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Large deep-water coral banks in the Porcupine Basin, southwest of Ireland

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Abstract

The Porcupine Basin, southwest of Ireland, was one of the earliest sites from where the deep-water corals *Lophelia* sp. and *Madrepora* sp. were recovered. These deep-water corals have since been found all along the Atlantic margins of Europe, in water depths ranging from 50 to more than 2000 m. Recent geophysical studies have demonstrated the mound-building potential of deep-water corals. Available data indicate that three major provinces of coral bank occurrences can be identified in the Porcupine Basin: (1) high-relief surface mounds which have a dimension of 1 by 5 km and a height up to 200 m ('Hovland' mounds), flanked to the north by (2) a swarm of buried mounds, somewhat smaller (up to 90 m), and with more irregular shapes than those recognised in area 1 ('Magellan' mounds), and (3) outcropping or buried, conical mounds (single or in elongated clusters, up to 150 m high) occurring on the southeastern slope of the basin ('Belgica' mounds). As far as can be inferred from shallow cores, the surface lithology predominantly consists of an upper layer rich in foraminiferal sand and terrigenous silty clay with intercalations of biogenic rubble. The banks host a remarkable number of colonies of living and dead *Lophelia pertusa* and *Madrepora oculata*. The living and dead assemblages are underlain by a significant layer of coral debris in a muddy matrix. Deep-water coral debris together with a living association of the same species covers the surface of the 'Belgica' and 'Hovland' mounds, which may suggest that these corals have played a significant role in the development of the mound structures. The capacity for mound formation by scleractinian corals in the aphotic zone has been known for some time. Examples are found at different locations along the shelves and the continental margins of the North Atlantic. The role of the corals in these deep-water build-ups is still a point of debate. Though the genesis and initial control of mound settings in this basin might be related to hydrocarbon seeps, it appears that the major development of the Porcupine coral banks in recent geological times has most likely been controlled by oceanic circulation and dynamics in water masses and nutrient supply.

Keywords: coral banks; Mediterranean outflow water; deep-water corals; Porcupine Basin; NE Atlantic

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1. Introduction

This study describes and discusses large deep-water coral banks in the Porcupine Basin, off southwest Ireland. It is based on high-resolution seismic profiles, side-scan sonar images, gravity cores, TV grabs and dredge samples (Fig. 1). Deep-water coral banks are widespread along the North-East Atlantic Margin, at shelf breaks and on the upper continental slope (Table 1). The majority of these coral banks (Table 1), whose biodiversity is comparable to those of tropical coral reef settings, are constructed by the framework builder *Lophelia* and associated fauna (Jensens and Frederiksen, 1992; Mortensen et al., 1995; Freiwald, 1998; Rogers, 1999; Hovland and Mortensen, 1999). This framework is filled by fine-grained sediment and may form large topographic features on the seafloor, resembling mounds or banks. The presence of deep-water coral banks is considered to be closely related to oceanographic conditions favourable for the azooxanthellate corals, of which nutrient supply, current activity, and slow sedimentation rate seem most important (Stetson et al., 1962; Cairns and Stanley, 1981; Mullins et al., 1981; Frederiksen et al., 1992; Freiwald et al., 1999; Mortensen et al., 1995). On the other hand, Hovland (1990) and Henriet et al. (1998, 2001) suggest that some deep-water coral banks in hydrocarbon basins may initially form in areas of seepage. In this paper we combine stratigraphic, geomorphological, sedimentological and biological data in a discussion of the oceanographic and geological setting of the large deep-water coral banks in the Porcupine Basin and test different hypotheses regarding their origin and evolution. In this paper the neutral term ‘mound’ is used for the description of the features whereas the term ‘coral bank’ is an interpretation, which cannot be confirmed without deep drilling.

The mounds in the Porcupine Basin reach spectacular size, up to 200 m high and 5 km long. They occur in three mound provinces (Fig. 1), each with a different mound type with distinct morphological features. The ‘Hovland’ mound province, in the central part of the basin, is characterised by large conical mounds or elongate ridges associated with deep moat structures at the seafloor (Hovland et al., 1994) (Fig. 2). The ‘Magellan’ mound province occurs north to northwest of the ‘Hovland’ mound province (Fig. 1) and is characterised by smaller buried mounds in a large variety of shapes (Fig. 2). The ‘Belgica’ mound province is located Southeast of the basin (Fig. 1) and is characterised by large mounds, whose downslope side is well exposed at the seafloor but the upslope flank almost entirely buried. This variety of structures in well-delineated provinces makes the Porcupine Basin a unique site to study the environmental and geological control on the origin and evolution of deep-water coral banks.

2. Geological and hydrodynamic setting of the Porcupine Basin

2.1. Geological setting

The Porcupine Seabight, off the west coast of Ireland, forms a N–S-oriented, pear-shaped embayment in the Irish Atlantic shelf (Fig. 1). It is approximately 150 km long, 65 km wide in the north and widening to 100 km in the south. Water depth increases from 250 m in the north to over 1700 m in the south. The underlying basinal structure is bound on three sides by shallow basement platforms, the Porcupine Ridge to the west, the buried Slyne Ridge to the north, and the Irish Mainland Shelf to the east. Goban Spur forms the southern limit. To the southwest, the Porcupine Basin continues into the Porcupine Seabight Basin (Fig. 1). The Porcupine Basin is a Middle to Late Jurassic failed rift of the proto-North Atlantic (Shannon, 1991). Mesozoic and Cenozoic deposits reach a maximum thickness up to 10 km, thinning to the north and to the flanks of the

Fig. 1. Bathymetric setting of the Porcupine Basin off SW Ireland (contours in m), showing locations of mounds, seismic profiles, side-scan sonographs and sample sites referred to in figures and text.

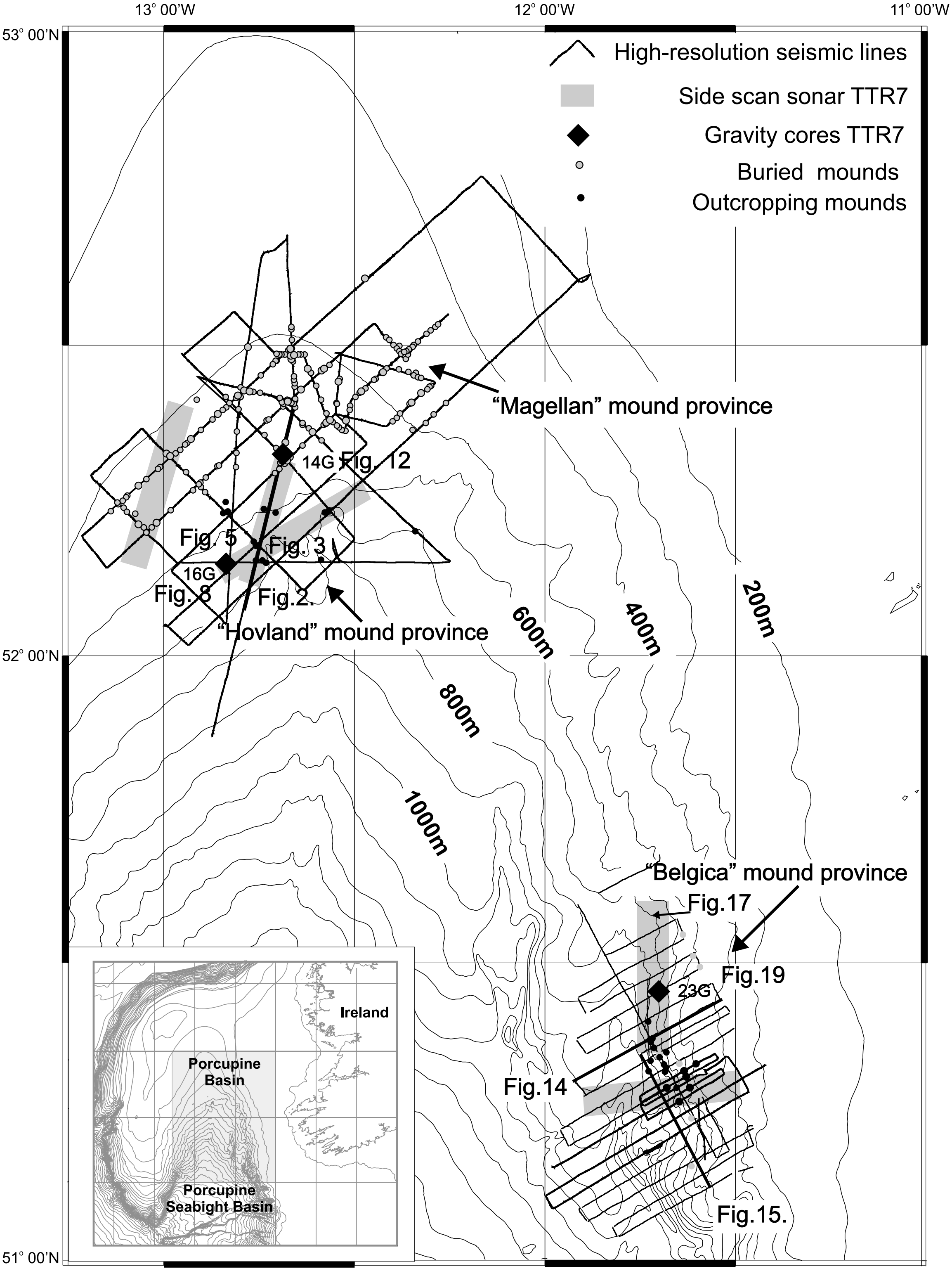

13° 00'W
12° 00'W
11° 00'W
53° 00'N
52° 00'N
51° 00'N
High-resolution seismic lines
Side scan sonar TTR7
Gravity cores TTR7
Buried mounds
Outcropping mounds
"Magellan" mound province
"Hovland" mound province
"Belgica" mound province
14G
16G
23G
Fig. 12
Fig. 5
Fig. 3
Fig. 8
Fig.2.
Fig.17
Fig.19
Fig.14
Fig.15.
200m
400m
600m
800m
1000m
Ireland
Porcupine Basin
Porcupine Seabight Basin

Table 1
Deep-water coral occurrences in the North Atlantic

Reference	Locality	Depth (m)	Temperature (°C)	Oceanography	Dimension	Classification	Predominant coral	Substratum
Norwegian coast (Mikkelsen et al., 1982)	Drøbak, Oslofjord	20–40				Bush	*Lophelia pertusa*.	
West Finnmark (Dons, 1935)	Stjernsund and Oksfjord	250–260	8–6	$S = 33.3$ ‰	$L = 10$			Hard substrate
Norwegian fjord (Strömgren, 1971)	Trondheimfjord	50–250	6–10	$S = 32–35$ ‰, strong currents	$H = 30$		*Lophelia pertusa*	
Norway (Dons, 1944)	Off Norway 57–70°N	57–300	4–6.5–8.4		$H = 60$	Banks, coppice	*Lophelia pertusa, Madrepora oculata*	
Northern Norway West Finnmark (Freiwald and Henrich, 1997; Henrich et al., 1996)	Stjernsund sill upper western slope 70°N	235–260	5–6	CS = 40 cm/s, $S = 34.5$ ‰, estuarine circulation pattern	80° slope till, 15° $H = 10$, 100 across, $W = 60$, domed reef	Framework thickness 10 m	*Lophelia pertusa*	Morainic basement, fjord
North Brattholmen (Burdon-Jones and Tambs-Lyche, 1960)	Near Bergen 60°24′30″N 5°07′E	90–110				Patch	*Lophelia pertusa*, *Madreopora* sp.	
Norwegian Shelf (Mortensen et al., 1995)	64°N Haltenbanken–Frøyabanken	240–290	250 m 7.5, 320 m 6.3	$S =$ 35.1–35.2 ‰, CS = 4–5 cm/s at 300 m	$H = 2–31$, 1500–50 600 m^2	Bioherm	*Lophelia pertusa*; associated fauna is not typical for only this habitat (Jensens and Frederiksen, 1992; Burdon-Jones and Tambs-Lyche, 1960)	Soft bottom, mixed (> 10% stones), dead, living *Lophelia* and *Lophelia* rubble
Sula Ridge (Freiwald et al., 1999)	64°N	270–310	7.8	NAC, $S = 35.05$ ‰	$L = 13\,000$, $H = 20–35$, $W = 300$	Coral reef	*Lophelia pertusa*	Sill, iceberg plough marks
Sula ridge (Henrich et al., 1996	64°N between Frøyabank and Haltenbank, NE plunging	280–310			Chain of coalesced coral mounds of $L = 4000$, $H = 20–45$	Reef	*Lophelia pertusa* and less common *Madrepora* sp.	Sill
Mid Norway (Hovland and Thomsen, 1997)	64°01′N 7°58′E	100–350			$H =$ up 30, $W = 150$, $L = 400$, NNW–SSE 50–40°slope	Bank	*Lophelia pertusa*	Clay ridge

Table 1 (*Continued*).

Reference	Locality	Depth (m)	Temperature (°C)	Oceanography	Dimension	Classification	Predominant coral	Substratum
Mid Norway coral banks (Hovland et al., 1998)	Continental shelf off Mid Norway 63°55′N, 7°53′E	220–310			$H = 31$, 57 individual banks in local clusters of up to 9 banks/km^2	Coral bank or bioherm	*Lophelia pertusa*	Subcropping bedrock, light hydrocarbon micro-seepage of thermogenic HC
European margin (Le Danois, 1948)	Off Ireland to Bay of Biscay 54–44°N	180–200	9–12			Thickets, massive	*Lophelia pertusa*, *Madrepora oculata*	
Bay of Biscay (Wilson, 1979a)	Biscay	250–1000			10–50 across	*Lophelia* colonies	*Lophelia pertusa*, *Madrepora oculata*, *Desmophyllum cristagalli*	
European margin (Le Danois, 1948)	Bay of Biscay to Cape Verde 44–15°N	600–1500	Up to 11				*Lophelia pertusa*, *Madrepora oculata*	
European margin (Le Danois, 1948)	Ireland to Northeast Africa	200–450	Up to 13				*Desmophyllum cristagalli*	
Faroe Shelf (Frederiksen et al., 1992; Jensens and Frederiksen, 1992)	61°43′4″N, 5°43′4″W, 60°33′3″N 6°32′1″W	252–260	6–8	Tidal currents, CS = 50–47 cm/s, 35 cn/s	$H = 10$, $W = 110$	Coral bank	*Lophelia pertusa*	
Around the Faroe Islands, Faroe shelf (Frederiksen et al., 1992)	Shelf and upper slope	220–300		Shelf break and upper slope internal tidal waves		Coral bank	Living and dead *Lophelia pertusa*, dead *Lophelia pertusa*	
Faroes (Frederiksen et al., 1992)	Faroe Bank	110, slope 210–446	6–8.6				*Stylasteridae*, *Lophelia pertusa*	
Faroes (Frederiksen et al., 1992)	Bill Baily Bank slope and Lousy Bank	500–1000, 730					Living *Lophelia pertusa*, *Madrepora oculata*	
Rockall Bank (Wilson, 1979c)		130–400			$H = 1$–1.5, 10–50 m across		*Lophelia pertusa*	
Rockall Trough (Kenyon et al., 1998)	Both margins, 53°45′–54°15′N and 14°15′–13°45′W, 55°20′–55°45′N and 16°–15°W	500–1000		Strong bottom currents	$H =$ up to 350, $L =$ up to 2000, subcircular NE–SW ridge	Carbonate mud mounds	*Lophelia pertusa*, *Madrepora oculata*	Upper slope, volcanic? Erosive surface
Porcupine Basin (Le Danois 1948)			8–12°		$H = 61$	Massif Bank	*Lophelia pertusa*, *Madrepora*, *Caryophyllia*, *Desmophyllum*, *Dendrophylia*, *Solenosmilia*	

Table 1 (*Continued*).

Reference	Locality	Depth (m)	Temperature (°C)	Oceanography	Dimension	Classification	Predominant coral	Substratum
Porcupine Bank (Scoffin and Bowes, 1988)		100–200 250–500			5.5 m across, $H = 1$ m	Coral patches	*Lophelia pertusa*, *Stylaster* sp.	Coarse lithic fragments near the margin of the bank. Tens to hundred metres apart, 250–500
Porcupine Basin (this paper; Henriet et al., 1998)	Belgica mounds, 51°10′N–51°35′N and 11°45′W–11°30′W	600–900	9.5–8.5	Strong bottom currents, MOW, seepage?	$H = 70–190$, $L = 4$ km, $W = 1$ km	Coral banks, carbonate mounds	*Madrepora occulata*, *Lophelia pertusa*	
Porcupine Basin (this paper; Hovland et al., 1994)	Hovland mound, 52°30′–52°N and 12–13°W	725–900	9–8.5	Strong currents, MOW? seepage?	$H = 100$ m, $L = 5.$m composite, $W = 1$ km, across = 1 km, total thickness 250 m	Coral bank, carbonate knolls, pseudobioherm	*Madrepora occulata*, *Lophelia pertusa*, *Desmophyllum*	
Porcupine Seabight (Tudhope and Scoffin, 1995)	Gollum Channel, 11°10W 50°40′N	725–920			25 m across	Patches	*Lophelia pertusa*	
British waters (Wilson, 1979b)	Scottish and Inner Hebrides	190–300			$H =$ up 18 m		*Lophelia pertusa*	
Gulf of Mexico (Moore and Bullis, 1960)	Mississippi Delta (27°N)	450–550	10.4		$H = 55$ m, small hillock	Banks	*Lophelia pertusa*	
Gulf of Mexico (Moore and Bullis, 1960 in Stetson et al., 1962)		512	10.4		320 m diameter, $H = 55$ m	Hillock	*Lophelia pertusa* and *Caryophyllia* sp.	
Gulf of Mexico (Ludwick and Walton, 1957 in Stetson et al., 1962)		100–180	18	$S = 32–37$‰	400 m across, $H = 9$ m	Pinnacle		
Off Central Eastern Florida (Reed, 1992)	Off Florida 27.5–28.5	70–100	7.5–15–26.5		About 25 m	Banks and thickets	*Oculina varicosa*	
Straits of Florida (Neumann et al., 1977)	Off little Bahama Bank (28.5°N)	500–700	5.5–10			Lithoherm	*Enallospammia profunda*	
Straits of Florida (Neumann and Ball, 1970)	Off Miami 26°N	825				Thickets	*Enallospammia profunda*, *Lophelia pertusa*	
Lithoherms in Blake–Bahama (Neumann and Paull, 1998)	Florida-Hatteras slope and extending 440–800 m on the inner Blake Plateau	400–800		CS = 100 cm/	Lithoherm complex: $W = 400$ m, 4.4 km long and $H = 150–50$ m, 30–60°	Lithoherm	*Lophelia pertusa*	

Table 1 (*Continued*).

Reference	Locality	Depth (m)	Temperature (°C)	Oceanography	Dimension	Classification	Predominant coral	Substratum
Lithoherms Northeastern Straits of Florida (Messing et al., 1990)	Western margin of Little Bahama Bank	500–700	10–12	Northerly bottom, CS = 10–20 cm/s, crest 100 cm/s	Elongated, $L = 300$ m, $H = 50$, 60° slopes till scarps	Lithoherm	*Gerardia* sp., *Lophelia pertusa*	Hardground of authigenic carbonate
Little Bahama Bank (Mullins et al., 1981)	North of Little Bahama bank 27.5°N	1000–1300	4–6		$H = 5$–40	Banks	*Solenosmilia variabilis*	
North of Little Bahama Bank (Mullins et al., 1981)	Patchy distribution in 2500 km^2	1000–1300	4–6	Antilles Current flows SE–NW, Florida current to form the Gulf stream, CS = 50 cm/s, $S = 34.5$–35.5 ‰	$H = 5$–40	Colony, thicket to coppice to bank	*Bathypsammia*, *Caryophyllias*, *Deltocyathus*, *Desmophyllum*, *Enallopsammia*, *Javania*, *Madrepora*, *Polymyces*, *Solenosmilia*, *Stephanocyathus* absent, *Lophelia* and *Dendrophyllum*	
Little Bahama Bank (Paull et al., 2000)	Hatteras Slope	440			$H = 150$, $L = 4400$, $W = 400$	Lithoherm	*Lophelia pertusa*	
Blake Plateau (Stetson et al., 1962)	Blake Plateau (30–34°N)	670–840	6–10		$L = 146$	coral bank	*Enallospammia* (*Dendrophyllia*) *profunda*, *Lophelia pertusa*	
Coral banks on the Blake Plateau (Stetson et al., 1962)	265 km southeast of Charleston, South Carolina 3108–3885 km^2, 31°45′N–32°10′N/77°45′W and 77°20′W	510–870	7–10	$S = 35$ ‰	200 features, $H = 10$–150, $L = 1200$, 800 across	coral banks	*Lophelia pertusa*, *Dendrophyllia pertusa*, *Lophelia* is dominant on the top of the bank, *Dendrophyllia* in general	North–south trend on the crest of an escarpment, smaller banks surrounding the escarpment. Substratum carbonate rock

S = salinity in ‰ ; CS = current speed in cm/s; L = length in m; H = height in m; W = width in m.

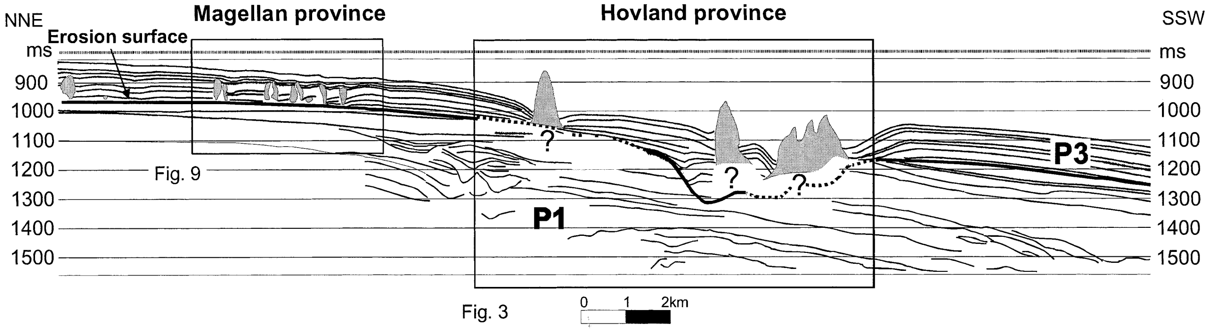


Fig. 2. Interpretation of high-resolution profile P970502c across the Magellan and Hovland mound province. This line drawing illustrates the seismic facies P1 and P3 separated by an erosional event.

basin. The basin contains proven hydrocarbons, with four significant discoveries in rocks of Jurassic and Cretaceous age (Croker and Shannon, 1987).

Few studies concern the Quaternary sedimentation in the Porcupine Basin. Pelagic to hemipelagic sediment deposition dominates most of the present-day sedimentation. Only at the southern part of the basin a well-developed channel system, the Gollum Channel, occurs on the slope and basin floor. The Gollum Channel forms the downstream component of a large fluvial system which extended onto the southern Irish shelf during sea-level lowstands in glacial periods. Wallace et al. (1988) measured in cores from the abyssal plain at the mouth of the Seabight an abrupt decrease in sedimentation rate from 13 cm/1000 yr during the last Glacial to 3.5 cm/1000 yr in the Holocene. Some channels remain active, transporting sediments at present (Wheeler et al., 1998). The Gollum Channel terminates on the Porcupine Abyssal Plain, but there is little evidence for a large fan system. According to Rice et al. (1991) sediment may have been reworked and redistributed in drift deposits by strong sea bottom currents in the Porcupine Abyssal Plain.

Minor channels are observed further north on the eastern slope of Porcupine Basin. These channels probably originated from glacio-fluvial erosion on the western Irish shelf during glacial periods but are most likely not active today (Wheeler et al., 1998). Iceberg ploughmarks on the seafloor (between 140 and 500 m water depth) of the Porcupine Bank (Belderson et al., 1973) and on the northern slope of the Porcupine Basin (300 m) (Colpaert, 2000) demonstrate the glacial influence on Quaternary sedimentation.

2.2. Hydrodynamic setting

The general hydrography of the Porcupine Basin is described by Hargreaves (1984), Ellet et al. (1986), and Vangriesheim (1985) and reviewed by Rice et al. (1991) and Vermeulen (1997). Eastern North Atlantic Water (ENAW) is found to a depth of about 750 m in the mouth of the Porcupine Seabight and along the eastern flank of the Porcupine Bank, where it overlies Mediterranean Outflow Water (MOW). The MOW is characterised by a salinity maximum and an oxygen minimum at a depth of about 950 m. Below the MOW, the influence of the Labrador Sea Water is expressed by a salinity minimum and oxygen maximum at about 1700 m depth. There is a permanent thermocline from about 10°C to about 4°C at a water depth of 600 m to 1400 m. A seasonal thermocline forms at about 50 m depth.

Data produced by Rice et al. (1991) from long-term Bathysnap deployments at 1300 m in the northwestern part of the Porcupine Basin, and at 4000 m at the mouth of the Porcupine Seabight, show dominant northward along-slope currents following the local topography. A north-flowing current is known to exist along most, if not all, of the North-East Atlantic Margin, from the Iberian Margin to the Norwegian Sea (Huthnance and Gould, 1989; Pingree and LeCann, 1989, 1990). Two Bathysnap deployments at about 2000 m in the centre of the Porcupine Seabight show more variability in both direction and speed. Current reversals at these sites indicate a complex current pattern (Rice et al., 1991). The intermediate water masses show a considerable overlap, which allows both diapycnal and isopycnal mixing. The presence of the continental shelf edge may enhance the diapycnal mixing (Garrett, 1991) and force the circulation near the margin to be aligned with the topography (van Aken, 2000). Pingree and LeCann (1989, 1990) and Rice et al. (1991) measured over a 9–12-month interval at various sites, between 800 and 1000 m in the Porcupine Basin, a mean northward current of MOW with a speed of 3–10 cm/s near the seafloor. van Aken (2000) suggests that due to the deep winter convection, supported by the cascading of winter water from the Celtic continental shelf, the effects of the MOW seasonally change in the Porcupine Seabight.

3. Data

The data available for this study include high-resolution seismic profiles (*Belgica* 1997 and 1998 cruises), side-scan sonar images (TTR7-CORSAIRES cruise), and short gravity cores (TTR7-CORSAIRES cruise) (Fig. 1). The data were acquired in the framework of two European Mast III projects, ENAM and CORSAIRES, in cooperation with the UNESCO–IOC ‘Training Through Research’ programme. They paved the way for the new European projects GEOMOUND, ECOMOUND and ACES, which respectively focus on internal controls on mound genesis, external controls on mound development and the role of deep-water corals.

About 1400 km of high-resolution seismic data were obtained in the Porcupine Basin during two seismic surveys with R/V *Belgica*, in 1997 and in 1998. Two seismic grids with an average line spacing of 5 km were acquired in the Belgica mound province along the eastern slope of the basin, and in the Hovland and Magellan mound provinces in the north. The seismic source was a SIG sparker fired at 500 J. At this energy level, the seismic signal frequency ranges from 200 to 3000 Hz.

During the TTR7-CORSAIRES cruise (Kenyon et al., 1998), 120 km of side-scan sonographs were recorded, 80 km in the Hovland–Magellan provinces and approximately 40 km in the Belgica province. The OREtech system was operated at 30 kHz and towed about 130 m above the seafloor. The sea bottom was imaged over 1 km at either side of the track line with a resolution of 0.4 m.

During the same cruise, a total of 25 gravity cores, with a recovery of 1–4 m, were taken at the top and flanks of several mounds and in the adjacent moats (Kenyon et al., 1998). The crest of a Hovland mound has been sampled for biological analysis with means of two TV-controlled grab deployments, as well as a site on the crest of a Belgica mound. Two dredge samples have been taken on Hovland mounds (Kenyon et al., 1998).

4. General aspects of the mounds in Porcupine Basin

The occurrence of high concentrations of cold-water corals (e.g. *Madrepora*, *Lophelia*) in the Porcupine Basin was first described by Thomson (1873) and Le Danois (1948), who however did not recognise the large seafloor mounds. The mounds cluster in two major geographical locations: in the southeast part and in the central part of the Porcupine Basin. Based on mound morphology and their exposure at the seafloor, three mound types can be identified, each type occurring in a geographically well-delineated mound province (Fig. 1).

- The Hovland mound province, named after their first description by Hovland et al. (1994), is situated on a gentle slope break in the central part of the basin. These outcropping mounds have a conical shape and occur as single build-ups or in elongated clusters. They are typically flanked by deep moat structures.
- The Magellan mound province flanks the Hovland province to the north, on a very gentle slope. The Magellan mounds were named after the commercial survey ship R/V *Svitzer Magellan* that discovered the features in November–Decem-

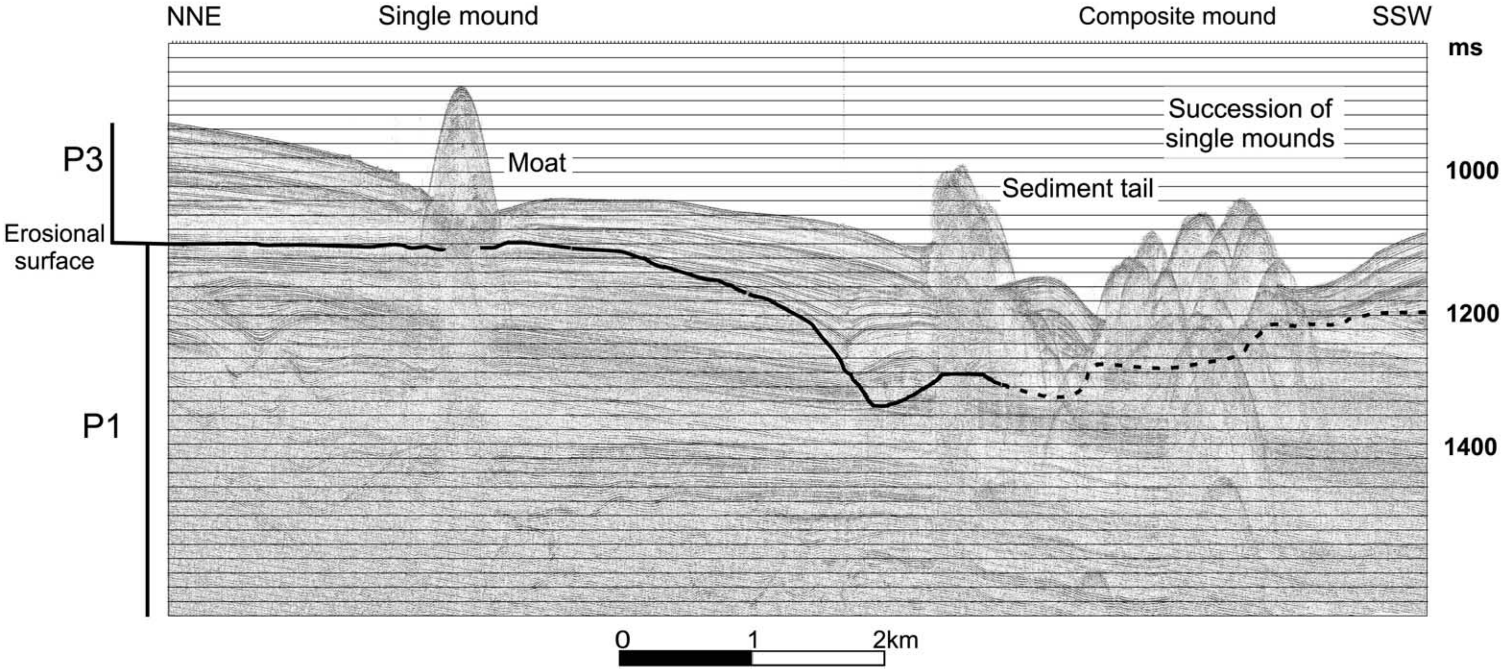


Fig. 3. Zoom of Fig. 2 This part of profile P970502c in the Hovland mound province illustrates single and composite mounds, the associated moats, the depositional sediment tail, and the characteristics of seismic facies P1 and P3.

ber 1996. With the exception of a few outcropping mounds at the western boundary of the Magellan province, most mounds are buried features, only visible on seismic sections. They occur in large numbers in a very well-delineated area and are characterised by a wide variety of mound shapes and sizes.

- The Belgica mound province is situated in the southeast part of the basin, north of the Gollum Channel system. Belgica mounds are named after the oceanographic research vessel R/V *Belgica*, which discovered the mounds during a survey in May 1997. The Belgica mounds are outcropping or buried conical mounds (single, or in elongated clusters) and occur on the eastern slope within a bathymetric interval of 200 m over a distance of 20 km. They typically feature sediment tails at their upslope side, which is consequently buried, while their seaward side is well exposed and forms a steep step in the bathymetry.

The base of the Hovland mounds is poorly imaged due to numerous diffraction hyperbolae and side echoes, but it appears that they occur on top of an important erosion surface (Fig. 3), the top of a thick cut-and-fill type facies (seismic facies P1 of possible Pliocene age). The recent sedimentary sequence in which the mounds are embedded (seismic facies P3 of estimated Late Pliocene–Pleistocene age) is characterised by a subparallel to parallel seismic facies with continuous reflections of varying amplitude. In the Belgica mound province, Late Pliocene–Pleistocene deposits appear to consist of a sediment drift which was redistributed by northward bottom currents (see 2.2. Hydrodynamic setting). In the Magellan–Hovland area, the effect of strong bottom currents is also visible on the seafloor but sediment supply is mainly from the Irish shelf to the east (see 6. The Magellan mounds). Unfortunately, an unambiguous correlation of the topmost sedimentary facies between the central and Southeastern part of the Porcupine Basin is not yet possible.

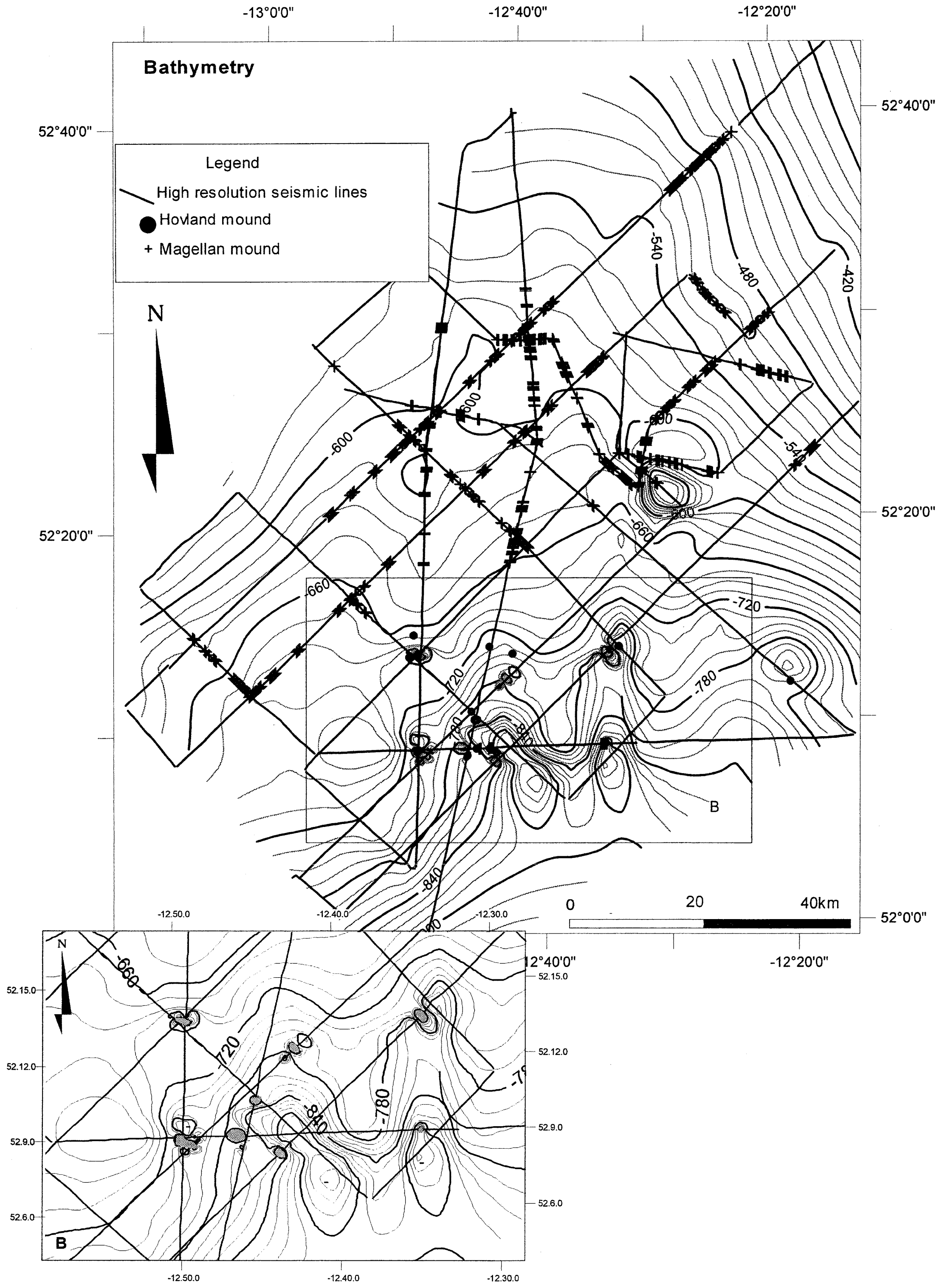
No clear indications of past migration, as columnar disturbances (Hovland and Judd, 1988) or escape structures have been observed on the seismic profiles (Fig. 3). Some irregular reflections below the mounds could be interpreted as columnar disturbances but are probably due to signal absorption and velocity effects caused by the rapid changes in seafloor elevation and sedimentologic facies in the mound provinces. Other artefacts are hyperbolic reflections from mound tops and discontinuous high-reflective events within the mounds as well as side-echoes from nearby mounds. Such artefacts are not consistent on crossing lines and can be easily identified.

5. The Hovland Mounds

The Hovland mounds occur in the central part of the Porcupine Basin between 52 and 52°30′N and 12 and 13°W, in water depths ranging between 725 and 900 m. They are located close to a roughly north–south-trending seafloor depression (Figs. 2 and 4).

5.1. Seismic description

In the Hovland mound province, 31 mounds have been described by Hovland et al. (1994) on base of a grid of industry reflection seismic data. Only 16 seabed mound structures have been observed on the seismic sections presented in this paper, and four of them have also been imaged on side-scan sonar data (Fig. 5). The seismic character inside the mounds is almost reflection-free, although a few high-amplitude patches occur, possibly from side reflections. Hovland mounds occur as single conical mounds or elongate composite mounds (Fig. 3). Typically, a single mound measures about 1 km across and has a height of about 100 m above the seafloor. The largest structure observed on seismic and side-scan data is an elongated composite mound composed of single conical units, coalescing into a sinuous pattern. It is about 5 km long, with a maximum width of about 1 km and it covers an area of c. 5.5 km^2. It stands 150 m above the surrounding seafloor and reaches a total thickness of about 250 m. Linear segments of composite mounds are mostly oriented NE–SW to NW–SE, apparently independent of bathymetry; their relationship to structural lineaments is unclear at present. In general the mounds have an average slope of


Bathymetry
Legend
High resolution seismic lines
● Hovland mound
+ Magellan mound
N
-13°0'0"
-12°40'0"
-12°20'0"
52°40'0"
52°20'0"
52°0'0"
-420
-480
-540
-600
-660
-720
-780
-840
B
0
20
40km
-12.50.0
-12.40.0
-12.30.0
52.15.0
52.12.0
52.9.0
52.6.0
-660
-720
-780
-840
B

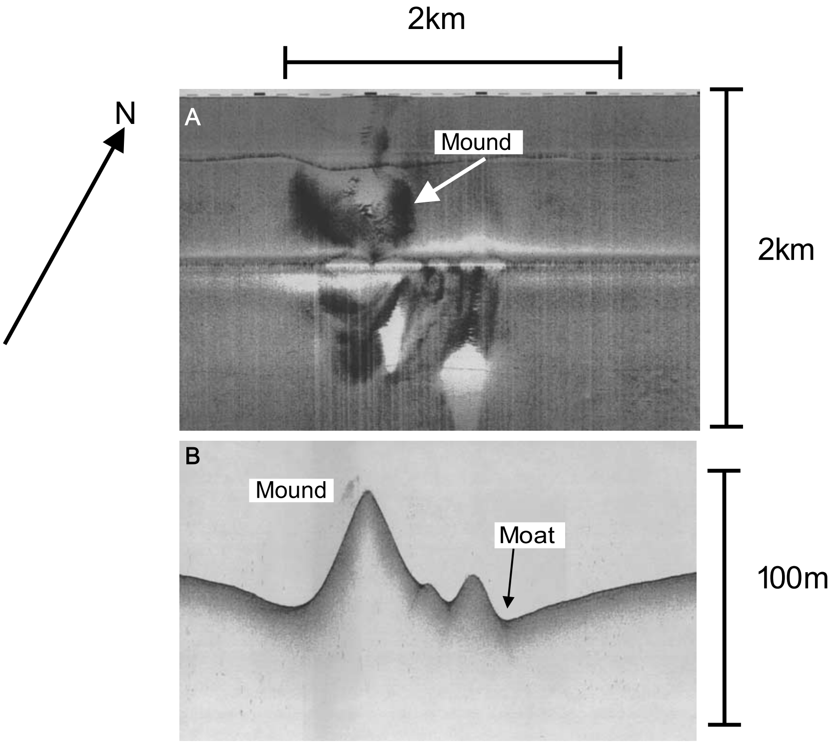


Fig. 5. Side-scan sonograph (part of TTR7-AT-Orat 1) and 6.5-kHz profiler of a mound in the Hovland province (Wheeler et al., 1998). The sonograph illustrates the complex shape of the mound and associated moats.

10°. The steepest flanks are located just below the crest, with slopes up to 25°.

The Hovland mounds root on an erosional surface, the youngest boundary of a complex cut-and-fill system (Figs. 2 and 3). This system filled a large erosional depression, which is deepest below two N–S to NW–SE channel-like depressions in the present-day topography. Hovland mounds appear to cluster around this depression (Figs. 4 and 6).

The seabed mounds are flanked by erosional moats formed by bottom currents (Figs. 3–5). The moats are elongated in shape and have a length on the seismic profiles ranging from 1 to 3 km. Moat depths vary from 20 m up to 150 m. They occur on all sides of the mounds but are not always symmetrical. The seismic profiles document in most cases large differences in depth, onset of erosion, and timing of maximum activity in moats on different sides of the mounds. No clear trend however can be identified. Such differences may indicate variations in the current pattern but also migration of moats in time, possibly in pace with the development of the mound.

The mounds are embedded in a recent sediment drape (Unit P3), of probably Late Pliocene–Pleistocene age. The seismic facies of the drape is characterised by continuous parallel or subparallel reflections of medium amplitude (Fig. 3). The unit

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Fig. 4. (A) Bathymetric map based on seismic profiles. The Hovland province occurs around two N–S- and NW–SE-oriented irregular erosional incisions. The Magellan province is located to the north in an almost flat present-day topographic area. (B) Detailed bathymetry map based on seismic profiles and side-scan sonar sonographs. Hovland mounds occur at the perimeter of the erosional depression and are flanked by current induced moats. Mounds are indicated in grey.

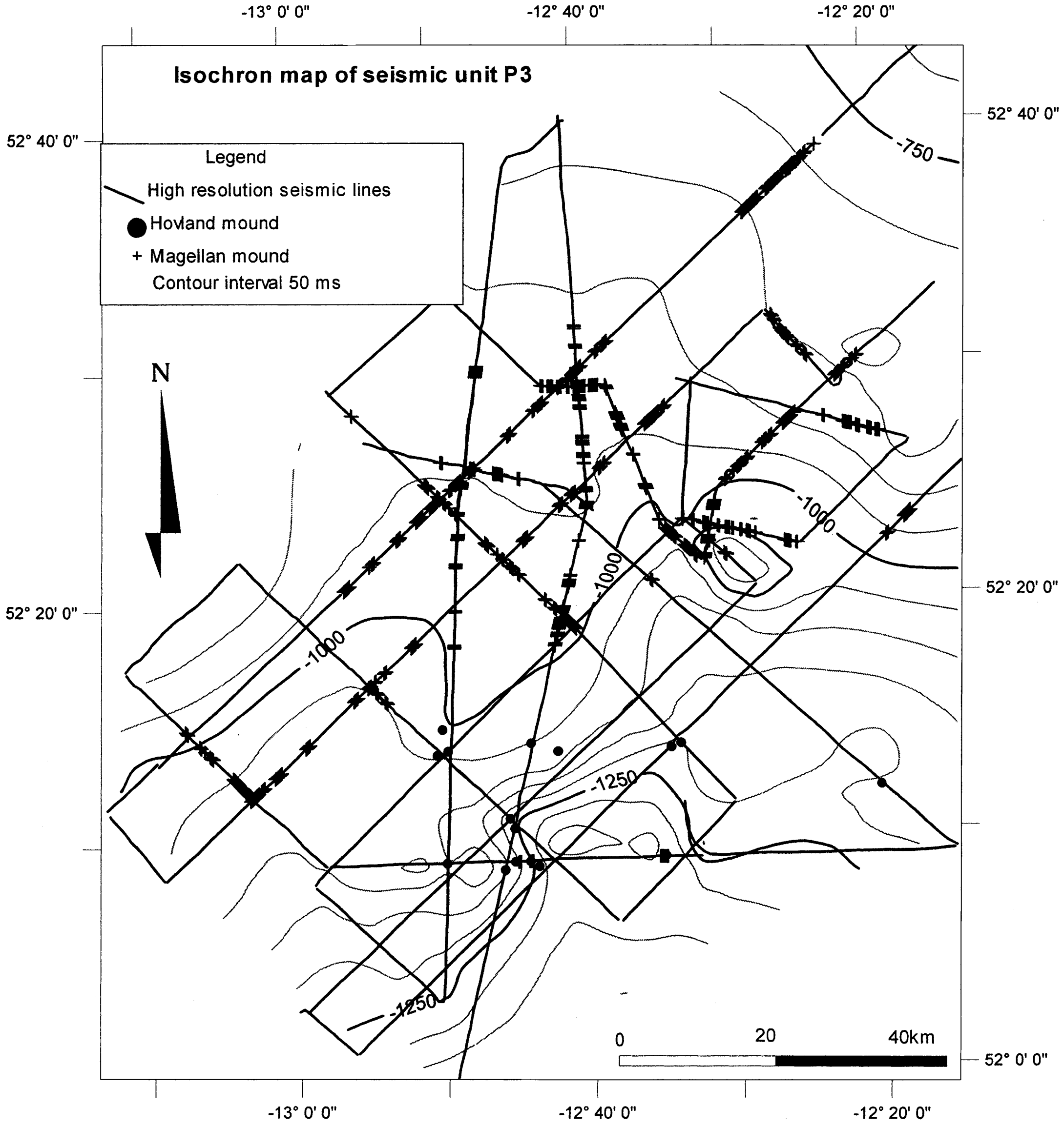


Fig. 6. Time–structure map in ms TWT of the erosional surface between seismic facies P1 and P3 in the Hovland and Magellan mound provinces (see Figs. 2 and 7) based on seismic profiles.

thickens to the east, towards the Irish continental shelf. The minimal thickness occurs in a 10 km wide zone stretching northwards from the Hovland mound cluster (Fig. 7). The fill in the centre of the erosional incision creates a local depocentre. Erosional moats and depositional tails flanking the seabed mounds also create local variations in thickness (Fig. 7).

5.2. Sedimentology

On-mound cores (six TTR7 cores and four out of Coles et al., 1996) are intensely bioturbated and the matrix is dominated by nannofossil ooze and terrigenous siliciclastic components (Coles et al., 1996; Swennen et al., 1998). They also contain a large amount of bio-detritic material, corals and

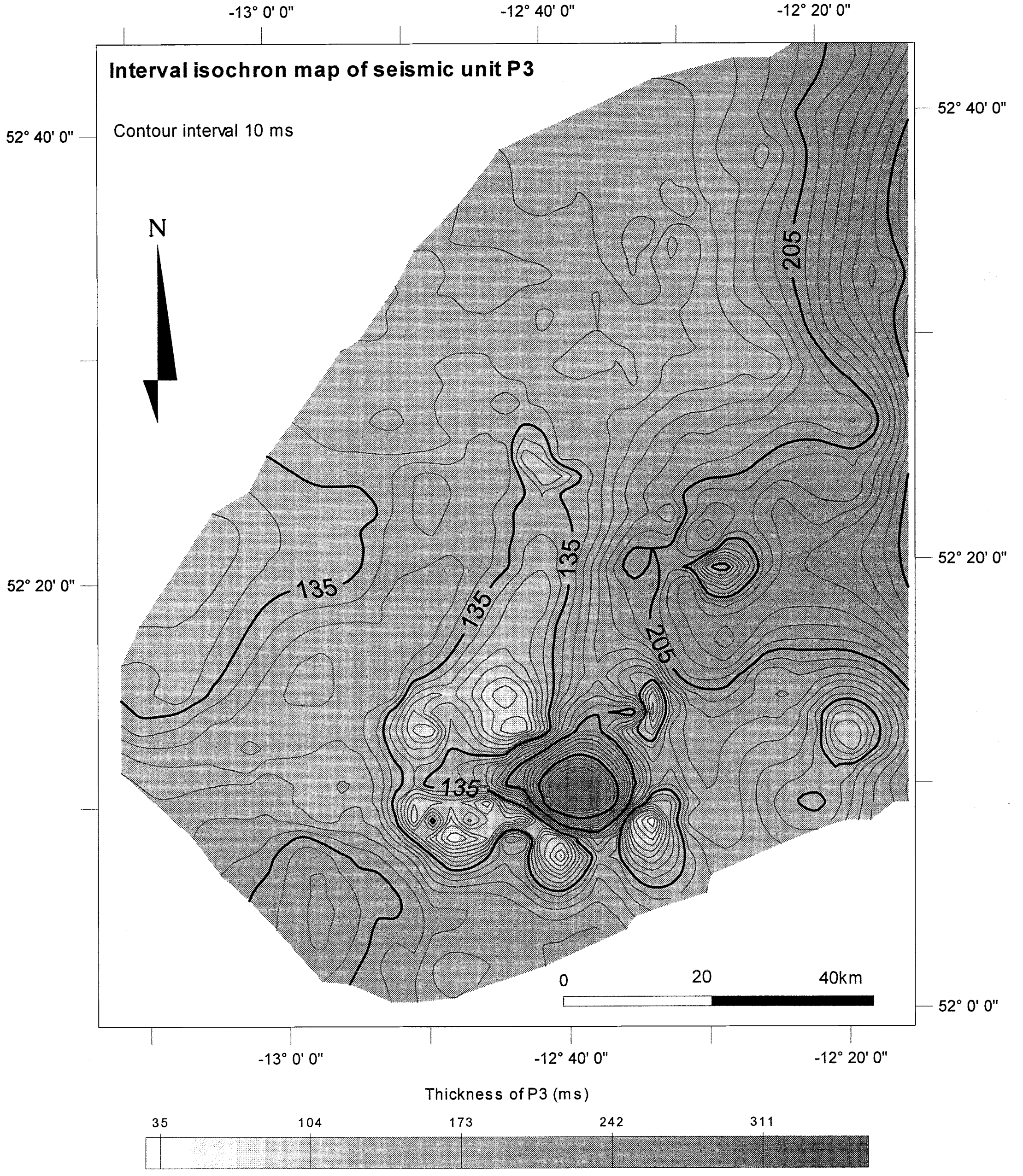


Fig. 7. Interval isochron map in ms TWT of seismic Unit P3. Remarkable is the thinning of seismic facies P3 in the vicinity of the mounds and the occurrence of a N–S-trending zone of minimum thickness.

shells. On-mound cores generally comprise an upper surface layer of yellow foraminiferal sand with occasional azooxanthellate corals (dominating species are *Madrepora* and *Lophelia* as well as *Desmophyllum* and the hydroid *Stylaster*), shell fragments and echinoderm spines. This surface layer covers a sequence of silty-clayey units alternating with sands containing coral and shell fragments. The siliciclastic sand content is variable but generally low and the clay fraction steadily

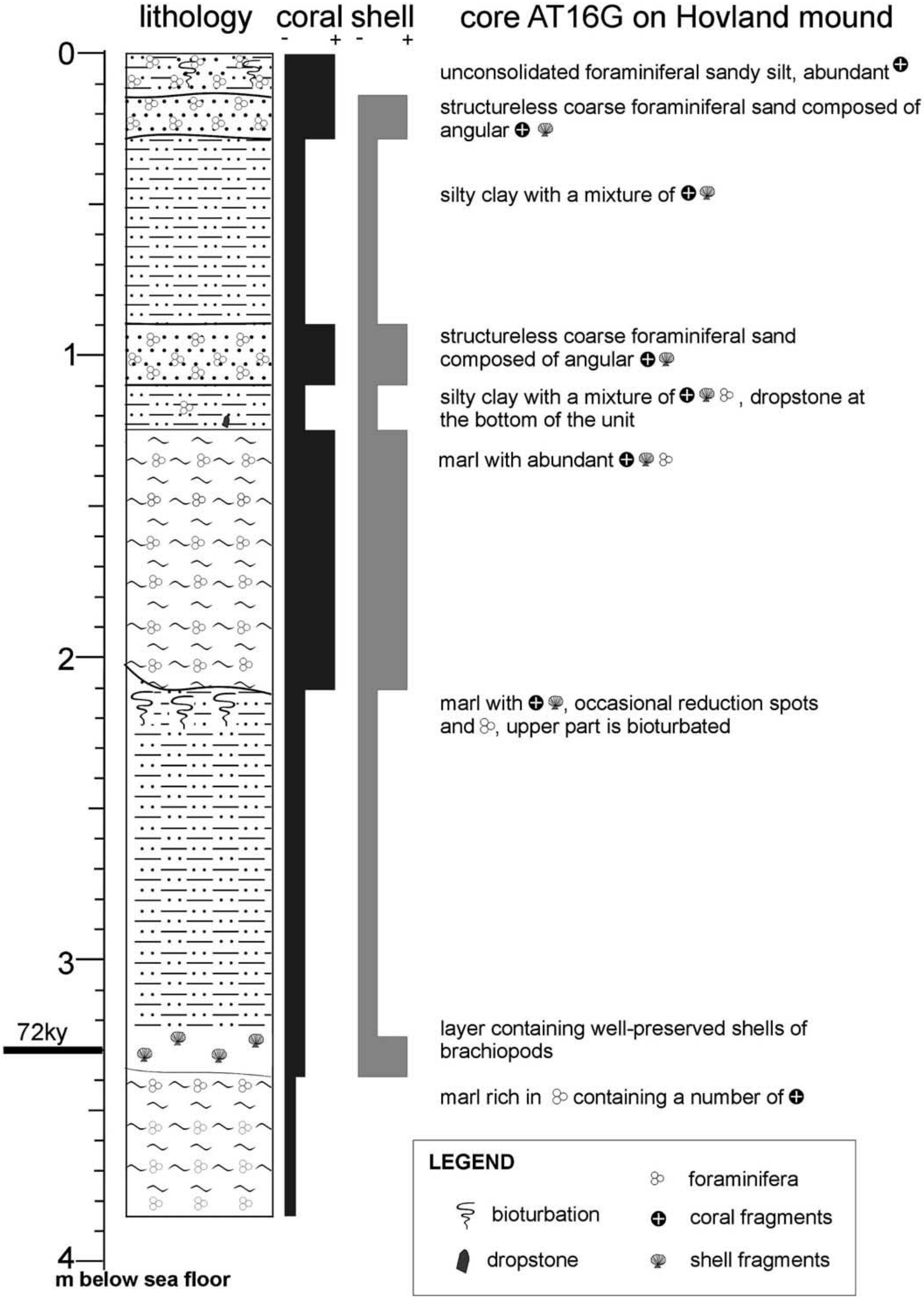


Fig. 8. Description of core AT-16-G taken on the upper flanks of a Hovland mound (Swennen et al., 1998). See Fig. 1 for location.

increases downwards. The amount of coral fragments is highest on the upper flanks of mounds and decreases to the crest and to the lower flanks. The carbonate fraction is composed of coccoliths, foraminifers, spicules of octocorals, gastropods, crustaceans and coral rubble.

The off-mound samples (Coles et al., 1996; Swennen et al., 1998) are dominated by fine-grained nannofossil ooze and terrigenous siliciclastic grains. Generally, the surface layer consists of soft homogeneous bioturbated olive brown to olive, clayey sand that overlies a soft greyish brown to brown silty clay, often with black organic-rich material. The carbonate content is less in these cores than the on-mound cores.

Core TTR7-AT-16G (Fig. 8) with a recovery of 389 cm is located on the upper flank of a large complex mound located at 52°08.80′N and 12°19.80′W, in a water depth of 691 m (Swennen et al., 1998). The upper 111 cm of the core consist of light olive brown (2.5Y 6/3–5/3) silty clay with coarse, angular, grey to greyish brown, clast-supported sand intervals. Numerous angular coral and other bioclastic fragments occur at 15–30 cm and 89–111 cm. One large (1 cm diameter) coral was located at 106 cm. The interval between 111 and 205 cm comprises a strongly bioturbated marl with foraminiferal, shell and coral fragments. It is associated with colour changes (5Y 5/3–2.5Y 6/2), mottling and strong burrowing. Some of the burrows are filled with a grey, soupy mud. The deepest interval (206–389 cm) is composed of greyish brown to dark and light grey (2.5Y 7/0) marls, which coarsen downwards to silty foraminiferal marls. Scattered black (reduction) spots, coral fragments and shells are found in this interval. Coles et al. (1996) analysed a similar core on the Hovland mounds on the biostratigraphy (Foraminifera, Ostracods and Dinocysts). According to his results it seems that the upper 2 m of sediment ranges from Late Pleistocene to Holocene in age. Age estimations based on calcareous nannofossil (Coccolithophores, Foraminifera) biostratigraphy of core TTR7-AT-16G (Saoutkin, 1998) provide an approximate age of 72 kyr at 3.3 m sediment depth. If the inferred sedimentation rate is extrapolated to the base of this particular mound, mound initiation would have occurred during the Late Pliocene, about 2.2 Ma BP.

6. The Magellan mounds

The Magellan mound province is situated north and northeast of the Hovland mounds, between 52°12′N and 52°38′N and 12°22′W and 13°08′W, in water depths of 450–700 m (Fig. 4). The mound province has a clear-cut crescent-shaped outline with a surface area of about 1200 km^2 and is separated from the Hovland mound province by a 4–10-km-wide zone which lacks any indication of mound structures. In contrast with the Hovland and Belgica mounds, Magellan mounds are very numerous: 224 buried mounds were observed on 250 km of seismic lines.

6.1. *Seismic description*

With only few exceptions, all mounds in the Magellan province are buried and embedded in seismic facies P3 of Late Pliocene–Pleistocene age (Fig. 2). The mounds are characterised by an acoustically transparent facies and are up to 100 ms two-way travel time (TWT) (about 80 m) high and 300–800 m across (Fig. 9). The mounds appear to be larger in the southern part of the Magellan province and become smaller to the northeast, the direction of the greatest thickness of the sediment drape (Fig. 7). At least three mounds in the Magellan province reach the present-day seafloor, others are buried by up to 100 ms TWT (about 80 m) of sediment. In contrast to the conical Hovland mounds, Magellan mounds are predominantly vertical, stock-like features with a convex, often wider, top. The mounds occur close to each other and show different configurations (Fig. 10). Some occur in symmetric (Fig. 10B) or asymmetric (Fig. 10D) twin patterns, which may suggest sections through ring structures (Henriet et al., 1998) or profiles through adjacent mounds. The mounds are outlined by abrupt reflection terminations of the embedding horizons (Figs. 9 and 10). Such horizons progressively onlap the higher parts of the mounds, and finally mould the convex top.

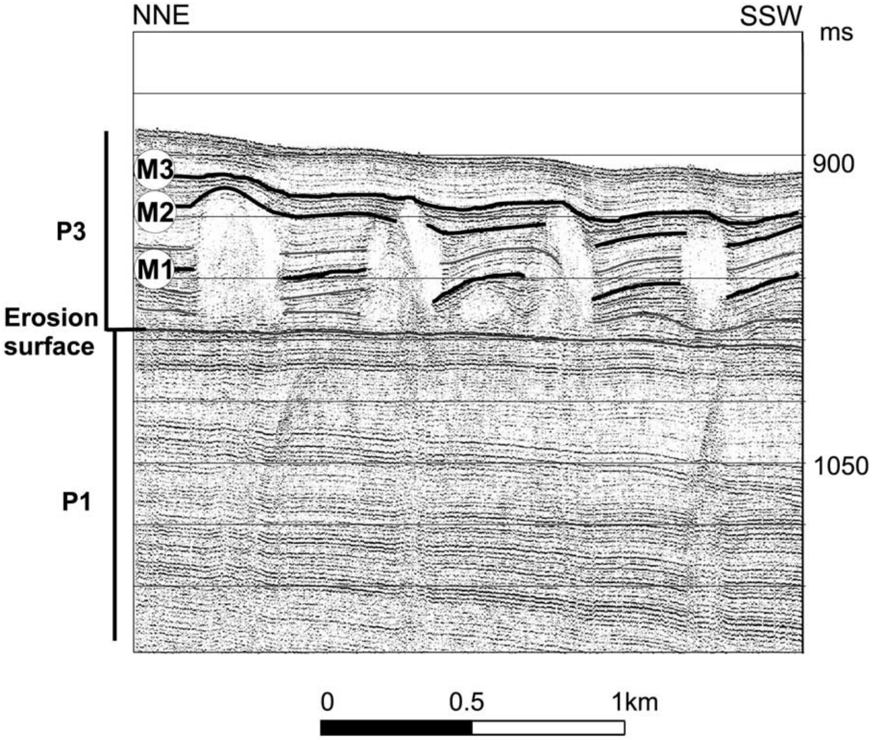


Fig. 9. Zoom of Magellan mounds shown in Fig. 2. On the seismic section (profile P970502c) the erosional surface at the base of the mounds and the three marker horizons M1, M2 and M3 are indicated. The configuration of the horizons illustrates the effect of currents on the sedimentation around the mounds during their individual evolution.

Magellan mounds are often associated with moats, similar to but smaller than those in the Hovland province. Typically moats have a depth up to 40 ms TWT (about 34 m) and they also indicate differences in timing, magnitude and duration of erosion on opposite sides of a mound. Although most moats and mounds are buried, sometimes the morphology is reflected at the present day seafloor (Fig. 10C).

Some mounds are quite small, 10–20-ms-high reflection-free hummocks. At the other end of the spectrum, some mounds grew tall, and at least three of the tallest mounds pierce the seafloor. To study the distribution of mounds at a given time interval, three marker horizons have been defined (M1, M2 and M3) (Fig. 9) and mounds have been coded according to the highest marker horizon that was penetrated (Fig. 11). The most important result of this exercise is that there are two main intervals in which mound growth stopped. About 50% of the mounds terminated growth before the first marker horizon (M1). In the eastern part of the Magellan mound province, closest to the terrigenous sediment source, mounds are limited to this first interval. Of the remaining mounds 70% penetrate the M2 horizon but not the M3. The tallest mounds, which penetrate the M3 horizon, are more or less located within the area of least sedimentation, but otherwise there is no trend observed in the spatial distribution of mound growth at a given time.

6.2. *Sedimentology*

Core TTR7-AT-14G (Fig. 12) was taken at the crest of an outcropping Magellan mound at 52°18.88′N, 12°40.70′W in 642 m water depth (Swennen et al., 1998). The total recovery was 145 cm. The core consists of bands of dead coral interbedded with olive grey (5Y 5/2) silty forami-

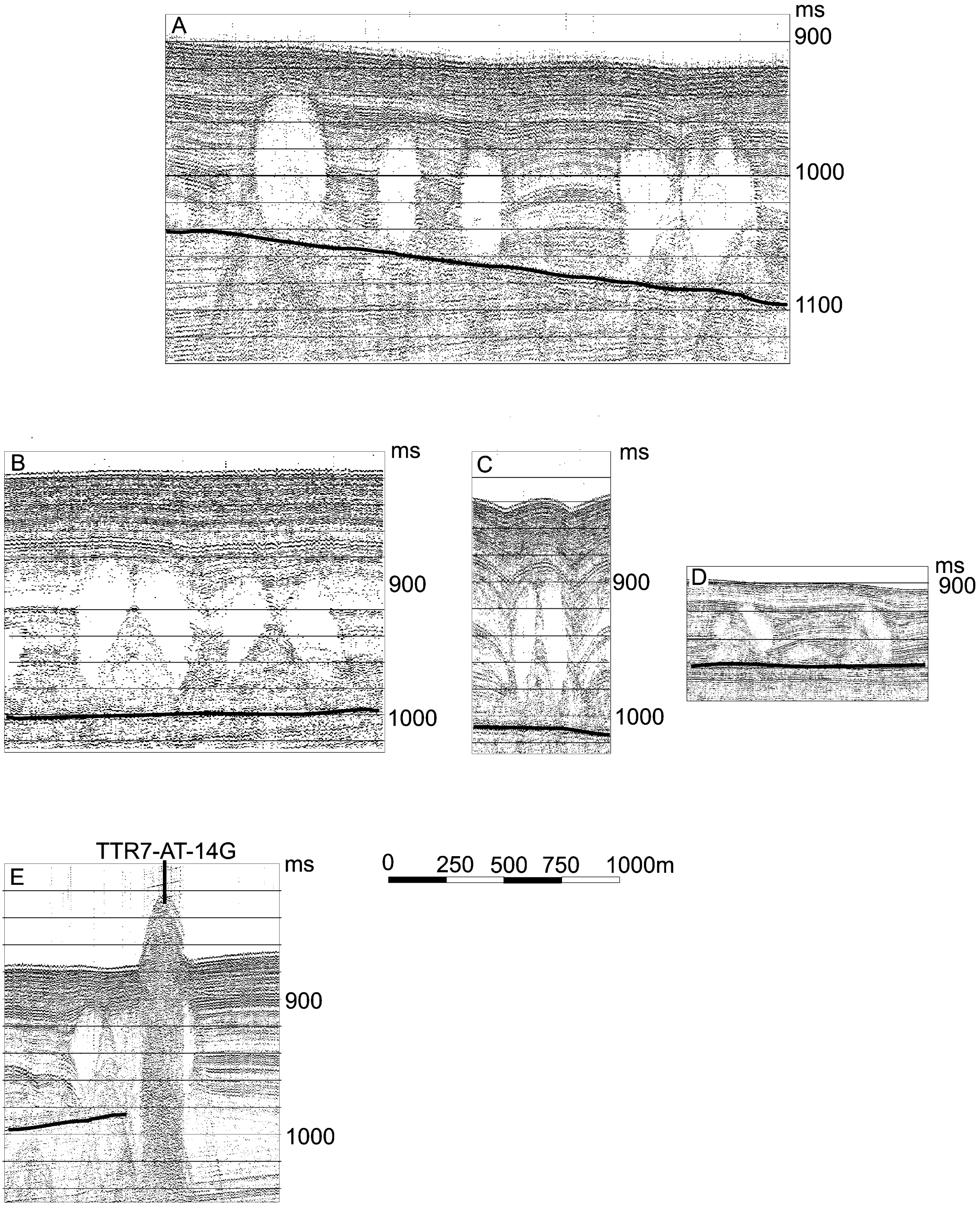


Fig. 10. High-resolution seismic profiles showing examples of the morphological variation of the Magellan mounds. All examples have identical vertical and horizontal scale; the erosional surface at the base of the mounds is marked by the thick black line. (A) Three independent single mounds with associated moats and one paired mound. (B0 Two pairs of symmetrical twins, one pair is closing to the crest and the other is opening. (C) Twin mounds. (D) Asymmetric twin mounds. (E) Location of core TTR7-AT-14G at a mound piercing the seafloor flanked by smaller buried mounds.

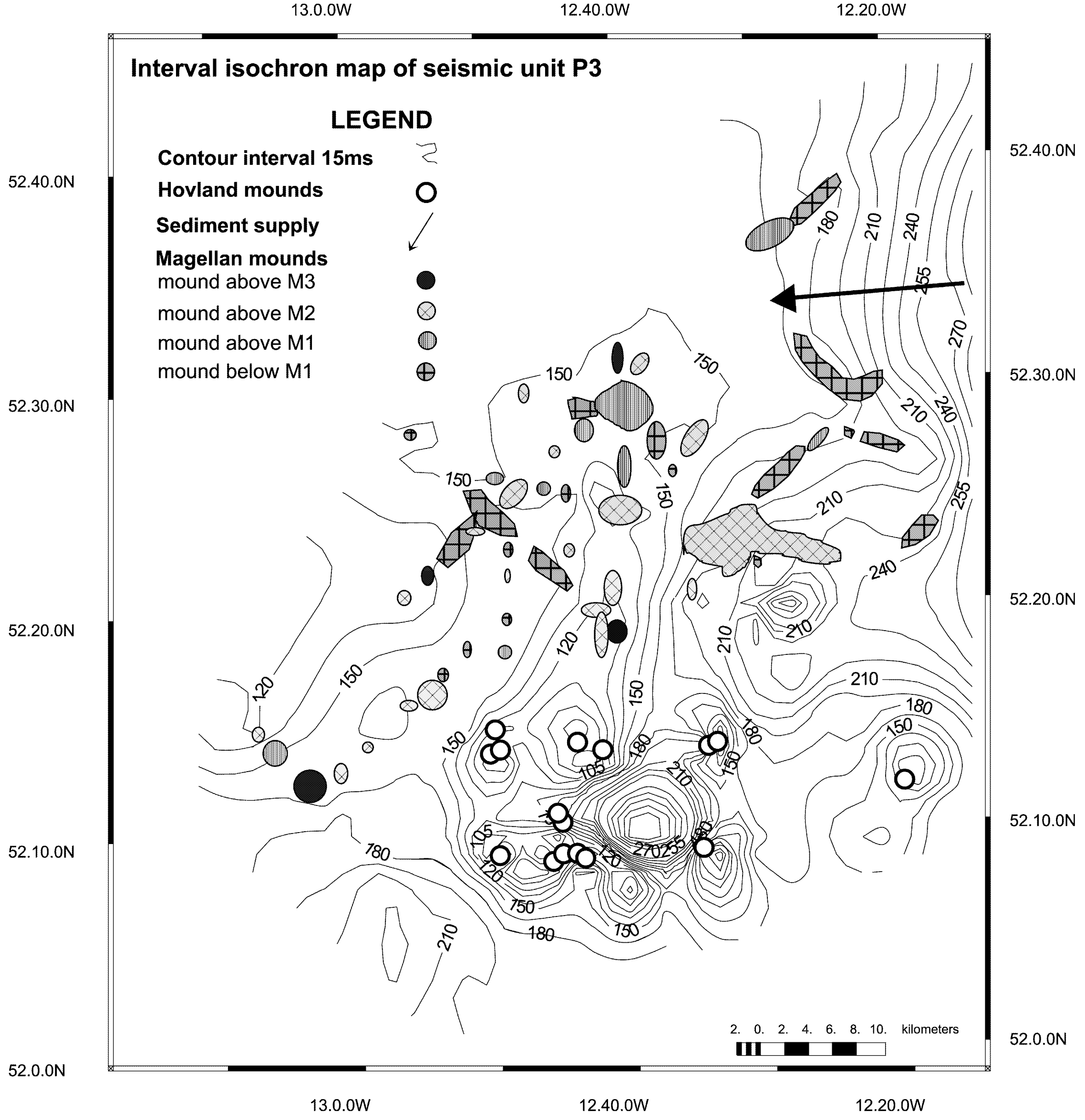


Fig. 11. Interval isochron map of unit P3 in ms TWT with the distribution of Magellan mounds in relation to the highest marker horizon they reach. The increasing sediment thickness to the east indicates sediment supply from the western Irish shelf.

niferal mud with coral fragments. The top 80 cm consist of about 80% of branching corals with some silt and coral fragments. A dropstone of 2 cm diameter occurs at 21 cm. Silty foraminiferal marl with occasional coral fragments is found between 80 and 90 cm. A second band consisting of 80% of coral branches in a clay-silt matrix is observed between 90 and 93 cm. Interval 93–105 cm comprises silty foraminiferal marl with occasional coral fragments, and interval 105–112 cm contains up to 80% coral fragments in a silty clay matrix. Interval 112–120 cm comprises silty foraminiferal clay, while interval 120–145 cm consists of olive grey (5Y 4/2) clay and 50% corals.

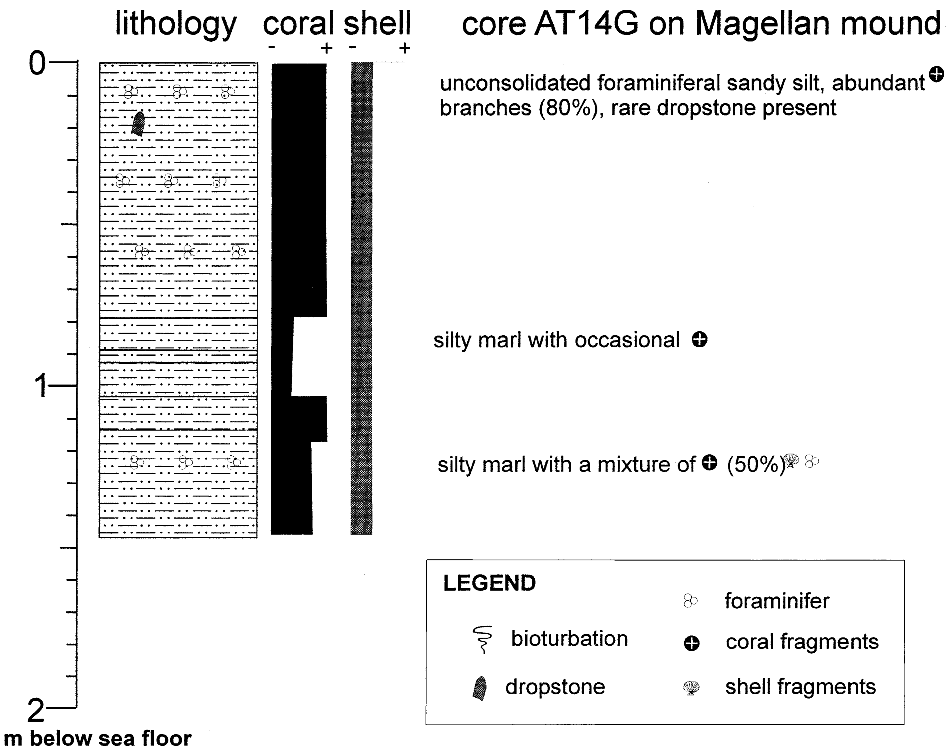


Fig. 12. Description of core TTR7-AT-14G. See Figs. 1 and 10E for location (Swennen et al., 1998).

7. The Belgica mounds

7.1. Description of seismic data

The Belgica mounds are located on the south-eastern slope of the Porcupine Basin between 51°10′N and 51°35′N and 11°30′W and 11°45′W in water depths of 600–900 m (Figs. 1 and 13). On the available dataset 21 outcropping mounds and 14 buried mounds are observed. Outcropping mounds are located on the steepest part of the slope between 750 m and 850 m. They are largest in the south and decrease in size to the north where the slope is gentler. Buried mounds occur in a wider bathymetric interval but are in general found upslope and to the north of the outcropping mounds, in water depths of 600–850 m.

Typically, the eastern upslope flank of the outcropping mounds is ponded with sediment while the entire western, downslope flank of the mounds remains exposed (Fig. 14). Downslope, the mounds border a wide erosive, N–S-oriented channel (Figs. 13 and 14). Despite the evident asymmetry in depositional environment on the flanks of the mounds, ‘Belgica’ mounds appear conical on seismic profiles, with an average slope of 10–15°. The larger mounds merge into ridge-like structures, which trend in a NNE–SSW direction and are arranged en échelon (Figs. 15–18). These composite mounds are 50–200 m high, 1 km to over 3.5 km long and have a width between 500–1500 m. The smaller mounds mostly occur as single conical mounds and are 70–100 m high and measure 260–1500 m across. These show a more random distribution between the larger mounds.

The channel on the seaward side of the mounds, mentioned above, lies in a water depth ranging from about 1050 m in the north to 1550 m in the south (Figs. 13 and 14). The origin of the channel seems to be related to the drift processes along the continental slope. Once formed, this channel has apparently funnelled the discharge

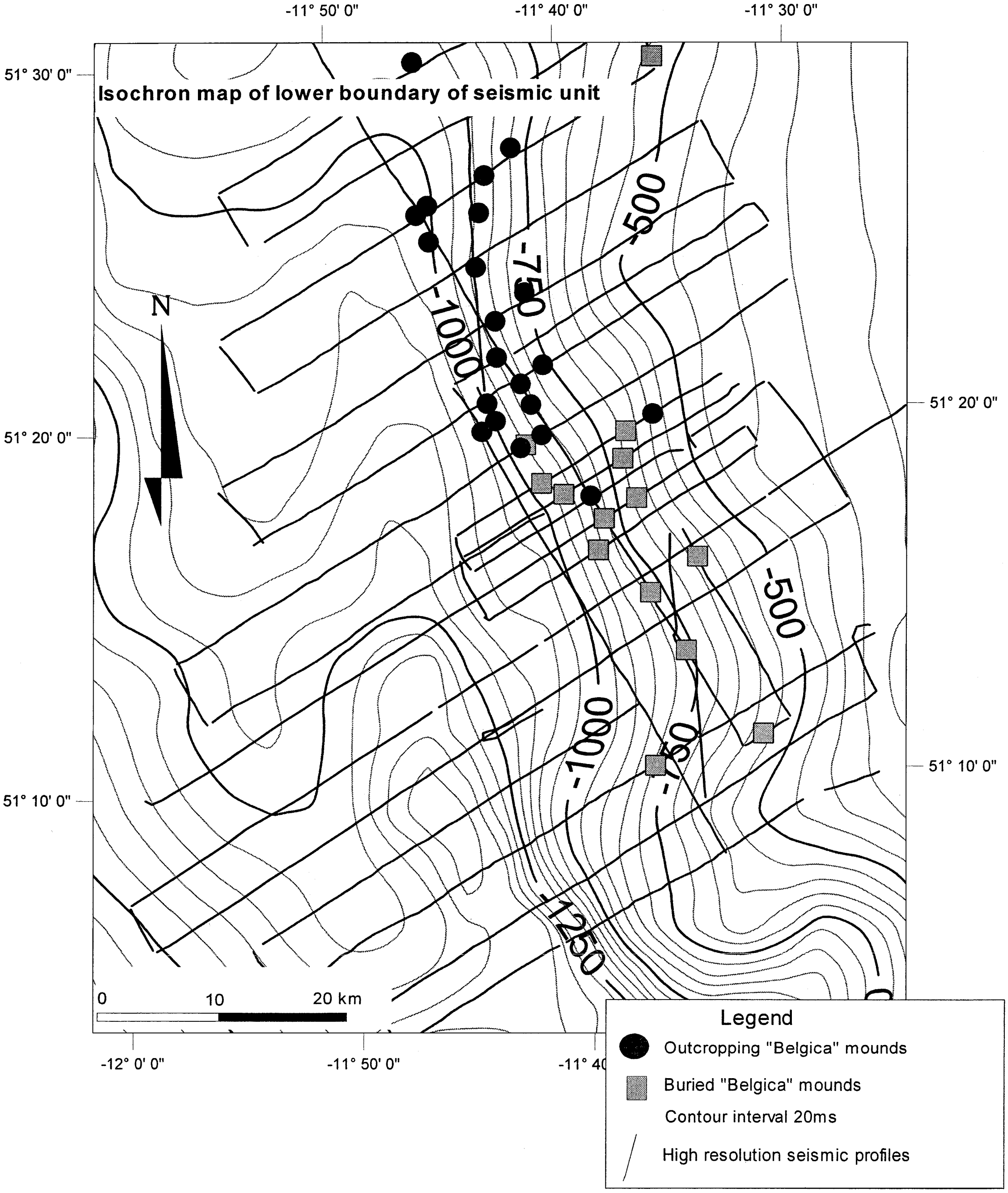


Fig. 13. Bathymetric map of the Belgica mound province based on seismic profiles with location of outcropping and buried Belgica mounds. The outcropping mounds are located near the maximum gradient of the slope. Note the wide channel at the base of the slope.

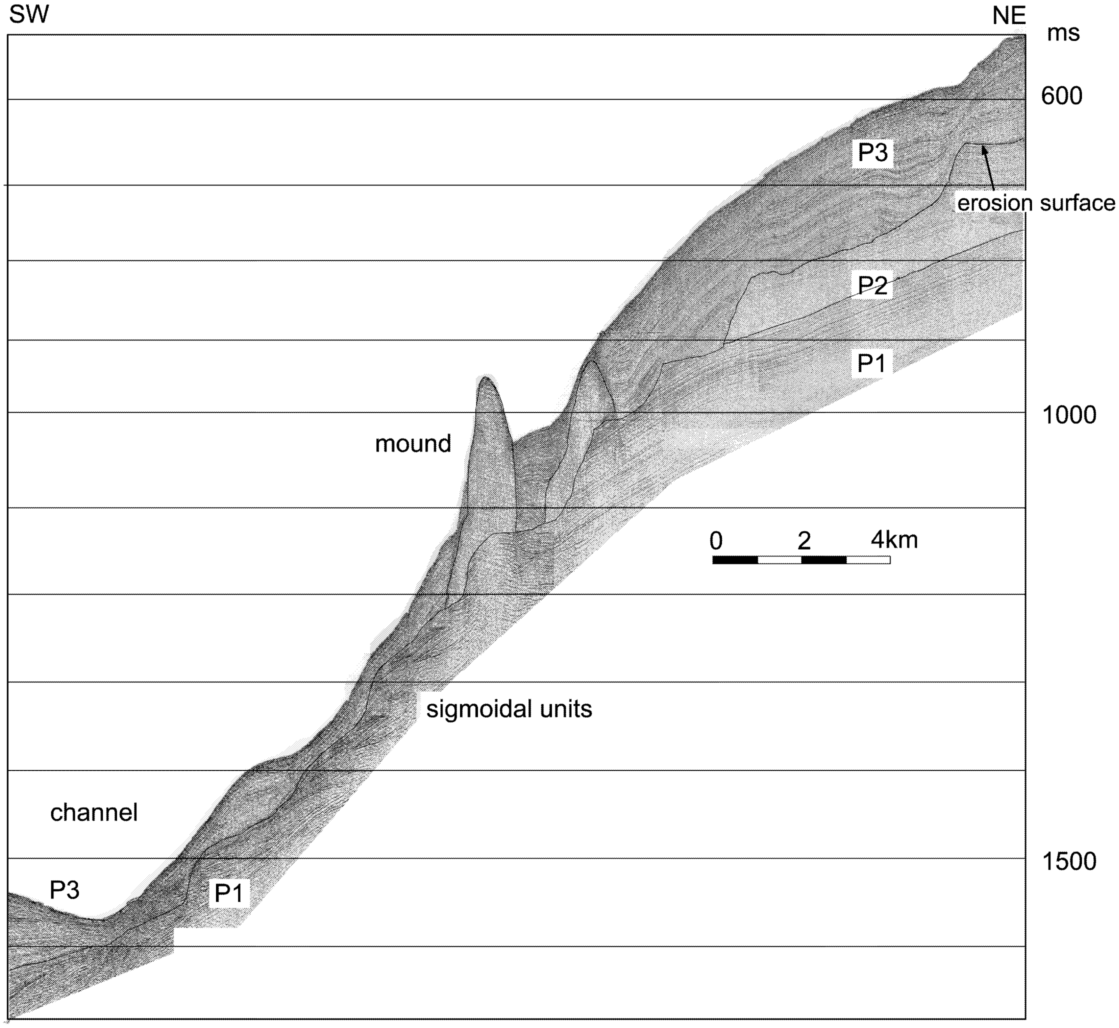


Fig. 14. High-resolution seismic profile of the Belgica mound area, perpendicular to the slope.

of a number of small downslope valleys that coalesce within this N–S-trending main channel. At 1450 m water depth, the channel switches to a NW–SE orientation, almost parallel to the overall slope strike, for about 3 km and then returns to a N–S to NNE–SSW orientation, down the overall slope gradient. The channel has a maximum width of 8 km and is over 35 km long.

Belgica mounds usually do not feature well-developed moats although the rough seafloor and the presence of sand waves indicate strong, northerly-flowing, bottom currents (Fig. 17) (De Mol et al., 1999). In general, the wave crests are oriented in an E–W direction, sometimes following the contours of local mounds. The waves are large and have a wavelength of about 20–25 m in the western part of the Belgica mound province. Wave height and wavelength (10–15 m) decrease upslope.

The base of the Belgica mounds is formed by a continuous erosional surface, probably of Miocene age (Fig. 14). This implies a probably earlier origin for the Belgica mounds compared to the central mound provinces. The deeply incised substratum features a very faintly stratified seismic facies (P2) which is absent in the central part of

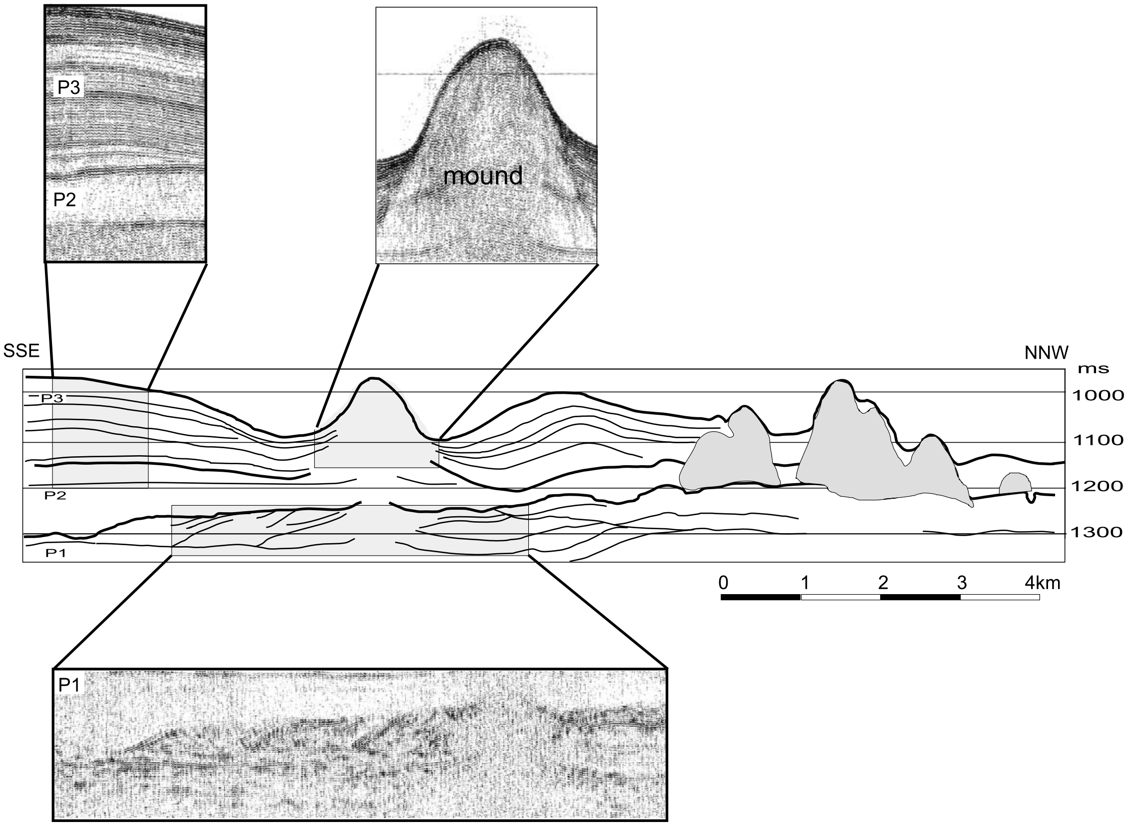


Fig. 15. Line drawing and parts of NNW–SSE high-resolution seismic profile in the Belgica mound province illustrating single and composite mounds and seismic facies P1, P2 and P3.

the province (Figs. 14 and 15). It is underlain by a sequence of sigmoidal deposits (seismic facies P1).

7.2. Sedimentology

Surface (boxcores) sediment samples taken from the basinward flanks of the mounds yielded *Lophelia* and *Madrepora* and also a rich variety of sponges, bryozoa, octocorals and hydrozoa, but samples recovered on the landward side only contained sediment and small remains of organisms. On the landward side the biological cover of the mound is buried and has not been significantly resettled by benthic organisms. Fauna that preferentially colonise these flanks cause intense backscatter on sonographs (Huvenne et al., 2002) (Fig. 17).

Several attempts to sample the basinward flanks of the mounds with a gravity core were unsuccessful due to the dense coral cap. All recovered sediment cores are from the crest or landward side. Gravity cores from Belgica mounds generally yield a dark brown, silty/sandy, heavily bioturbated marl. The top few cm are composed of foraminifer-rich silty sand. This layer also generally contains a few pebbles, on which living and dead bryozoans and coral debris may be attached. Only one core (TTR7-AT-23G) contained some coral rubble deeper in the core. The carbonate fraction of the sediments is largely composed of calcareous nannoplankton. The clay and silt particles, as well as the organic matter, are of terrigenous origin (Kenyon et al., 1998).

A typical coral/pelagic sediment sample from the basinward upper flank of a Belgica mound is

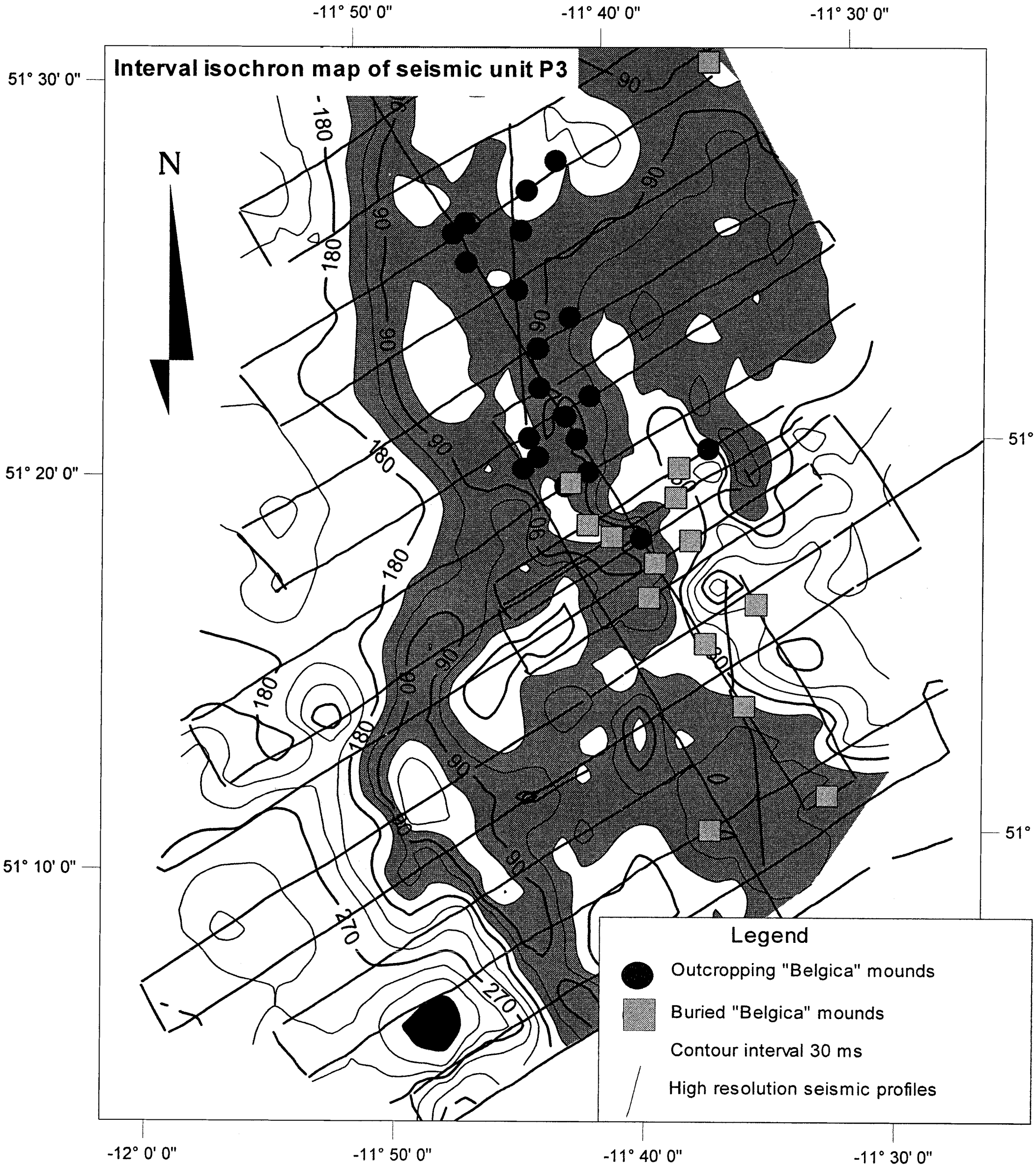


Fig. 16. Interval isochron map in ms TWT of seismic facies P3 in the Belgica province. A zone of thinning (grey) is found with a general north–south trend. The patchy character of the thickness illustrates the drift character of the seismic unit.

core TTR7-AT-23G taken at 51°27.28′N and 11°42.08′W (Fig. 19) (Swennen et al., 1998). The upper 0–13-cm interval comprises a foraminiferal, light olive brown (2.5Y 5/3), soupy sand. A well-rounded 1-cm dropstone is found at 10 cm, and the unit is rich in coral fragments, small shell fragments and echinoderm spines. A large 7-cm-diameter dropstone is found at 13 cm. Interval 13–235 cm includes dark greyish brown (2.5Y 4/2) to olive grey silty marl, which is locally bioturbated. Coral fragments are found both at the very top of the unit (15–17 cm), and between 30 and 35 cm. A solitary coral head was found at 155 cm. There is a slight increase in foraminif-

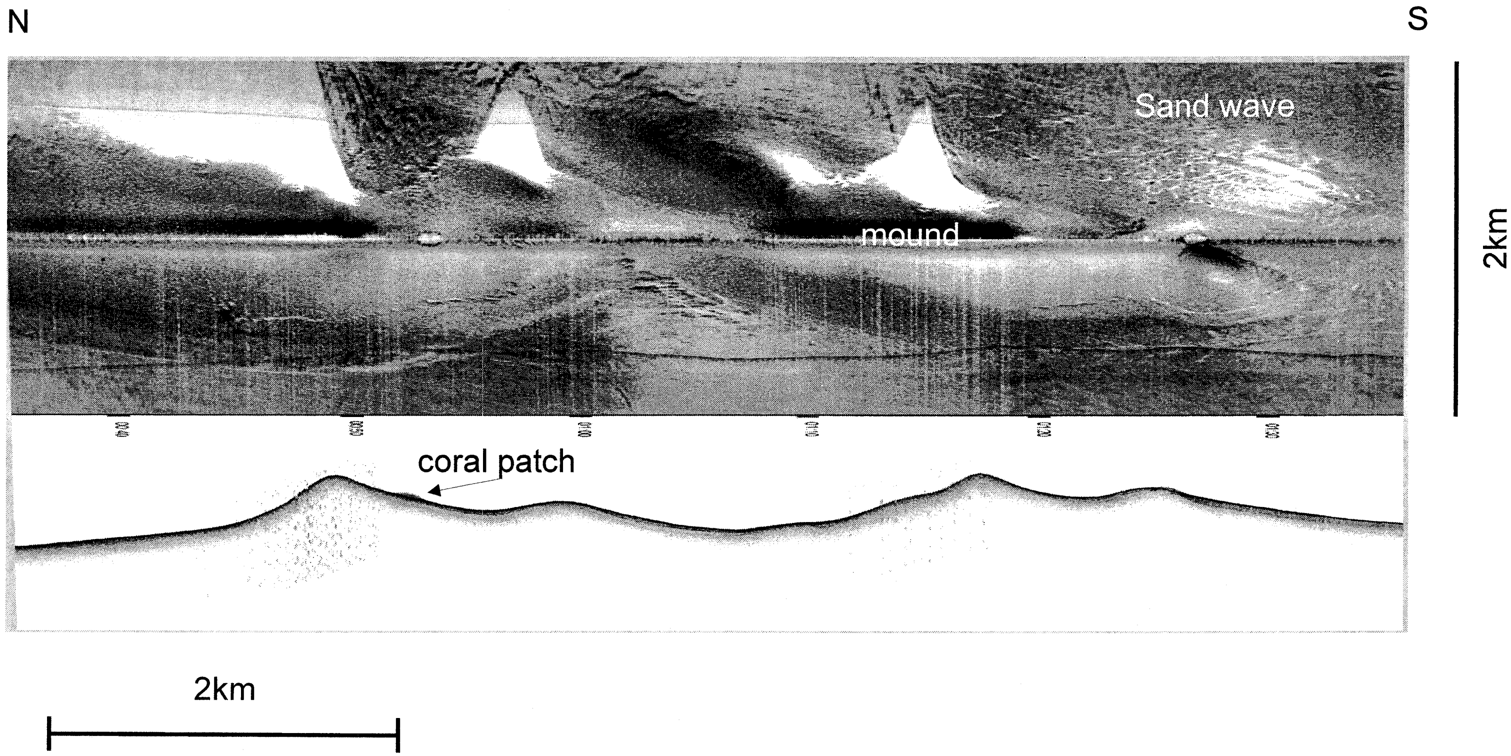


Fig. 17. Side-scan sonogram Orat 5 and 6.5-kHz profiler recorded during TTR7 cruise. Bottom striations, sand waves and ripple marks suggest the influence of mainly north–south-oriented strong bottom currents.

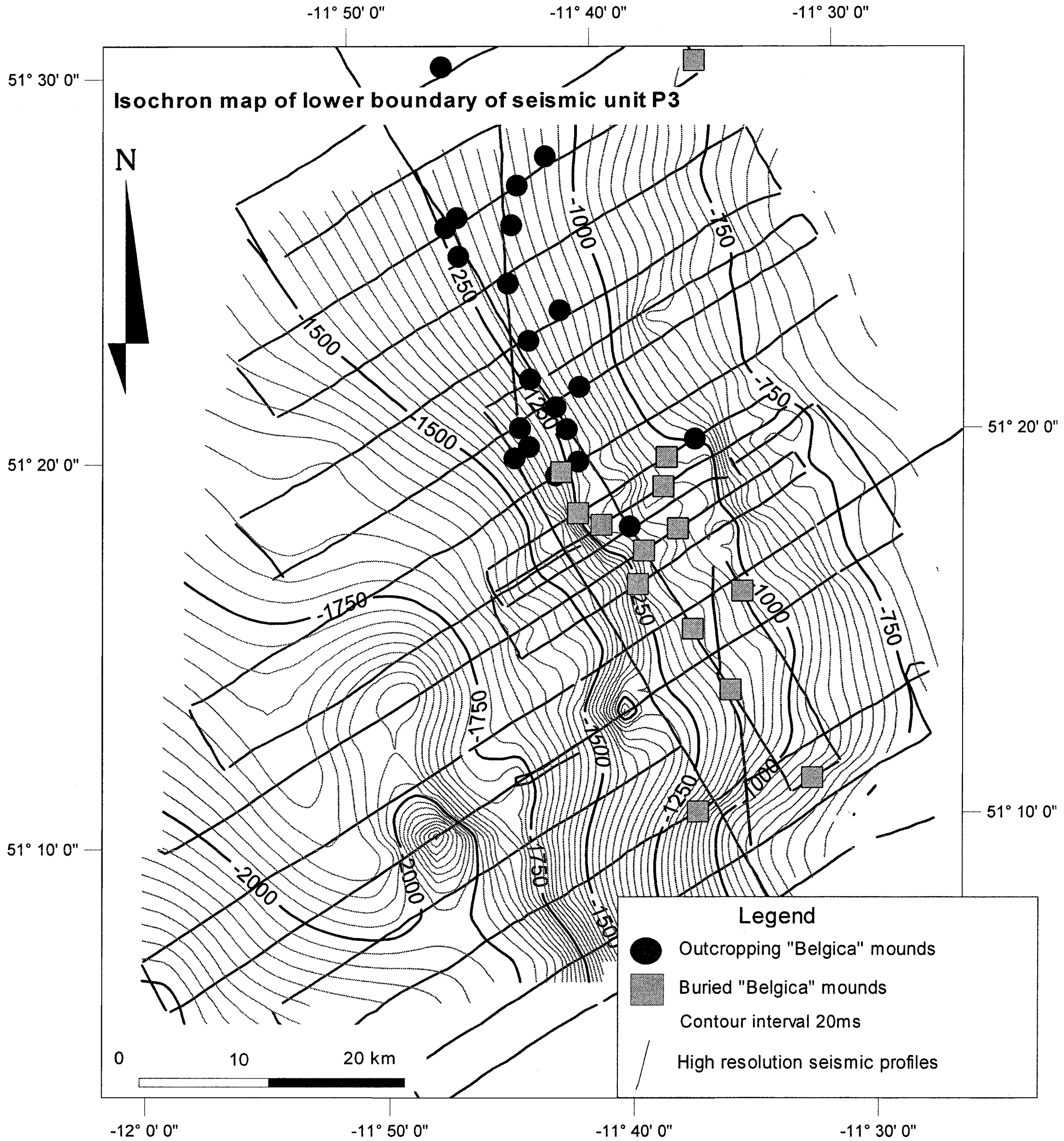


Fig. 18. Time structure map in ms TWT of the erosional surface at the base of the mounds. See Figs. 14 and 15.

eral content and grain size below 35 cm. Some complete bivalves are present at 15 cm. Interval 235–239 cm comprises greyish brown sandy marl. Interval 239–282 cm consists of dark greyish brown (2.5Y 4/2), foraminiferal, biogenic-rich silty clay. Two larger dropstones are observed at 239–282 cm, and one smaller dropstone at 310 cm. A gastropod is found at 286.5 cm. Reduction spots and some burrowing are also scattered through the section. Grain size increases from silty mud to medium sand within the interval 313–326 cm.

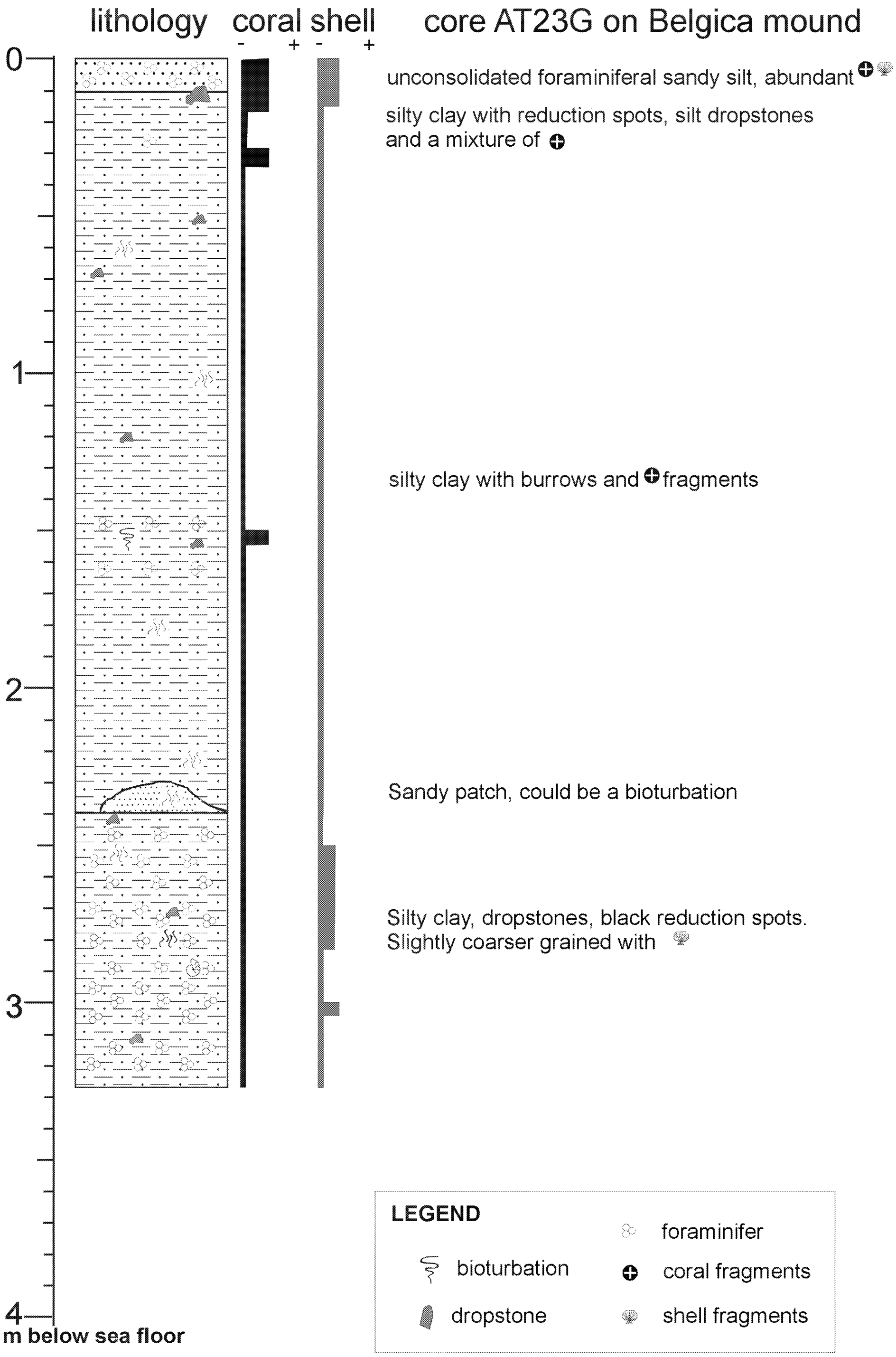


Fig. 19. Description of core TTR7-AT-23G on a Belgica mound (Swennen et al., 1998).

8. Discussion

This paper describes large mounds in the Porcupine Basin. *Madrepora oculata* and *Lophelia pertusa* are found in association with as many as 101 taxa of deep-water megafauna (Sumida and Kennedy, 1998) on top of large conical or elongated mounds. The most remarkable observations are:

- the relatively large concentration of benthic life including corals on the mounds
- the association of corals with large amounts of terrigenous siliciclastic mud
- the dimensions of the mounds
- the occurrence of three different types of mounds, each in a separate, well-delineated province
- within each province, the mounds have a common base which suggests a simultaneous initiation of mound growth
- the association of seafloor depressions, moats and channels with some mounds.

The data collected allow us to describe the setting and morphology of the mounds and the sediment characteristics at the seafloor but do not provide information about the internal mound structure and composition. Nevertheless, the description is comparable with other coral banks in the North Atlantic ocean, as described by different authors (Cairns and Stanley, 1981; Hovland et al., 1998; Pratje, 1924; Reed, 1992; Stetson et al., 1962; Teichert, 1958) and as reviewed by Freiwald (1998). The term 'coral bank' is used for any topographic elevation consisting predominantly of corals. The coral bank represents the final evolutionary step in the formation of deep-water coral structures and shows greatest similarities to shallow-water coral reefs. Principally, a coral bank is characterised by three distinct units: (1) a cap of living coral colonies, which rests on (2) an open-spaced but dead coral framework and debris zone, and (3) a zone of coral framework and debris that is clogged solidly with sediment. In reality, however, recolonisation by corals takes place on each of these three delineated zones. The greatest density of living coral colonies is observed on the top and the upper flanks of the bank (Mortensen et al., 1995).

Due to their size and muddy matrix the mounds in the Porcupine Basin are different from other azooxanthellate (mostly *Lophelia*) coral banks or reefs. Azooxanthellate coral banks described in the literature (Table 1) consist mostly of a coral frame supported by sponges (Freiwald et al., 1999), with biogenic material and terrigenous mud infill. They generally occur on top of a pre-existing topography (e.g. glacial sill, morainic ridge, seamount, iceberg plough ridge) (Cairns and Stanley, 1981; Freiwald et al., 1999). Seismic facies analysis has resulted in little information about any internal structure. The following sections will discuss the present-day setting of the mounds, the results of the analysis of shallow cores and surface samples, and the possible origin of these large seafloor structures.

8.1. Environmental setting of deep-water coral banks in the Porcupine Basin

8.1.1. Deep-water coral occurrences

Shallow cores recovered from the mounds consist of a muddy matrix, identical to the surrounding seafloor sediment, interlayered with biogenic calcareous rubble and coral fragments. Dense coral patches and associated fauna occur on the upper flanks of the mounds, grading into dead coral colonies in a muddy matrix lower on the flanks and into coral rubble in a muddy matrix at the base of the mounds. *Madrepora oculata* and *Lophelia pertusa* are the dominant azooxanthellate coral species found on the mounds. Both coral species are widely distributed throughout the Atlantic Ocean and occupy the same ecological niche. *L. pertusa* occurs in water depths ranging from 50 m (Strömgren, 1971) to over 2000 m in the Atlantic (Le Danois, 1948), from 0 to 13.6°C and in salinities ranging from 31.85 (Strömgren, 1971) to 37‰ (Freiwald, 1998). *Lophelia pertusa* produce 30–100-cm-high massive, dendroid and bushy skeletal colonies but the neighbouring branches commonly merge, thus increasing the architectural stability of the framework. *Madrepora oculata* has been the object of fewer investigations but occurs in the same environments as *L. pertusa*. In contrast to *Lophelia*, it forms fan-shaped colonies, maximum 30–50 cm high. The potential for framework aggradation or progradation of this fragile growth habitat is rather limited. *Madrepora*-dominated coral structures are generally characterised by thickets and/or rubble facies, rather than stable frameworks (Freiwald, 1998; Stetson et al., 1962).

The requirements for *Lophelia* and *Madrepora* corals to grow is a hard substratum, an adequate food supply and protection against burial. Concentrations of *Lophelia* corals are found where currents (upwellings, internal waves between stratified water masses, etc.) prevent deposition of fine-grained sediment and supply large quantities of food (Cairns and Stanley, 1981; Freiwald, 1998; Mortensen, 2000). In these favourable areas, azooxanthellate corals might form patches or banks mostly on top of topographic elevations, for example on moraine ridges where they attach to dropstones (Freiwald et al., 1999; Mortensen, 2000), on seamounts (Zibrowius and Gili, 1990), on carbonate-cemented rocks (Neumann et al., 1977; Messing et al., 1990), in hydrocarbon seep areas (Hovland, 1990, 1992; Hovland et al., 1994, 1998; Hovland and Thomsen, 1997), on outcropping rock (Stetson et al., 1962) or even on submarine pipelines (Hovland, personal communication) and oil rigs (Bell and Smith, 1999; Roberts, 2000). Topographic irregularities in areas with strong currents cause local current accelerations, which can increase food supply and protect the corals from sediment settling (Mortensen, 2000). When environmental conditions are favourable the corals can produce extensive frameworks which trap sediments and provide niches for other benthic life (e.g. sponges, fish, etc.) (Rogers, 1999).

8.1.2. *Oceanographic regime*

Current-induced features such as moats, sediment tails and sediment waves are closely associated with coral banks in the Porcupine Basin. Texture analysis of the side-scan sonar images from Hovland and Belgica mounds confirms the presence of variable seafloor currents but suggests that currents in the Hovland mound province are weaker than in the Belgica mound province (Huvenne et al., 2002; White, 2001). Deep-water currents in the Porcupine Basin have been measured (Rice et al., 1991) or are predicted by hydrodynamic models (New et al., 2001). Internal tidal waves at the boundary between the MOW and the overlying ENAW are probably a corollary of the strong current regime (White, 2001). The MOW features a zone of maximum salinity near the oxygen minimum zone. Internal tidal currents across the slope in the Porcupine Basin have been analysed by Rice et al. (1990) in terms of seafloor slopes and slopes of the ray paths. Currents across the slope in the Porcupine Basin are enhanced due to the breaking of internal tidal waves where the slope of the ray path of the tidal waves exceeds the slope of the seafloor (Rice et al., 1990). This ‘critical’ slope is inversely proportional to the density gradient between the different water masses and is therefore more easily attained at the upper boundary of the MOW where the density gradient is largest (Sherwin and Taylor, 1987). According to this analysis the Belgica mounds would be located within an area of enhanced near-bottom currents but the Hovland mounds are not. Rice et al. (1990) based their calculations on hydrographic data of Pingree and Morrison (1973) but recent hydrographic models from Levitus and Boyer (1994) and Levitus et al. (1994a,b) suggest a shallowing of the top of the MOW from 700 m at 51°N (Belgica mound area) to about 500 m at 52.5°N (Hovland mound area). The average slope gradient in the Hovland mound province is probably less than the ‘critical’ slope defined by Rice et al. (1990), but the observed large depression may locally increase the slope angle. The present-day distribution of mound outcrops and corals within the Porcupine Basin seems to be related to areas of strong currents and low sediment supply.

8.1.3. *Burial history*

Buried mounds, for example the Magellan mounds and some Belgica mounds, occur in positions where sediment supply is relatively greater or currents are weaker. The Magellan mounds and the northernmost Belgica mounds occur on gentle slopes, probably well below the ‘critical’ slope for internal tidal currents. Above and below this zone the environment is less suitable for coral growth and coral bank development and they may fail to keep up with sediment supply.

It seems that these mounds have been relatively stable during their entire evolution. Rather paradoxically, though sedimentation is one of the inhibitors of coral growth, there seems to be a positive feedback between some degree of mud accumulation and the growth of a coral bank. The coral framework traps suspended sediment, and the high concentration of micro- and macrofauna (especially sponges) on the coral banks probably stabilise the build-up (Freiwald et al., 1999). On the other hand, the mud matrix prevents framework collapse in the dead coral zone. Sediment accumulation keeping pace with coral growth might help to form large topographic elevations on the seafloor. The question, however, is how this process got started.

8.2. *Structure of the deep-water coral banks in the Porcupine Basin*

As stated above there is no direct information regarding the internal structure of the mounds. The seismic facies is acoustically transparent with a few odd, incoherent bright reflections. Cores only penetrate the upper few metres of a mound, which may be 150 m high. Where the base of the mounds is observed, it is a continuous, mostly erosional, horizon. In the Belgica and Hovland mound provinces it may be irregular with steep slopes (escarpments) but in the Magellan mound province it appears to be a locally smooth surface. Except for erosional features, there are no clear indications for underlying faults, slumps or mud volcanoes that would create an initial topographic relief.

Though care should be taken in comparing different scales of deep-water coral habitats, it could be said that the spatial organisation of clusters of mounds in the Porcupine Basin may evoke – at a different scale – the description of the architecture of a single *Lophelia* reef on Sula ridge, offshore Norway. There, a 13-km-long coral bank was found to consist of coalescing, relatively small coral mounds. Each individual coral mound on Sula Ridge is circular in plan view, has an average height of 20–25 m and a width of 50 m. They consist of hemispherical coral colonies with a height of 1.5 m, which form subunits within the mound construction (Henrich et al., 1996; Freiwald, 1998; Freiwald and Wilson, 1998; Freiwald et al., 1999). In the Porcupine Basin, composite mounds in the Hovland and Belgica provinces possibly suggest a higher evolutionary step in this nested architecture.

8.3. *Origin of deep-water coral banks in the Porcupine Basin*

Various observations argue for a brief moment of rapid initial growth of the mounds in the Porcupine Basin. The Belgica mounds apparently developed to virtually full size before the drift sediments draped their flanks. A wide-spread, initial phase of rapid mound growth is also apparent in the Magellan mound province. About 50% of all observed Magellan mounds are small hummocks. The remaining mounds seem to have formed aggrading, widening build-ups, which for a certain time could keep pace with sedimentation and burial. But they ultimately never approached the scale of mound-building displayed in the Hovland or Belgica provinces. Apparently, the environment in the Magellan mound province was not suitable for the long-term survival of the mound-building habitats.

But if the present-day distribution of living *Lophelia* and *Madrepora* coral concentrations and outcropping coral banks correlates well with areas of favourable environmental conditions (strong currents, slow sedimentation rate), it is still not understood why coral banks started to develop in such large numbers on specific sites.

Observations can be summarised as follows.

- Within each province mound initiation occurred rapidly and more or less simultaneously.
- There are no observations of several start-up phases within the same area.
- Mound initiation seems to be restricted to well-delineated areas – the presently defined mound provinces.
- In all three provinces, the start-up phase occurred after an erosional event, possibly during a period of non-deposition.

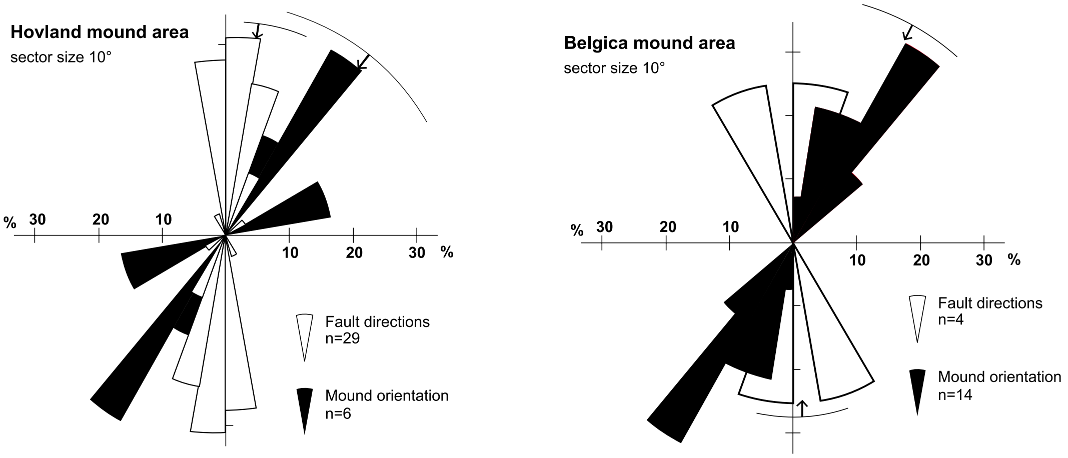


Fig. 20. Rose diagram of orientation of elongated mounds and strike of deeper faults (from McCann et al., 1995a,b) in the Hovland and Belgica mound provinces.

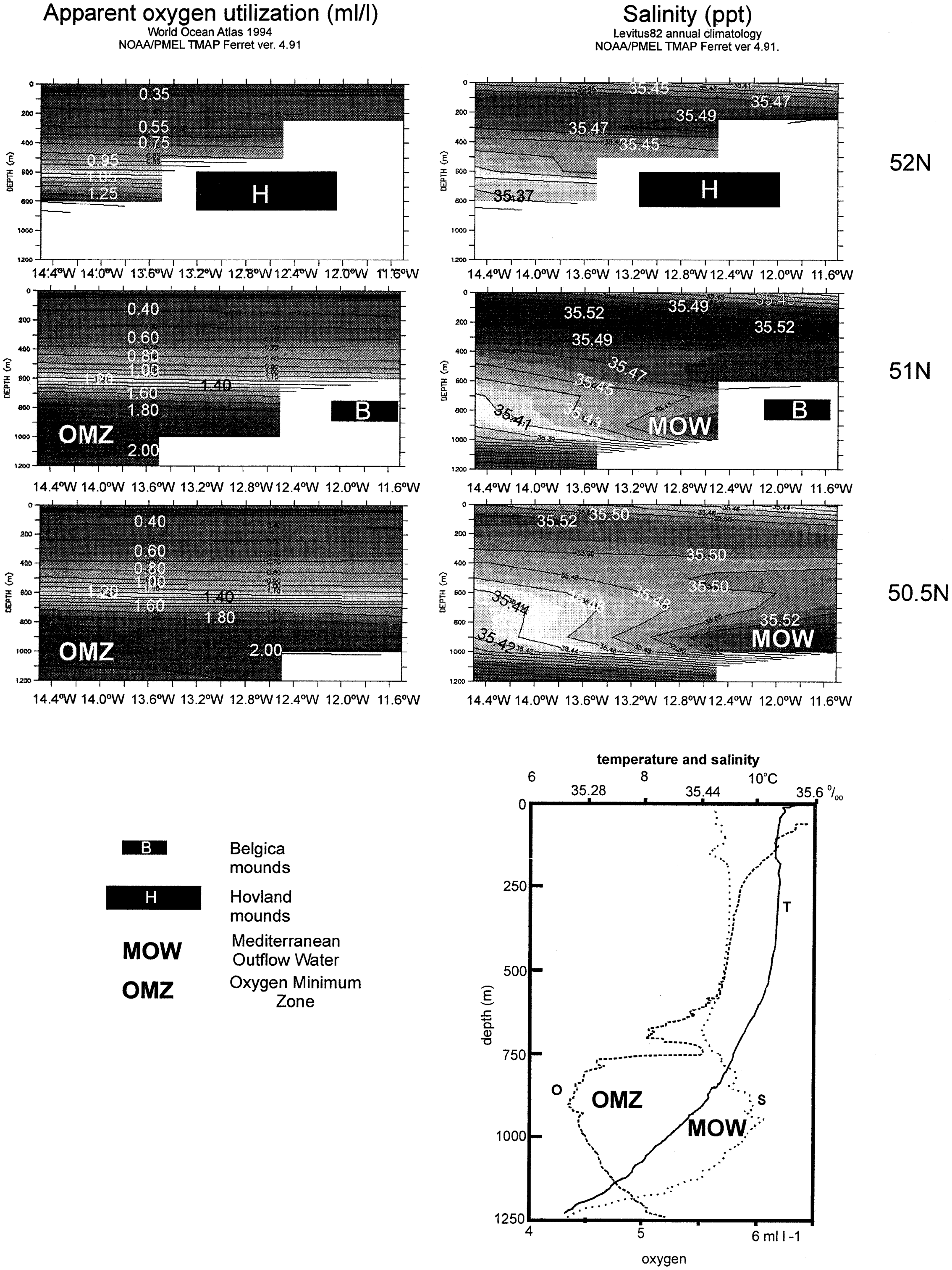
These observations suggest that the start-up phase of each province in the Porcupine Basin could have been caused by a basin-wide, environmental event. This event may be of geological (endogenic) or oceanographic (exogenic) nature.

8.3.1. Endogenic control

Hovland (1990), Hovland et al. (1994, 1998) and Hovland and Mortensen (1999) suggest a causal relationship between deep-water coral banks and seepage. Deep-water coral banks could form as a consequence of local fertilisation that results from focused hydrocarbon seepage. In the case of the Hovland mounds in the Porcupine Basin, Hovland et al. (1994) suggested that the mounds are located immediately above faults or fissures, which could be hydrocarbon migration pathways. Seepage of thermogenic hydrocarbons at the seafloor does occur in the northern and central parts of the Porcupine Basin, in the non-commercial Connemara field about 65 km north of the Magellan mound province and elsewhere (Croker, personal communication). These seeps appear clearly on industrial seismic data and high-resolution seismic sections as amplitude brighting along reflectors, vertical disruption of seismic reflections or vertical zones of chaotic facies ('gas chimneys'). In the Magellan, Hovland or Belgica mound provinces however, such features have not been recognised. Most large faults do not extend to the seafloor and there are no clear indications so far for vertical fluid migration pathways on the interpreted high-resolution seismic data. In Fig. 20, the orientation of linear coral banks has been plotted for the Hovland and Belgica provinces against the strike of deeper-lying faults, as compiled by McCann et al. (1995a,b). If deep-water coral banks were caused by a close, direct link between hydrocarbon seepage along faults, we might expect the mounds to be strictly lined up along the faults, which is apparently not the case. Furthermore, *Lophelia* coral banks in other parts of the North Atlantic Ocean mostly occur independently of proven hydrocarbon seeps (Table 1).

The potential role of methane in triggering mound growth in the Magellan province has further been evoked by Henriet et al. (1998, 2001) in

Fig. 21. Position of mound provinces in relation to ocean water stratification in terms of apparent oxygen utilisation and water salinity. Oxygen minimum zone (OMZ) is indicated as maximum apparent oxygen utilisation; the MOW is characterised by a higher salinity at intermediate depths on the salinity plots. A CTD profile near the mouth of the Porcupine Seabight shows the characteristic oxygen (O), temperature (T) and salinity (S) profiles for the basin (Rice et al., 1991).

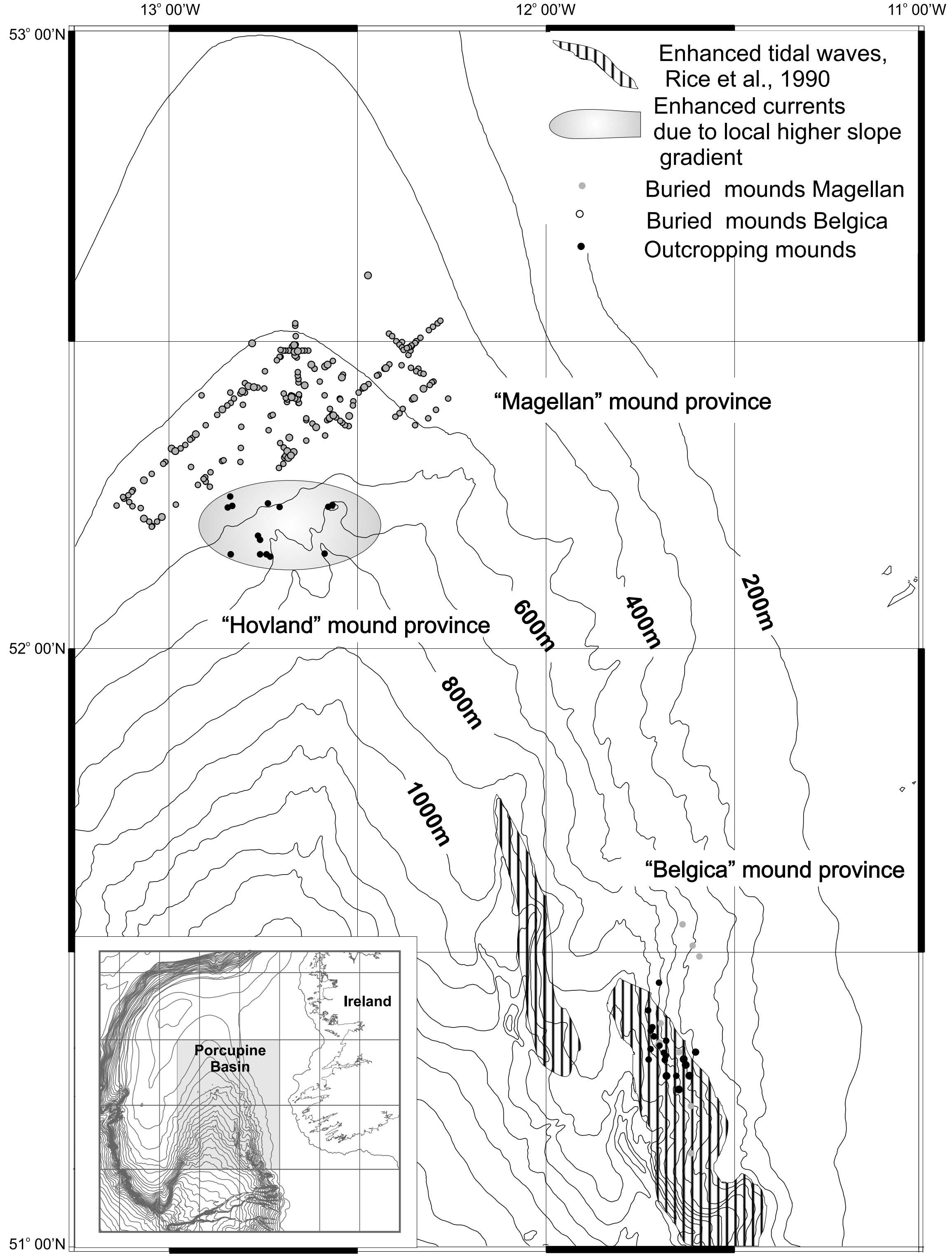

Apparent oxygen utilization (ml/l)
World Ocean Atlas 1994
NOAA/PMEL TMAP Ferret ver. 4.91
Salinity (ppt)
Levitus82 annual climatology
NOAA/PMEL TMAP Ferret ver 4.91.
DEPTH (m)
14.4°W 14.0°W 13.6°W 13.2°W 12.8°W 12.4°W 12.0°W 11.6°W
52N
51N
50.5N
0.35
0.55
0.75
0.95
1.05
1.25
H
35.45
35.47
35.49
35.37
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
OMZ
B
35.52
35.41
35.43
35.50
35.48
35.44
35.42
MOW
Belgica mounds
Hovland mounds
Mediterranean Outflow Water
Oxygen Minimum Zone
temperature and salinity
6
8
10°C
35.28
35.44
35.6 ‰
0
250
500
750
1000
1250
depth (m)
T
S
O
4
5
6 ml l-1
oxygen

a model developed to unravel possible causal relationships between methane migration, slope destabilisation and mound growth. Such a model also implies a possible phase of hydrate build-up and decay, in an environment which has experienced extreme variations in bottom water temperatures in the recent sequence of glacial and interglacial periods.

8.3.2. *Exogenic control*

A third hypothesis concerns the oceanographic favourable conditions (Freiwald, 1998), in our case the initiation of MOW flow into the North Atlantic Ocean. The evolution of oceanic gateways within the Neogene and Quaternary had a strong impact on the global ocean circulation pattern. The closure of the Isthmus of Panama, which started 4.6 Ma ago (Haug and Tiedemann, 1998), deviated huge water masses from the tropical region of the Atlantic towards the north. They still control the present day surface water conditions of the NE Atlantic. Supposedly as a result of this transport of latent heat, northern hemisphere glaciation started, which increased the advection of deep water. In combination, the MOW resumed after the late Miocene–early Pliocene Messinian salinity crisis in the Mediterranean Sea (Maldonado and Nelson, 1999). A regional Late Pliocene hiatus has been found in the Rockall–Goban Spur transect and is interpreted in terms of the reintroduction of MOW into the NE Atlantic (Pearson and Jenkins, 1986). Based on microfaunal associations in deep cores of the North Atlantic (west of Rockall Bank and in the Western Approaches), Schnitker (1986) suggested that the present-day water stratification in the North Atlantic Deep Water was only established at the onset of modern glacial conditions about 2–2.5 Ma ago. The fluctuating glacial and interglacial climates and eustatic sea levels seem to have been the dominant control on the Mediterranean Outflow since the late Pliocene (Cremer and Faugères, 1993; Nelson et al., 1993; Caralp, 1988; Grousset et al., 1998). The oldest fossil record of *Lophelia* and *Madrepora* in the North Atlantic area is reported in the Mediterranean Sea where they occur since the early Pliocene (Chevalier, 1961; Cairns and Stanley, 1981; Esteban, 1996; Pérès, 1985). Deep-water corals, banks or patches occur all along the European shelf margin from Gibraltar up to Norway (Freiwald, 1998). It is therefore possible that larvae of azooxanthellate corals were introduced into the North East Atlantic Water together with the MOW and took advantage of the currents created by the intrusion of the high-density water mass into the North Atlantic to colonise the continental slopes. The MOW, however, only extends north as far as the Porcupine Bank or the Rockall Basin (New et al., 2001; van Aken, 2000). Larvae may have been carried further north by other poleward-flowing currents related to the North Atlantic Current (Freiwald et al., 1999). In this scenario, different start-up events could be related to major phases of MOW input and withdrawal in the Porcupine Seabight (Figs. 21 and 22). A first period of coral bank development could have taken place in the Belgica province where the mounds seem to root on Miocene sequences, while a second phase at the Plio–Pleistocene boundary could have been the origin of the Magellan and Hovland provinces. The estimated Late Pliocene age of a Hovland mound (see 5.2. Sedimentology) might fit with this hypothesis. Detailed dating of the base of the coral mounds is obviously required but difficult to achieve. The faunal diversity on the coral banks and the occurrence of typical Mediterranean species (Coles et al., 1996) also illustrate the close relationship between the coral banks and the MOW (source for corals, enhanced currents) but do not provide conclusive evidence regarding the origin of the coral banks in the Porcupine Basin. Only scientific drilling will provide such conclusive evidence.

Fig. 22. Coral bank distribution in relation to zones where current enhancement at the top of the MOW may occur (Rice et al., 1990). The Belgica mounds are located within a zone of current enhancement as predicted by Rice et al. (1990). The overall slope gradient in the Hovland mound province is below the critical angle but current enhancement may occur locally. The Magellan mounds are located well outside present-day favourable areas for current enhancement at the maximum density gradient.


13° 00'W
12° 00'W
11° 00'W
53° 00'N
52° 00'N
51° 00'N
Enhanced tidal waves, Rice et al., 1990
Enhanced currents due to local higher slope gradient
Buried mounds Magellan
Buried mounds Belgica
Outcropping mounds
"Magellan" mound province
"Hovland" mound province
"Belgica" mound province
600m
400m
200m
800m
1000m
Ireland
Porcupine Basin

9. Conclusion

This paper describes the morphology, seismic facies and sedimentology of large deep-water coral banks and their geological setting in the Porcupine Basin offshore Ireland. These coral banks are larger than most of their North Atlantic counterparts – they are about 1 km wide, can be up to 5 km long, and attain heights of almost 200 m above the seafloor. The banks are mound-shaped elevations hosting living deep-water coral and associated fauna on their upper flanks. This biologically active layer covers a dead assemblage of corals, filled with nannofossil ooze and terrigenous mud similar to the surrounding seabed sediments. The coral banks in the Porcupine Basin occur in three provinces, each characterised by a typical mound shape: seafloor mounds of conical shape in the Hovland mound province, partly buried conical mounds in the Belgica mound province, and large numbers of smaller buried mounds of various shapes in the Magellan mound province.

All coral banks, buried or outcropping, occur in association with current-induced features such as moats, sediment tails and sediment waves indicating their location in regions of strong bottom currents. Relatively few mounds are still outcropping today, which suggests that environmental conditions were more favourable to mound growth in the past. The depth range of these outcropping mounds coincides with the top of the dense MOW, where current enhancement through internal tidal waves could control coral growth. Mound growth started within each separate province at different times, probably since the Late Pliocene and after periods of erosion or non-deposition. Various phases of mound development in the past few millions years may have occurred and be related to important fluctuations in oceanographic conditions, where the MOW could play a major role. Any start-up event suggests drastic environmental changes that favoured coral growth at a certain period. Such changes may have been triggered by episodic gas release at the seafloor or changes in the oceanographic circulation patterns, with the influx of MOW into the Porcupine Basin. At present no conclusive evidence has yet been found for either hypothesis.

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