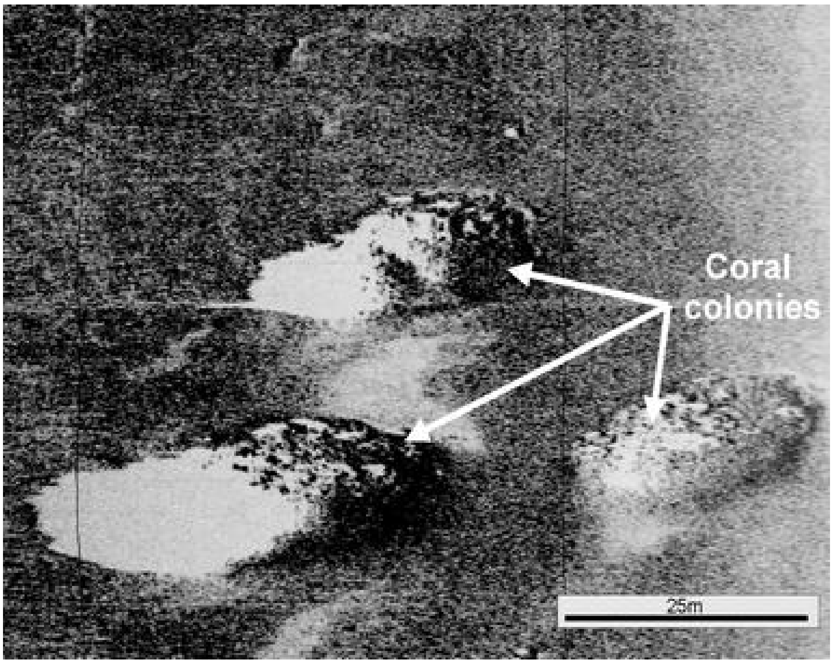

Figure 6: 410 kHz side-scan sonar image of small cold-water coral carbonate mounds (Moira Mounds), acoustic shadows are white.

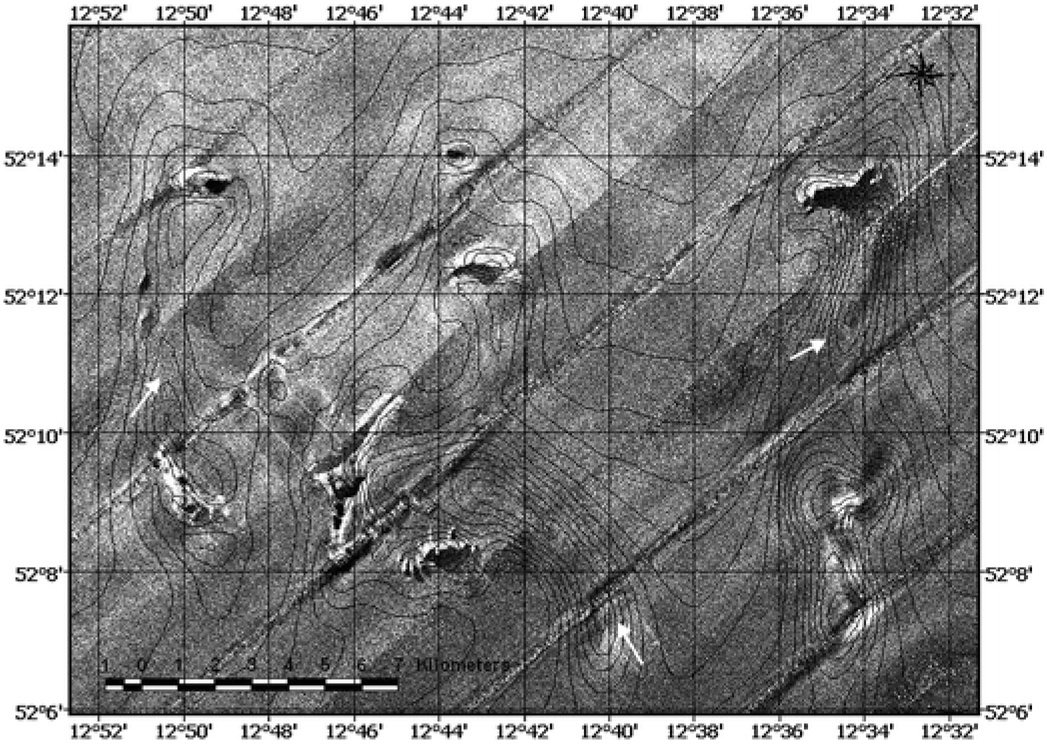

Figure 7: Detail of the central cluster of Hovland mounds from TOBI side-scan sonar imagery (contour interval 20 m). White arrows point to blind channels down-current of mounds. Bathymetry data courtesy of the Irish National Seabed Survey, Geological Survey of Ireland

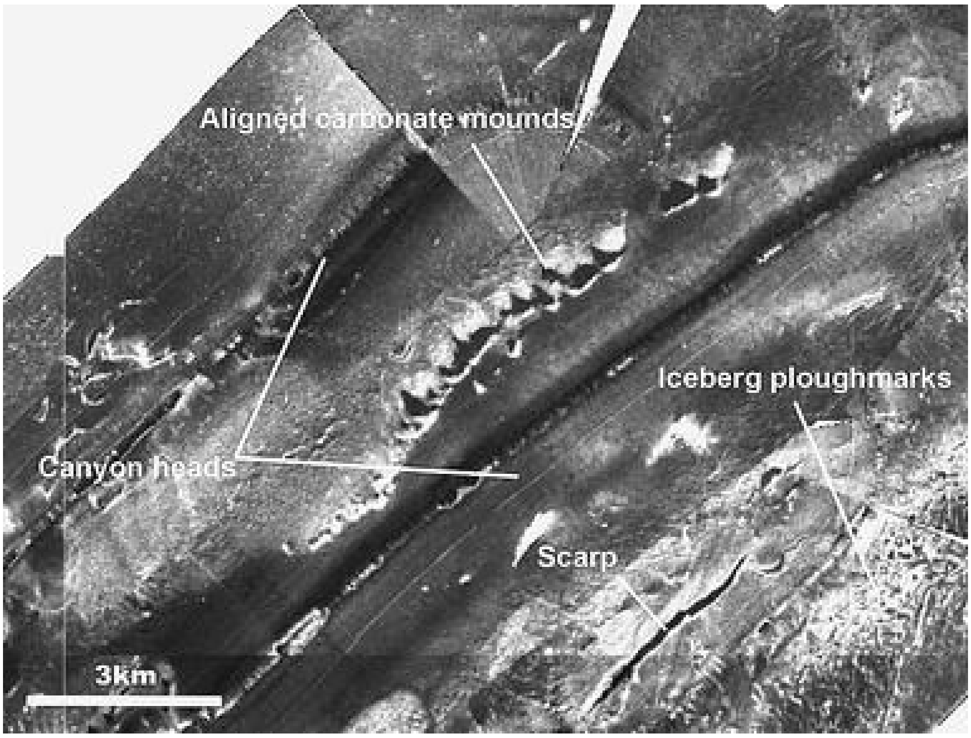

Figure 8: An alignment of Pelagia Mounds along a topographic ridge separating two canyon head feeder systems. An upslope erosional scarp and iceberg plough marks are also imaged. Downslope direction is to the north-west

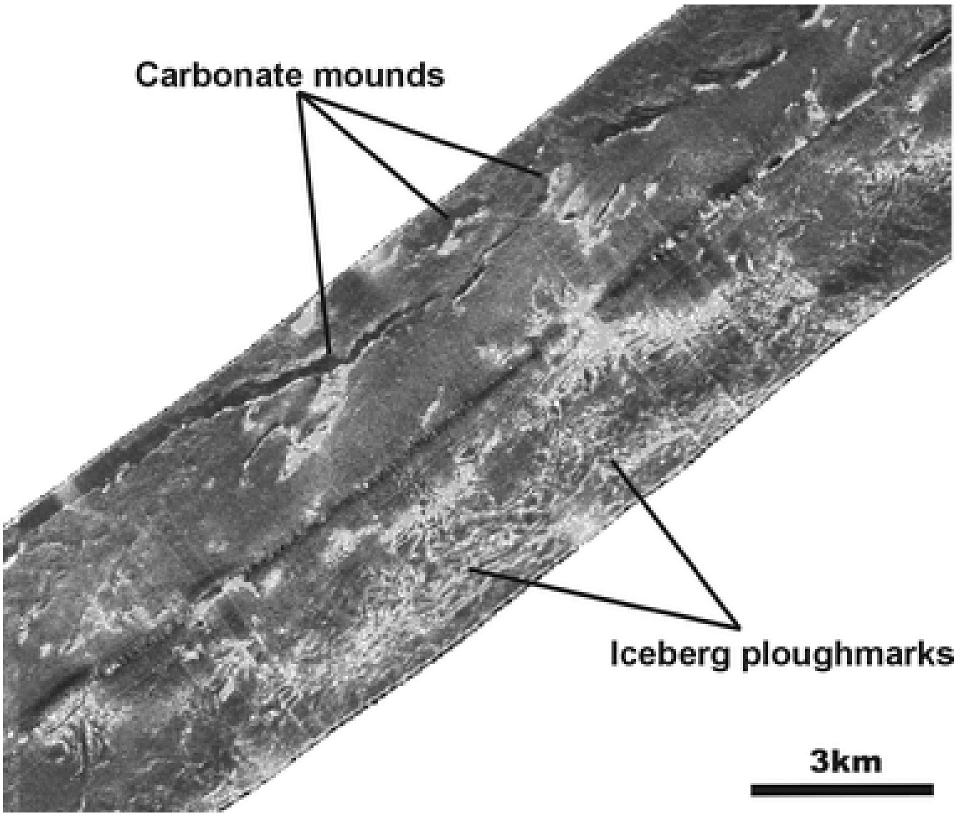

Figure 9: TOBI side-scan sonar image showing scarps with small mound development aligned along the crest and an upslope zone of iceberg plough marks in the Pelagia Mound province. Downslope direction is to the north-west

Figure 10. Video still (VICTOR ROV) showing consolidated sediment exposed by seabed erosion offering a suitably hard substrate for colonisation by the solitary cold water coral *Desmophyllum cristagalli* in the vicinity of the Pelagia Mounds.

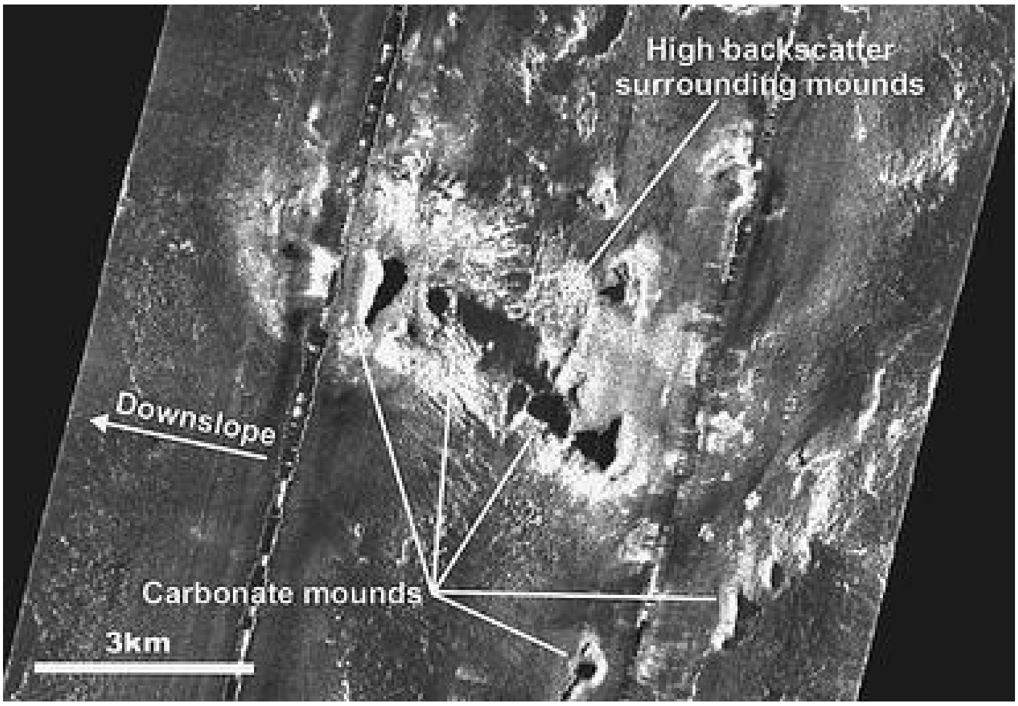

Figure 11: TOBI side-scan sonar image of a cluster of giant cold-water coral carbonate mounds in the Pelagia Mound province, Porcupine Bank. The cluster is aligned downslope and surrounded by high backscatter suggesting off mound coral colonisation or surrounding coarse sediment indicative of an erosive high current regime.

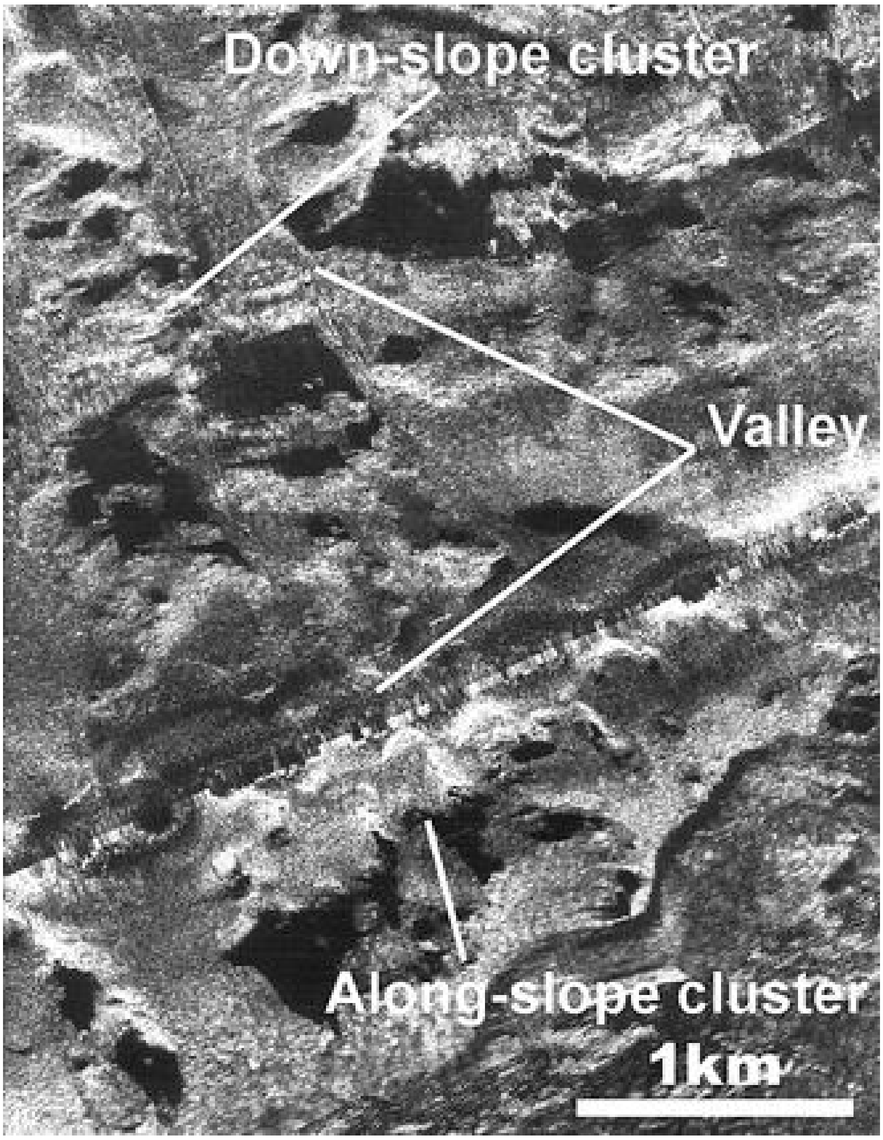

Figure 12: Down-slope and along-slope giant coral mound clusters separated by “valleys” in the Logachev Mound province.

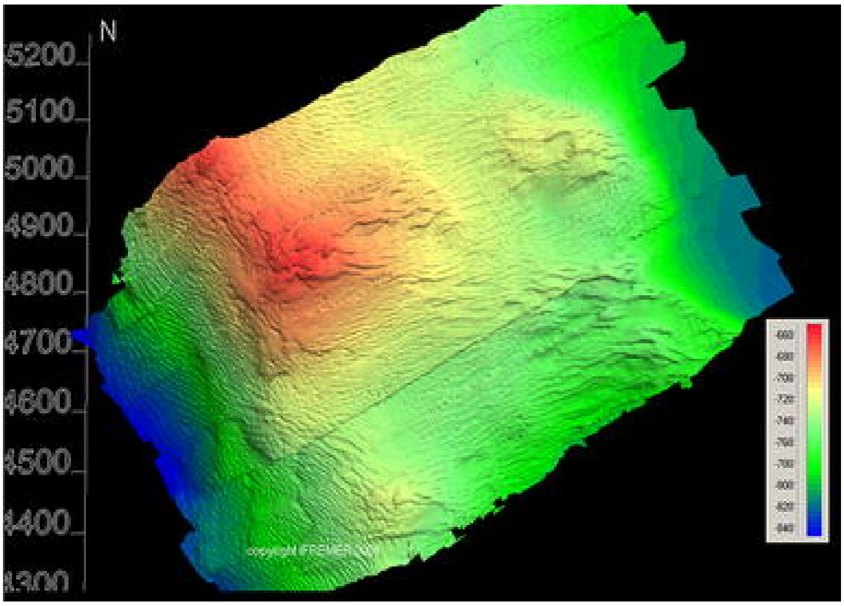

Figure 13. Microbathymetry map of a Logachev Mound showing a terraced morphology.

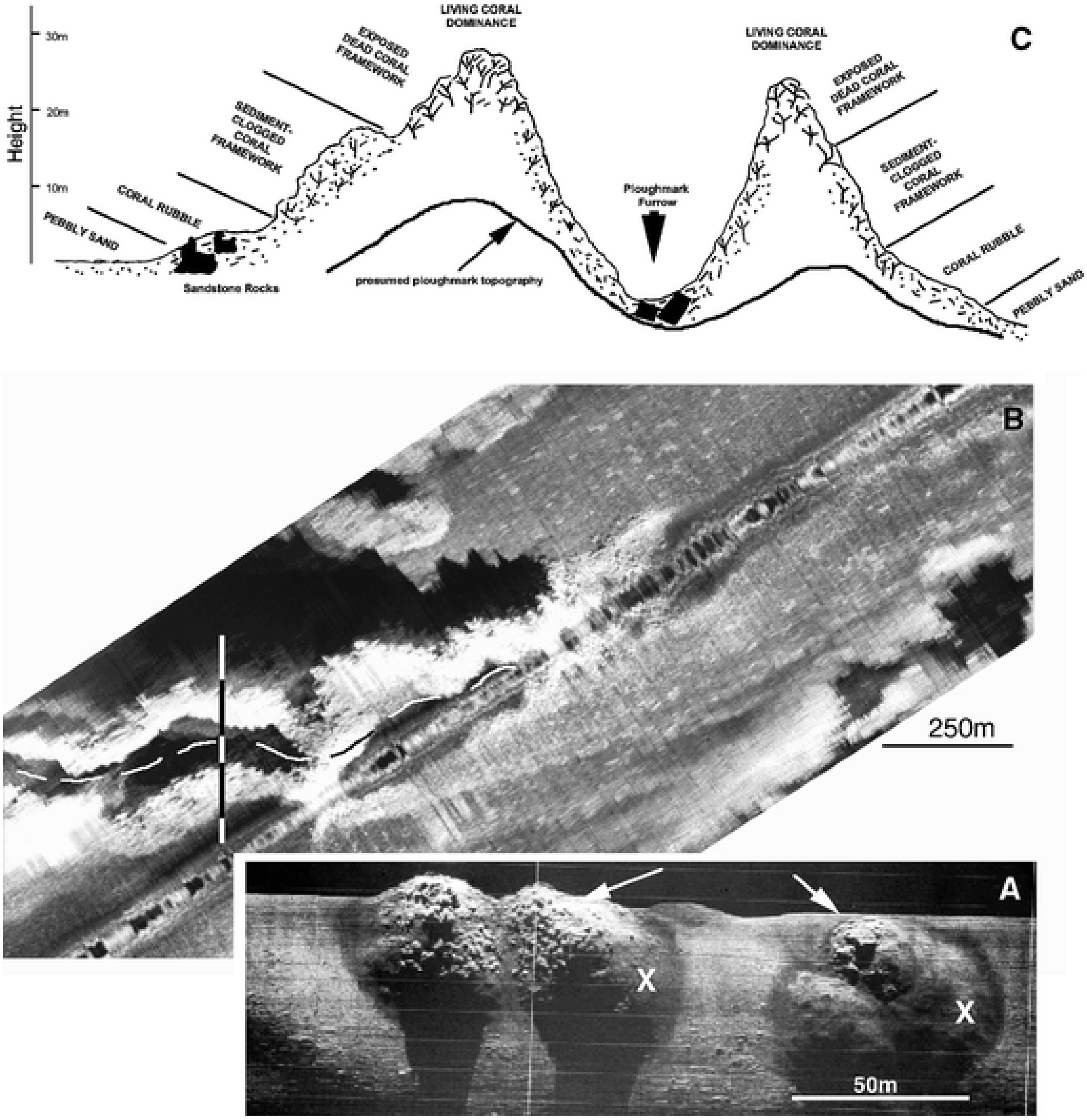

Figure 14: The Sula Reef Complex. (a) small circular *Lophelia* reefs with the cauliflower backscatter pattern (arrows) indicating the presence of metre-sized hemispheroidal coral colonies. Substantial portions of the reefs show a smooth backscatter signal (X) that represents the coral rubble facies rich in sponges (375 kHz-Sonograph). (b) A 100 kHz sonograph of a *Lophelia* reef chain growing along the boulder levees of an iceberg ploughmark (stripled line). The straight line across the ploughmark track is interpreted in **C** with the sedimentary facies succession. (c) Sedimentary facies sequence across a *Lophelia* reef complex (modified from Freiwald *et al.*, 2002).

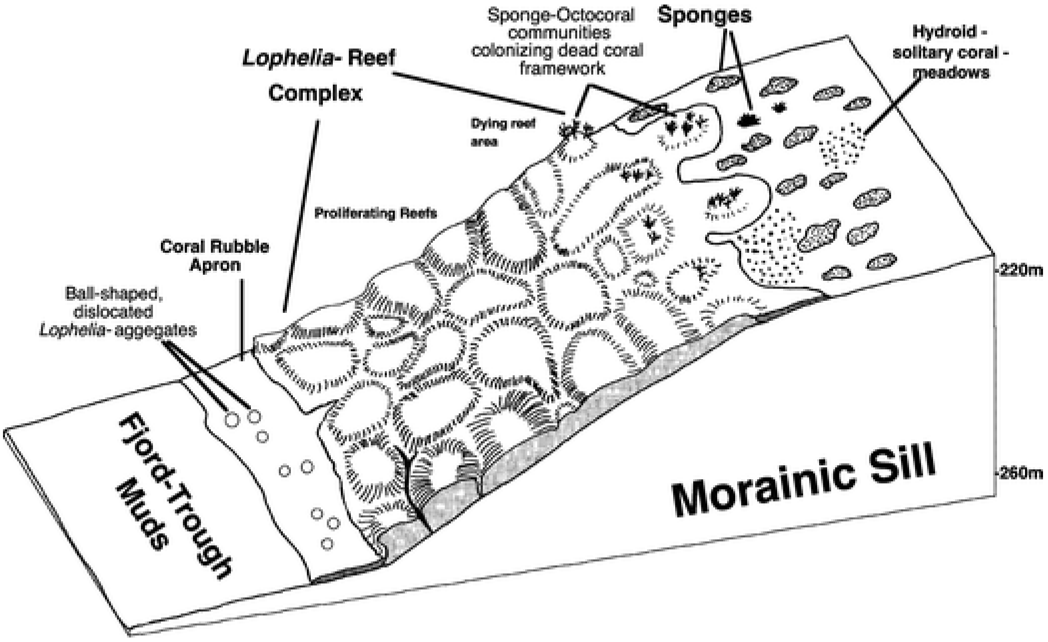

Figure 15. The Stjernsund Reef setting belongs to the northernmost biogeographic occurrence of *Lophelia pertusa*. Strikingly, the shallowest parts of the sill are colonised by sponges and anemones whereas the flank of the sill is inhabited by the coral reef (modified from Freiwald *et al*., 1997).

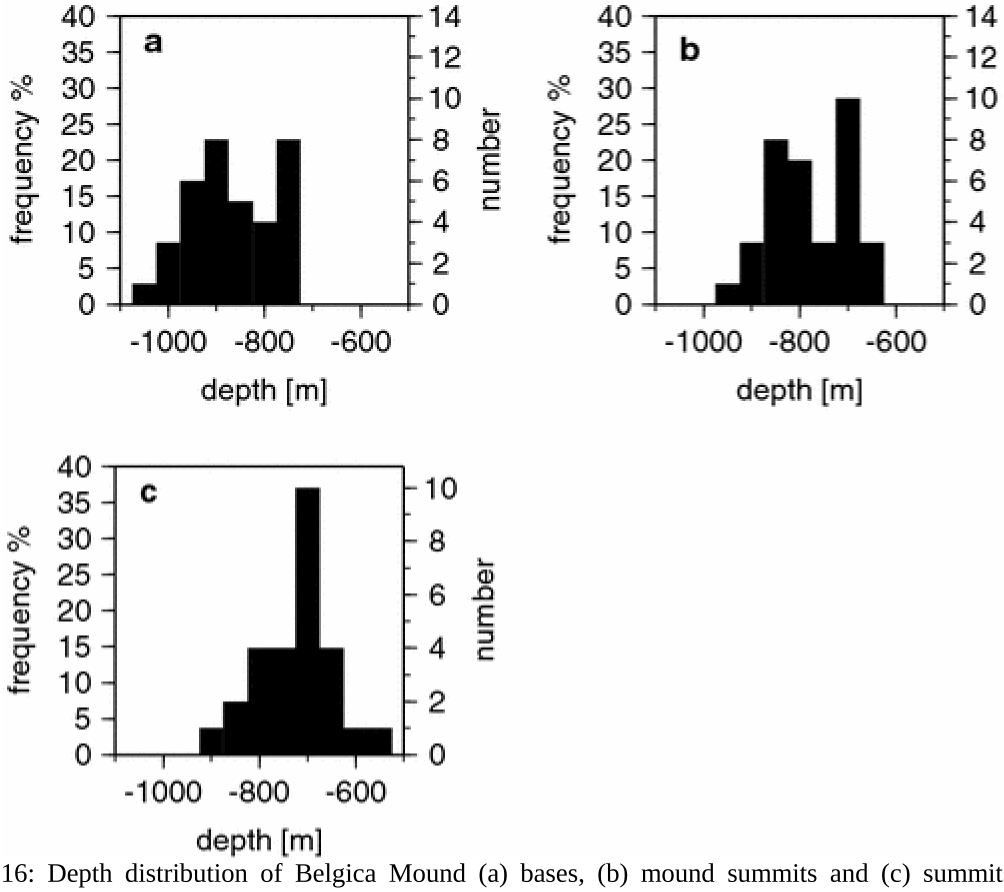

Figure 16: Depth distribution of Belgica Mound (a) bases, (b) mound summits and (c) summits of buried mounds. Two peaks are visible for the mounds accumulating in depth windows that are 100 m apart. Left scale represents frequency percent, right scale is absolute number of mounds.

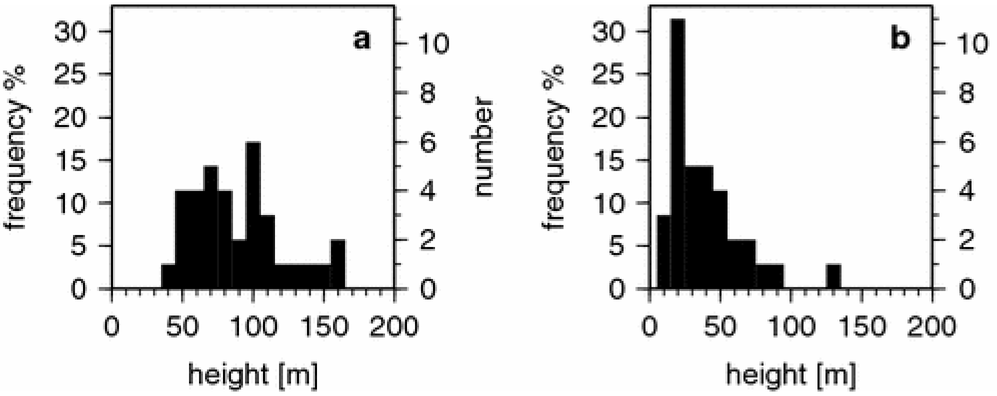

Figure 17: Distribution of the mound heights in the Belgica Mound province: (a) downslope heights of the mounds and (b) upslope heights of the mounds. Left scale represents frequency percent, right scale in absolute number of mounds.

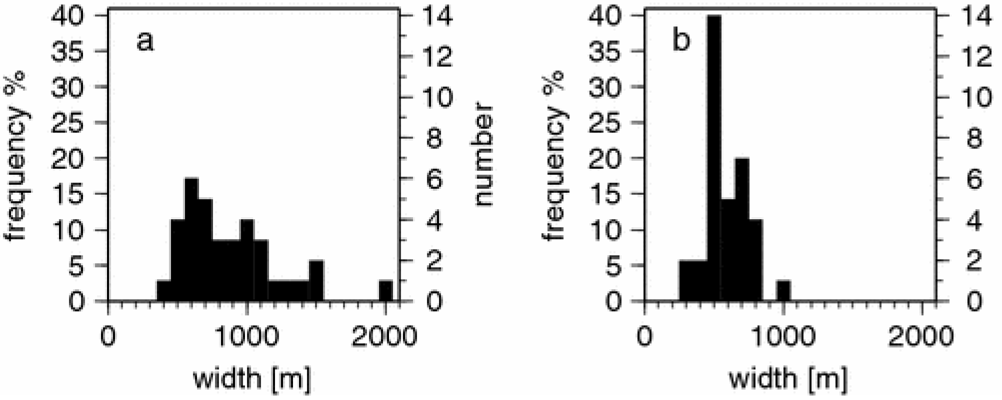

Figure 18: Distribution of the mound widths in the Belgica Mound province: (a) north-south and (b) east-west. Left scale represents frequency percent, right scale in absolute number of mounds.