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# Seismic evidence of current-controlled sedimentation in the Belgica mound province, upper Porcupine slope, southwest of Ireland

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## Abstract

The Porcupine Seabight is an embayment that takes a particular position in the NE Atlantic slope. Sonographs, a few current measurements and hydrodynamic modelling suggest the presence of a strong northward-flowing bottom current, locally enhanced by internal tides, affecting the eastern slope of the Seabight. At this location a province of coral banks is described, expressed as mounds lined up in along-slope-trending ridges. In this paper, very high-resolution single-channel seismic profiles are used to evaluate to what extent the bottom currents influenced the deposition of the sediments surrounding the mounds throughout the Late Cenozoic. Three seismostratigraphic units (P1, P2 and P3) can be identified in the Belgica mound area, separated by two margin-wide discontinuities (RD2 and RD1). Within Unit P1 (probably Early to Middle Miocene) upslope-migrating sediment waves are observed, suggesting strong bottom currents were already active in the Miocene. After an early Middle Miocene erosion event, represented by reflector RD2, an acoustically transparent layer (Unit P2) of as yet unknown lithology was deposited in the studied area. A second margin-wide erosional event, marked by the Late Pliocene RD1 reflector, removed a large part of Unit P2 and has cut deeply into Unit P1. Subsequently, the Belgica mounds were constructed spectacularly fast on topographic irregularities on the RD1 paleobathymetry. The onlap within the Quaternary Unit P3, which surrounds these mounds, suggests that the mounds were already present before the deposition of P3 and were big enough to affect the intensity of the currents around them. Furthermore, the channels and the mounds are, together with the complex oceanographic regime, the key morphological elements responsible for the shaping of a contourite system in the Belgica mound area during the Quaternary. One drift body is formed by an inferred south–north-directed current, with a drift levee and associated channel located on its western side. Between this channel and the mounds, large-scale sediment waves suggest an intensified bottom current running along the foot of the steep flanks of the mounds. The Belgica mounds are embedded in another drift body. Here, an interaction of bottom and turbidity currents is suggested, creating short turbidite channels at the southern and northern flanks of the mounds. Locally, small confined drifts can be observed where Unit P3 is deposited in a narrow passage made by the paleobathymetry of RD1 and the mounds.

*Keywords:* bottom current; turbidity current; seismic stratigraphy; Northeast Atlantic; Porcupine Seabight; Cenozoic; mound

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## 1. Introduction

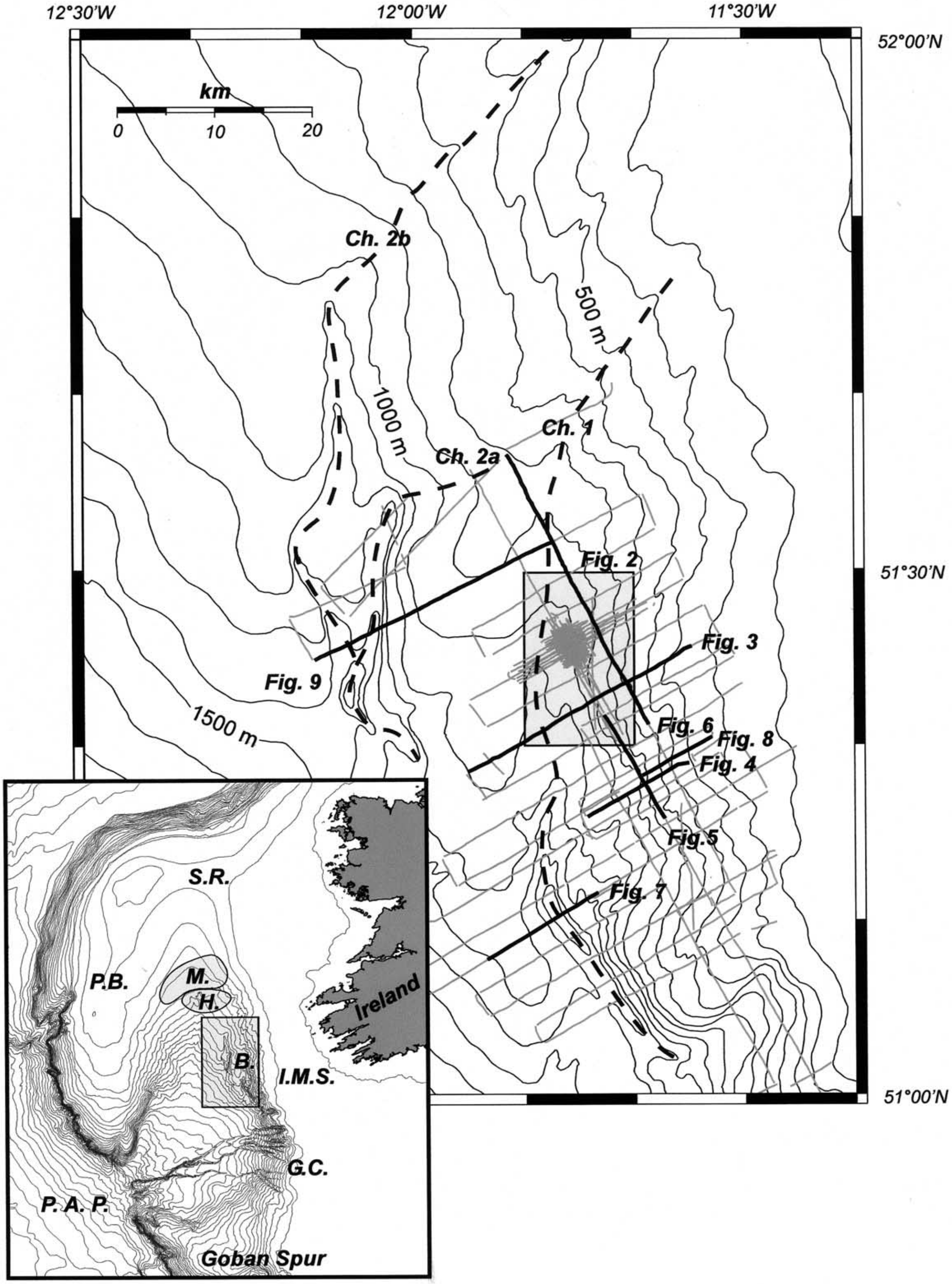
The Porcupine Seabight, lying off the west coast of Ireland, has been known since the end of the 19th century for its special deep water habitats (e.g. Thomson, 1873). A renewed interest in the Neogene and Quaternary evolution of the basin arose shortly after the publication of Hovland et al. (1994) on the presence of fault-associated seabed mounds within the northern part of the Seabight. The interpretation of commercial multichannel seismic profiles suggests these mounds are associated with underlying faults, which might act as migration paths for hydrocarbons. Industrial seismic profiles acquired on the eastern slope of the Porcupine Seabight revealed along-slope-trending ridges, interpreted as slump folds by Kenyon (1987). A high-resolution seismic survey with the R/V *Belgica* in May 1997 focused on this eastern slope to elucidate the structure of these slump folds. Unexpectedly a chain of partly buried and outcropping mounds was discovered (Henriet et al., 1998). In fact, a high concentration of *Madrepora* and *Lophelia* deep-sea corals and associated fauna has previously been reported by Le Danois (1948) at the same site and called 'Massif de la baie de Dingle'.

The Porcupine mounds occur in three well-delineated provinces, each featuring distinct morphologies (Henriet et al., 1998; De Mol et al., 2002). In the northern part of the Seabight, the 'Magellan' mound province features large numbers of small, buried mounds. South of them, complex mound structures at the seafloor are found in the 'Hovland' mound province. To the south, the 'Belgica' mound province, named after the R/V *Belgica* cruise in 1997, is characterized by conical mounds asymmetrically buried along the bathyal continental slope to the east of the Porcupine Seabight (Fig. 1).

De Mol et al. (2002) present a first general description of the morphology, seismic facies and sedimentology of the three mound provinces. They interpret the mounds as coral banks formed by a framework of corals and other macrobenthos, baffling sediments in an oceanographically dynamic environment. The influence of currents is known to be an important factor in mound initiation, growth and decay (Freiwald and Wilson, 1998; De Mol et al., 2002). Side-scan sonar imagery of the Belgica mound province reveals the presence of sand sheets and sand waves, suggesting the present-day seafloor is indeed swept by a relatively strong bottom current (Akhmetzhanov et al., 2001). Although the presence of bottom currents has been observed in the other mound provinces, texture analysis of the sonographs shows their strength is weaker than in the Belgica mound province (Huvenne et al., 2002). When such a current is forced to flow in topographically constrained areas like narrow passageways, troughs and along steep slopes, its energy tends to intensify and can be responsible for the shaping of a sediment drift body (Faugères et al., 1993, 1999). In the present-day morphologic and hydrographic setting of the Belgica mound area the energy and pathways of bottom currents are closely related to the position of the mounds.

In this paper we will present very-high-resolution single-channel seismic profiles with evidence of current-controlled sedimentation in and around the Belgica mound area throughout the Late Cenozoic. A preliminary correlation between the observed seismostratigraphic events and well-known margin-wide oceanographic events will be proposed.

Fig. 1. Map of the study area (Belgica mound province) on the eastern slope of Porcupine Seabight. The tracklines of the very-high-resolution seismic profiles of the R/V *Belgica* 1997, 1998 and 2000 campaigns used in this study are shown. The dashed lines delineate two slope channels. The inset map presents all topographic features and mound provinces in and around the Porcupine Basin named after De Mol et al. (2002). The gray inset box on the map represents the multibeam bathymetry presented in Fig. 2. P.B. = Porcupine Bank, S.R. = Slyne Ridge, I.M.S. = Irish Mainland Shelf, G.C. = Gollum Channels, P.A.P. = Porcupine Abyssal Plain, B. = Belgica mound province H. = Hovland mound province, M. = Magellan mound province.


12°30'W
12°00'W
11°30'W
52°00'N
51°30'N
51°00'N
km
0
10
20
Ch. 2b
500 m
1000 m
Ch. 1
Ch. 2a
Fig. 2
Fig. 3
Fig. 9
1500 m
Fig. 6
Fig. 8
Fig. 4
Fig.5
Fig. 7
S.R.
P.B.
M.
H.
Ireland
B.
I.M.S.
G.C.
P. A. P.
Goban Spur

## 2. Geological and hydrographic framework

### 2.1. Geological setting

The Porcupine Seabight may be regarded as an amphitheater-shaped embayment in the Atlantic Irish shelf, off the southwestern coast of Ireland (Fig. 1). The Seabight has a triangular shape with the longest side (230 km) oriented roughly north–south. It widens from approximately 65 km in the north to 100 km in the south. The water depth ranges from 200 m in the northeast, increasing gradually to 3000 m in the southwest, where the seafloor slopes down to the Porcupine Abyssal Plain to depths of 4000 m. The Seabight is enclosed by four shallow platforms: Porcupine Bank on the western side, Slyne Ridge in the north, the Irish Mainland Shelf in the east and the terraced Goban Spur in the south. The only opening towards the Porcupine Abyssal Plain lies between the Porcupine Bank and Goban Spur. All these barriers consist of metamorphic Precambrian and Paleozoic rocks. The underlying structure of the Porcupine Basin is a Middle to Late Jurassic failed rift of the proto-North Atlantic (Naylor and Shannon, 1982; Moore and Shannon, 1992). During the overall Cenozoic post-rift period, which is mainly characterized by thermal subsidence, approximately 10 km of sediment has been deposited in the center of the basin.

The Quaternary evolution of the Porcupine Basin has not been studied in any detail. Recent sedimentation is pelagic to hemipelagic, although (reworked?) foraminiferal sands can be found on the upper slope of the eastern continental margin (Rice et al., 1991; Swennen et al., 1998). It seems that the main sediment supply zone is located on the Irish and Celtic shelves, while the input from within the Porcupine Bank seems to be rather limited (Rice et al., 1991). In contrast to the slopes of the Celtic and Armorican margins, which are located east of the Porcupine Seabight, only one major sediment-supplying channel system is present on the southern margin of the Seabight. This east–west-oriented channel system was first described by Berthois and Brenot (1966) and subsequently named the Gollum Channel system by Kenyon et al. (1978). It is thought, by Berthois and Brenot (1966), to be the downstream component of a large fluvial system, which extended from the southern Irish Mainland Shelf during glacial periods. Rice et al. (1991) and Wheeler et al. (1998) suggest that the present-day channels are inactive. At a water depth of 3000 m, all channels converge into one deeply incised canyon, which flows into the Porcupine Abyssal Plain. Surprisingly, there is little evidence of a deep-sea fan. According to Rice et al. (1991) sediments may have been reworked and redistributed in drift deposits by strong bottom currents sweeping the Porcupine Abyssal Plain.

### 2.2. Hydrography

Oceanographic data collected at the mouth of the Seabight by Hargreaves (1984), Rice et al. (1991) and Van Aken (2000) show the stratification of the water masses in this region. Eastern North Atlantic Water is found to a depth of about 750 m where it overlies Mediterranean Outflow Water (MOW). The latter is characterized by a salinity maximum and an oxygen minimum at a depth of about 950 m. It is underlain at 1700 m by the North East Atlantic Deep Water and the Labrador Sea Water. At 1900 m depth, the influence of Norwegian Sea Water is detected. A permanent thermocline is found from 600 to 1400 m over which the temperature decreases from 10°C to 4°C. A seasonal thermocline is formed at about 50 m depth.

A north-flowing surface current is known to be present along the eastern North Atlantic slope, from the Iberian Margin to the Norwegian Sea (Pingree and Le Cann, 1989, 1990; Rice et al., 1991). According to Rice et al. (1991), it is not sure whether this current enters or completely bypasses the Seabight. Current meter data show a northward-flowing current along the eastern slope of the Porcupine Seabight with a mean flow of about 4 cm/s at the 1000-m contour, with larger along-slope residual flows near the seafloor. Although measured velocities reach 10 cm/s or more (Pingree and Le Cann, 1989, 1990), bedforms observed on sonographs indicate that the peak current can reach a considerable speed: up to 100 cm/s or even more (Akhmetzhanov et al., 2001). These complex and variable deep water currents are also predicted by hydrodynamic models (New et al., 2001).

On top of the general northward residual current, semidiurnal variations in current speed and direction were recorded at several locations (Pingree and Le Cann, 1989, 1990; Rice et al., 1991). Currents across the slope in the Porcupine Basin seem to be locally enhanced due to the influence of internal tides and waves, at those locations 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 e.g. the upper boundary of the MOW, where the density gradient is largest (Sherwin and Taylor, 1987).

## 3. Data acquisition

The seismic data available for this study were obtained during the cruises of R/V *Belgica* in May 1997, 1998 and June 2000 in the Porcupine Seabight. Most of the very-high-resolution seismic profiles are 30–40 km long and have a N60° orientation. Additionally, three along-slope (N155°) lines were recorded with a length of 50 km. Spacing between profiles was kept at 5 km, in order to provide a regular grid. A SIG surface sparker was fired at 500 J, creating a seismic signal frequency between 200 and 3000 Hz, which resulted in a 0.5–1-m vertical resolution. The acoustic penetration ranges from 400 to 800 ms two-way travel time (TWT). The data of all surveys were digitally recorded on an ELICS Delph 2 system with a sample rate of 4 kHz and processed with Landmark PROMAX software on a SUN workstation. The data processing involved a Butterworth bandpass filter (250 Hz with a 24 dB/oct slope and 700 Hz with a 36 dB/oct slope), minimum phase spiking deconvolution, and automatic gain control using a mean of 250 ms.

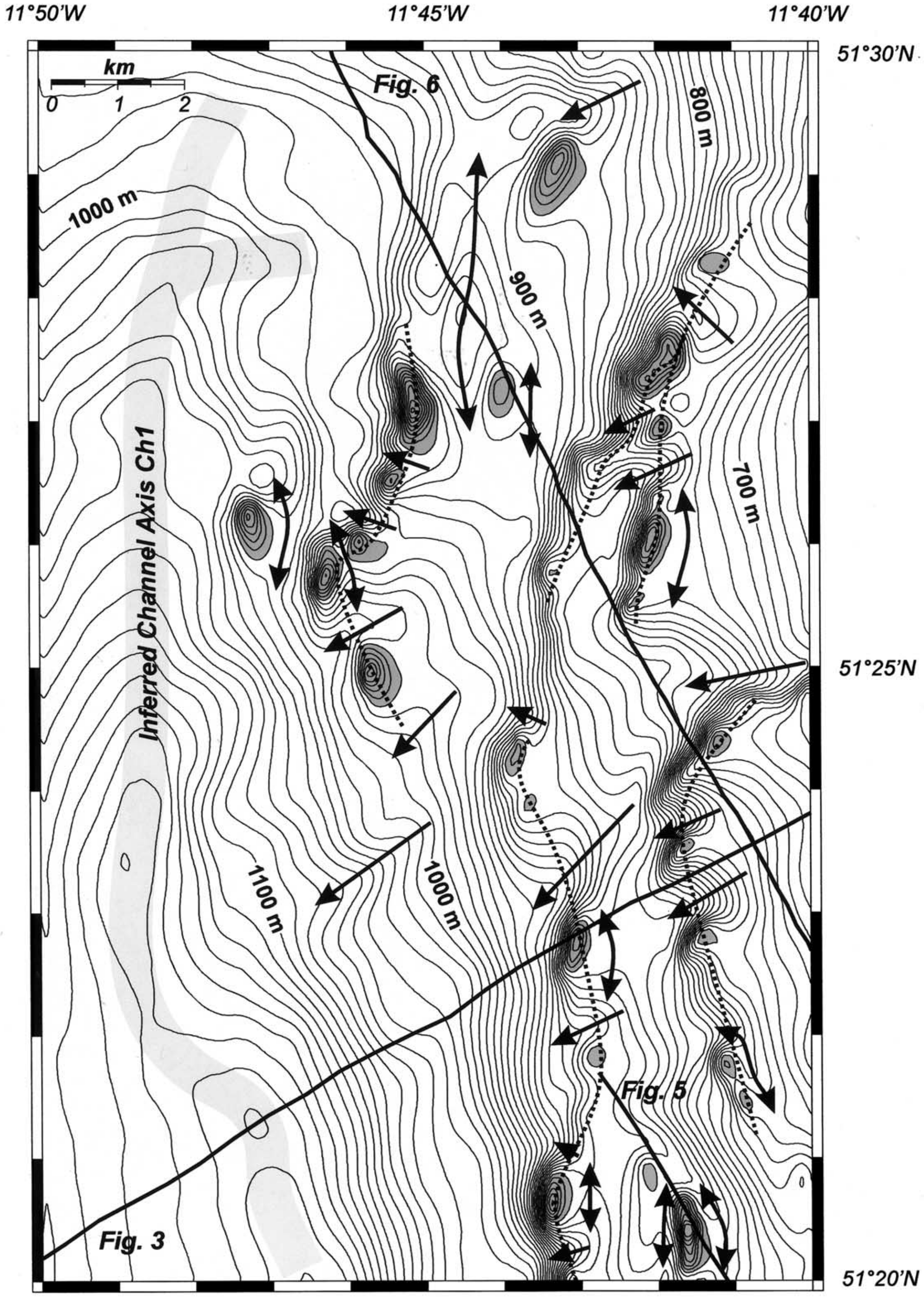
In addition to the seismic data, detailed bathymetry information from the narrow strip of the slope where the mounds lay was used in the interpretations. The data were collected by means of 15.5-kHz Hydrosweep 2DS multibeam echosounder, during the ANTXVII/4 cruise of the R/V *Polarstern* (Geomound project, May–June 2000). Data processing consisted of the application of locally measured water sound velocity profiles and the manual editing of both navigation and soundings (Geomound project, data courtesy of the Alfred Wegener Institute, Bremerhaven, Germany).

## 4. Morphologic features

The study area is situated on the upper eastern slope of the Porcupine Seabight, between 51°00′ and 52°00′N and 11°20′ and 12°20′W, in water depths of 200–1500 m. The morphology of this relatively gentle slope shows two remarkable morphologic features: along-slope channels (Fig. 1) and seabed mounds (Fig. 2).

Two major, partially along-slope-directed channels are recognized in the surveyed area (Fig. 1). The most upslope one (Ch1) is located between 11°40′ and 11°50′W, and between 600 and 1550 m water depth, with a total length of 50 km. The second channel, which has two converging branches (Ch2a and Ch2b), lies between 12°00′ and 12°10′W in water depths of 850–1600 m and has an overall length of 55 km (Fig. 1). A spur separates these two channels. At water depths of 1450 m and 1600 m, these channels are deflected towards the southeast, where they gradually lose expression.

The Hydrosweep bathymetry map (Fig. 2) shows a narrow strip of the slope (between 700 and 1000 m water depth) southeastward of Ch1, where a number of mounds are present. Most of the mounds appear to be more or less north–south elongated, with an approximate length of 1 km and a relief up to 100 m above the surrounding sea floor. As indicated in Fig. 2, the mounds seem to be aligned in four along-slope-trending ridges with steep west flanks (N25–40° and N160–170°). These are some of the ridges previously interpreted by Kenyon (1987) as slump folds. At the eastern side of the ridges the slope is generally shallower, suggesting an accumulation


11°50'W
11°45'W
11°40'W
51°30'N
51°25'N
51°20'N
km
0
1
2
Fig. 6
800 m
1000 m
900 m
700 m
Inferred Channel Axis Ch1
1100 m
1000 m
Fig. 5
Fig. 3

of sediments. These ridges are interrupted by downslope-running gullies with an approximate N225° orientation. However, sometimes a south–north orientation can be inferred. These gullies are relatively short (1–2 km long) and they do not seem to coalesce directly with channel Ch1.

## 5. Seismic stratigraphy

The relatively dense spacing of the seismic profiles allows us to distinguish three major seismic units within the Porcupine Seabight: P1–P3. These units are discussed below in terms of changes in seismic facies, thickness, local occurrence and bounding unconformities.

### *5.1. Unit P1*

The lowermost unit (P1) is generally characterized by gentle basinward-dipping (between 1.75 and 2.5°) continuous parallel strata with moderate to locally high amplitude reflections (Fig. 3). A paleoslope break separates a slope section with an apparent sub-horizontal stratification (0.75°) from a slope of approximately 2° (Fig. 4). On that paleo-upper slope a complex sigmoidal-wavy reflector configuration is encountered. This configuration, consisting of small lenticular bodies enclosed between wavy reflectors, is observed at a constant depth of approximately 1.2–1.5 s TWT (Figs. 3, 4 and 5). On NE–SW profiles these bodies seem to migrate upslope (Fig. 4), while on NNW–SSE profiles they seem to migrate SSE-ward, though more irregularly stacked (Figs. 5 and 6). The upper boundary of unit P1 is an erosional unconformity which strongly incises the lower slope sediments. The two modern channels Ch1 and Ch2 also incise this unit. Channel Ch1 cuts 300 ms TWT below the upper boundary of P1 in the south (Fig. 7), whereas more to the north it incises less deeply into unit P1 (Figs. 3 and 6).

### *5.2. Unit P2*

This unit is characterized by a nearly transparent seismic facies of limited lateral extent, deposited on the erosional unconformity described above. Within this unit, only a few sets of continuous, relatively high-amplitude reflectors are observed (Figs. 4, 5 and 8). The unit shows an irregular distribution, but generally disappears towards the NNW (Figs. 5 and 6) and towards the SW (Figs. 3 and 9), whereas it extends beyond the data coverage in the southeastern part of the study area, where it reaches its maximum thickness of over 200 ms TWT (Fig. 8). Here, the upper part of P2 has been incised, creating an undulating boundary. Between water depths of 650 and 800 ms TWT the thickness of P2 drops dramatically from approximately 100 ms TWT to 0 ms TWT over 350 m, creating relatively steep flanks of about 15° (Fig. 8). Downslope from this point, nearly the complete unit is eroded although some profiles in the southern part of the area still show some remnants of this transparent layer (Figs. 4 and 8). Hence, this second erosional surface largely coincides with the upper boundary of P1, thus forming a composite erosion surface (Figs. 4, 5 and 8). In channel Ch1, this erosion event is very pronounced, also cutting very deeply into P1 (Fig. 7). Only a few profiles show the presence of P2 at the western side of this channel, still with the same dip as on the eastern side (Fig. 3).

### *5.3. The Belgica mounds*

On the seismic profiles, the Belgica mounds are characterized as almost acoustically transparent elevated structures with a parabolic outline. Within the mounds no clear internal reflections are observed. The real shape of the mounds however is masked by diffraction hyperbolae. The best indication of the mound shape is deduced from the reflection termination of the surrounding sedi-

Fig. 2. Extract of the hydrosweep bathymetry map, kindly provided by the Alfred Wegener Institut in Bremerhaven. The contour interval is set at 10 m and all the outcropping mounds are indicated in gray. The dotted lines accentuate the apparent alignment of the mounds. The black arrows indicate the possible pathway of the currents running down the gullies close to the mounds.

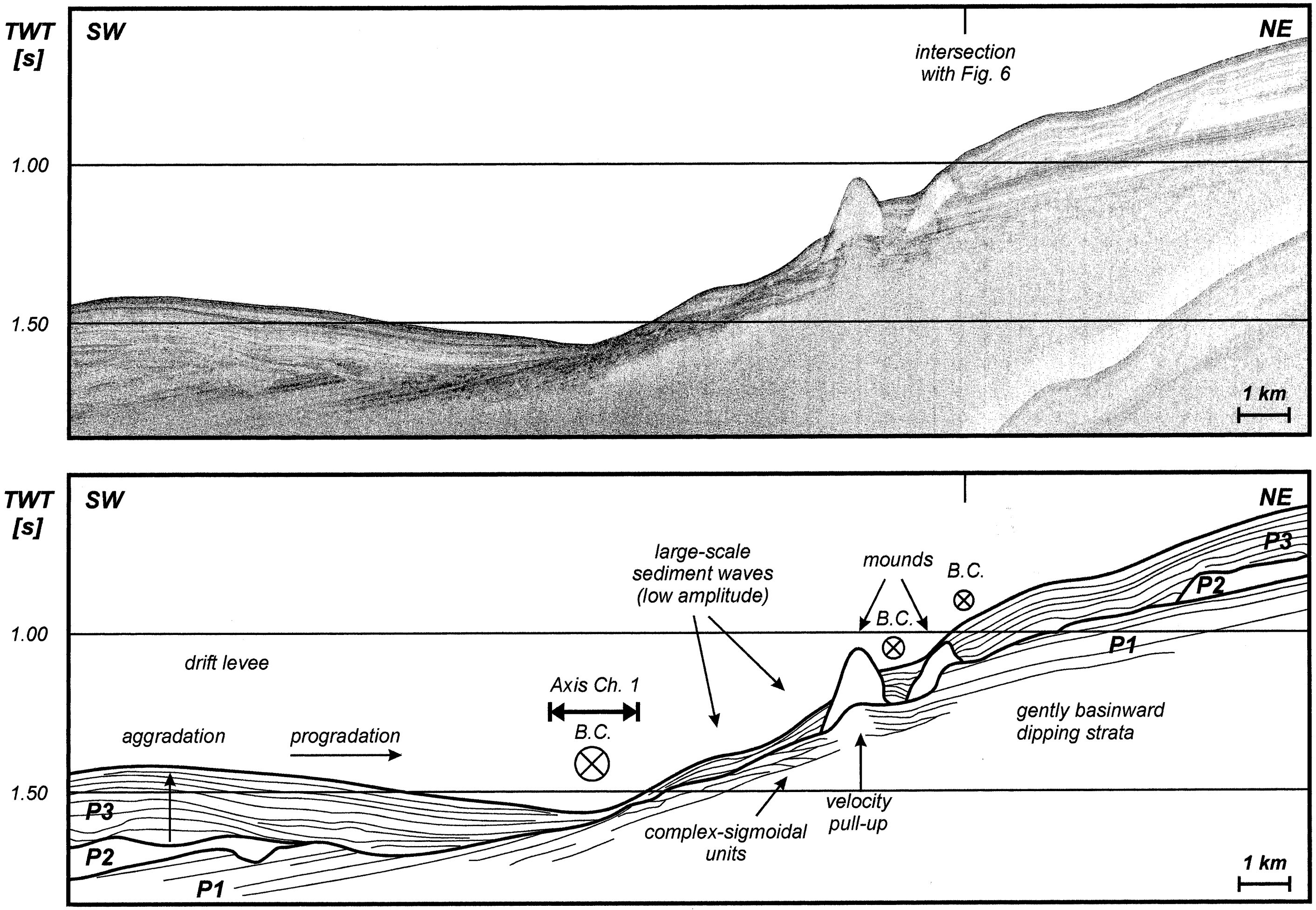


Fig. 3. Overview of seismic features and unit geometry on the eastern slope of the Porcupine Seabight in a NE–SW profile P980521. Several erosional features can be observed cutting into unit P1. This is one of the few profiles where unit P2 is observed southwest of the slope channel. B.C. = bottom current.

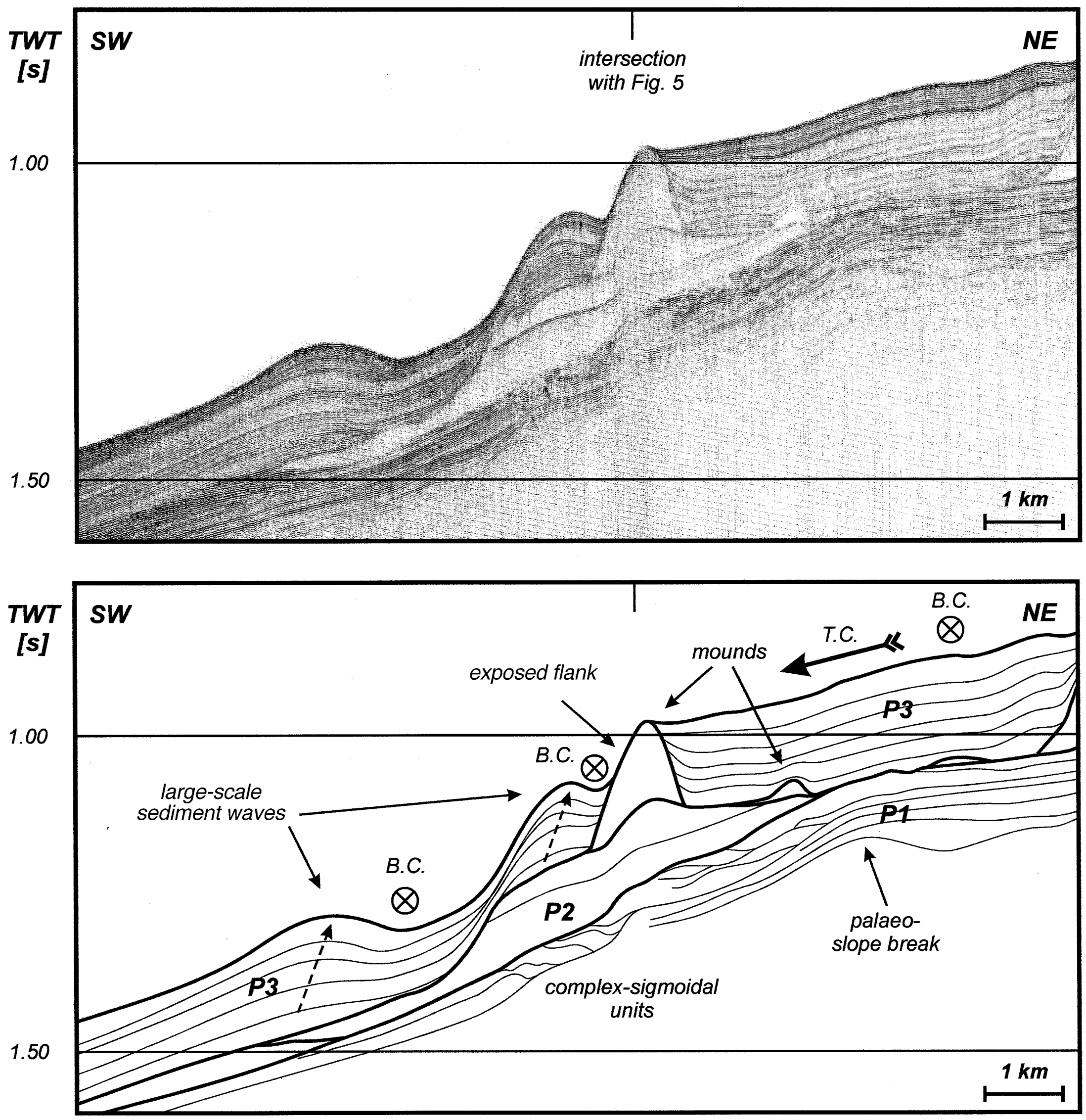


Fig. 4. NE–SW-oriented profile P970536 illustrating a large mound with surface expression, rooted on the acoustically transparent layer of unit P2. This conical mound is located on an elevated position in the paleobathymetry. The asymmetry in sediment burial is evident, showing a semi-exposed southwestern flank and a buried northeastern flank where the nearly parallel P3 reflectors onlap on the mound. On the steeper southeastern slope, the configuration features large-scale sediment waves. Note the presence of a paleoslope break in unit P1. B.C. = bottom current, T.C. = turbidite current.

ments at the mound and the apex of the hyperbolae (Figs. 4, 5, 6 and 8).

In general the mounds display a broad base, which roots on the composite erosion surface (Figs. 4, 5 and 6). In the SSE–NNW direction the mounds have a broader footprint than in the NE–SW direction. Some apparently single mounds merge at their base and form a composite mound. This results in ellipsoidal to conical structures with several summits, lined up in a general SSE–NNW direction. The base of the mounds is not always easy to delineate, especially on the

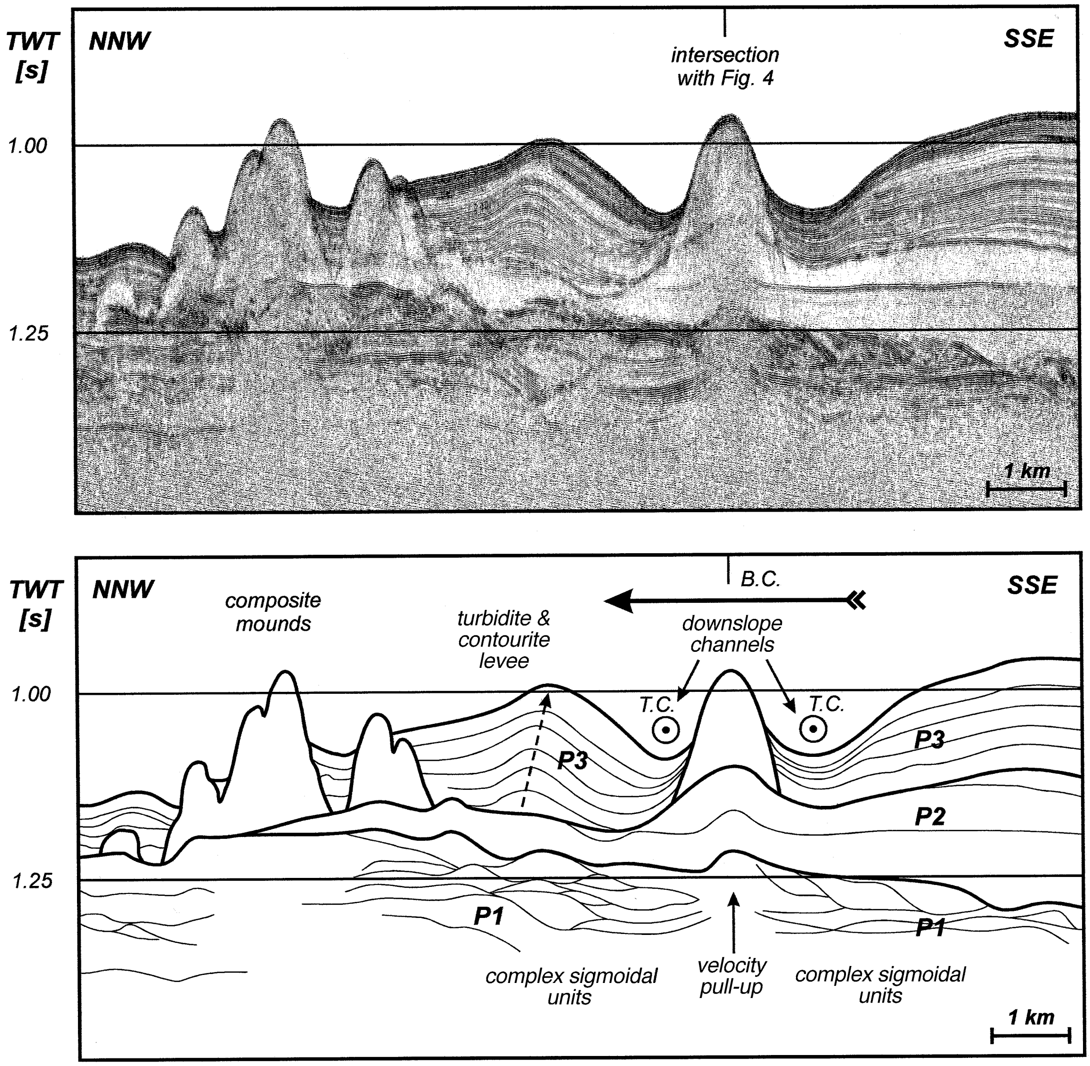


Fig. 5. SSE–NNW-oriented profile P980549 intersects the single mound of Fig. 4. In contrast with the latter figure, there is no geometric asymmetry of the sediments surrounding this single mound. At both sides, the mound is flanked by probable turbiditic channels, suggesting downslope transport. Unit P2 progressively thins and finally disappears towards the northernmost part of the profile, where the composite mounds are directly rooted on the upper boundary of unit P1. Underneath the mounds, velocity pull-up is observed, as well as the lack of sufficient penetration into unit P1. Elsewhere in this unit, a complex of sigmoidal units is observed. The dashed arrows indicate the apparent migration of the levees. B.C. = bottom current, T.C. = turbidite current.

southernmost profiles, where they root on Unit P2. Here, the remains of strongly eroded P2 strata occupy an elevated position in the paleobathymetry. This is expressed in a change of gradient from nearly horizontal to a slope of approximately 2° (Fig. 4). To the north, the mounds tend to step off the eroded P2 unit (Figs. 5 and 6). In this case, the mounds are resting on a scarp of P1 sediment. The base of the mound and underlying reflectors are distorted by velocity pull-up (Figs. 3, 5, 6 and 8). This acoustic artefact is particularly evident where the mounds are exposed (and the lateral acoustic velocity contrast is high).

The size of the mounds tends to decrease from north to south, where they generally are buried under a thin sedimentary cover (4–12 m). Their height can range from 35 to 175 ms TWT in the northern part. The basal width of the mounds varies from 300 to 1800 m. Hence, the average slope of a mound ranges between 10 and 15°.

## 5.4. Unit P3

### 5.4.1. Geometry and seismic characteristics of Unit P3

The most recent unit covers the entire study area. The seismic facies of this unit is characterized by high-frequency, continuous, parallel reflectors with variable amplitudes (Figs. 3, 4 and 5). Based on the differences in amplitude and internal unconformities, several sections can be distinguished. Over the entire study area, three major changes in geometry can be observed, possibly resulting from the interaction between the surrounding topography and the current regime.

In the area east of the mounds and the apparent along-slope-trending ridges, the thickness of P3 gradually decreases from 250 ms TWT in the south to 50 ms TWT in the north. In a SSE–NNW transect, the geometry is wavy with gentle undulations and condensed sections (Figs. 5 and 6). On NE–SW-oriented profiles, however, the thickness remains relatively constant with a sheeted geometry consisting of mainly parallel reflectors (Figs. 3 and 4). On the upper part of the slope this unit is deposited on the undulating upper boundary of P2 (Figs. 3 and 8). The slope of the seafloor and underlying strata dips about 2° to the SW. The P3 reflectors are downlapping or onlapping on this boundary, although they sometimes seem to be deposited conformably. A first visible change in geometry is encountered between approximately 500 and 600 m water depth, where the thickness of Unit P2 drops drastically, creating steep flanks in the paleobathymetry (Fig. 8). Unit P3 narrows towards the scarp. Here, the seafloor slope can locally increase up to 6°. Further downslope, the thickness and average slope of Unit P3 are the same as before, but more irregularities are met when approaching the mounds.

Between the mounds and the channels, the geometry, thickness and reflection termination of Unit P3 are quite variable. The total thickness is locally reduced to 50 ms TWT, creating a wavy reflector configuration. In Fig. 4, this can be seen as large-scale sediment waves migrating gently upslope. A few kilometers to the north, the amplitude of these sediment waves can be reduced (Fig. 3). They have been deposited on a paleoslope which is steeper in the south (approximately 4°) than in the north (2°). This, of course, is largely dependent on the proximity of the channel and the steepness of its eastern flank.

Finally, west of channel Ch1 a very thick P3 unit (200–250 ms TWT) has been deposited on the composite erosion surface (Figs. 3, 6 and 7). Towards the channel, the thickness of Unit P3 decreases but everywhere covers the western flank of the channel. The first strata are deposited unconformably on the basal discontinuity. The structure of this part of Unit P3, however, seems to change from south to north. In the south the strata gently onlap. The decrease in thickness towards the channel happens rather abruptly (Fig. 7). Further to the north, this decrease in thickness is more subtle (Fig. 3). Here, the aggradation of the main sediment body seems to be characterized by a prograding trend. In tracing the onlap of P3 strata upon the basal erosive discontinuity, a subtle upslope migration of the channel axis is observed. In Fig. 6, more complexity is added to this levee-like build-up. Initially, there is a southward progradation with downlapping reflectors (2°) on the erosion surface. This is followed by a subsequent reversed (northward-prograding) trend.

### 5.4.2. Depositional features and reflector terminations around mounds

The geometry and reflector terminations of the P3 strata around the mounds can give an indication of the relative chronology of mound growth. Also, they can help in the assessment of the influence of the mounds on the deposition of Unit P3. Therefore, a few mounds have been selected to study the nature of reflector termination and behavior of the subunits.

The mound shown in Figs. 4 and 5 appears as a single mound rooted on P2. To the northeast, all

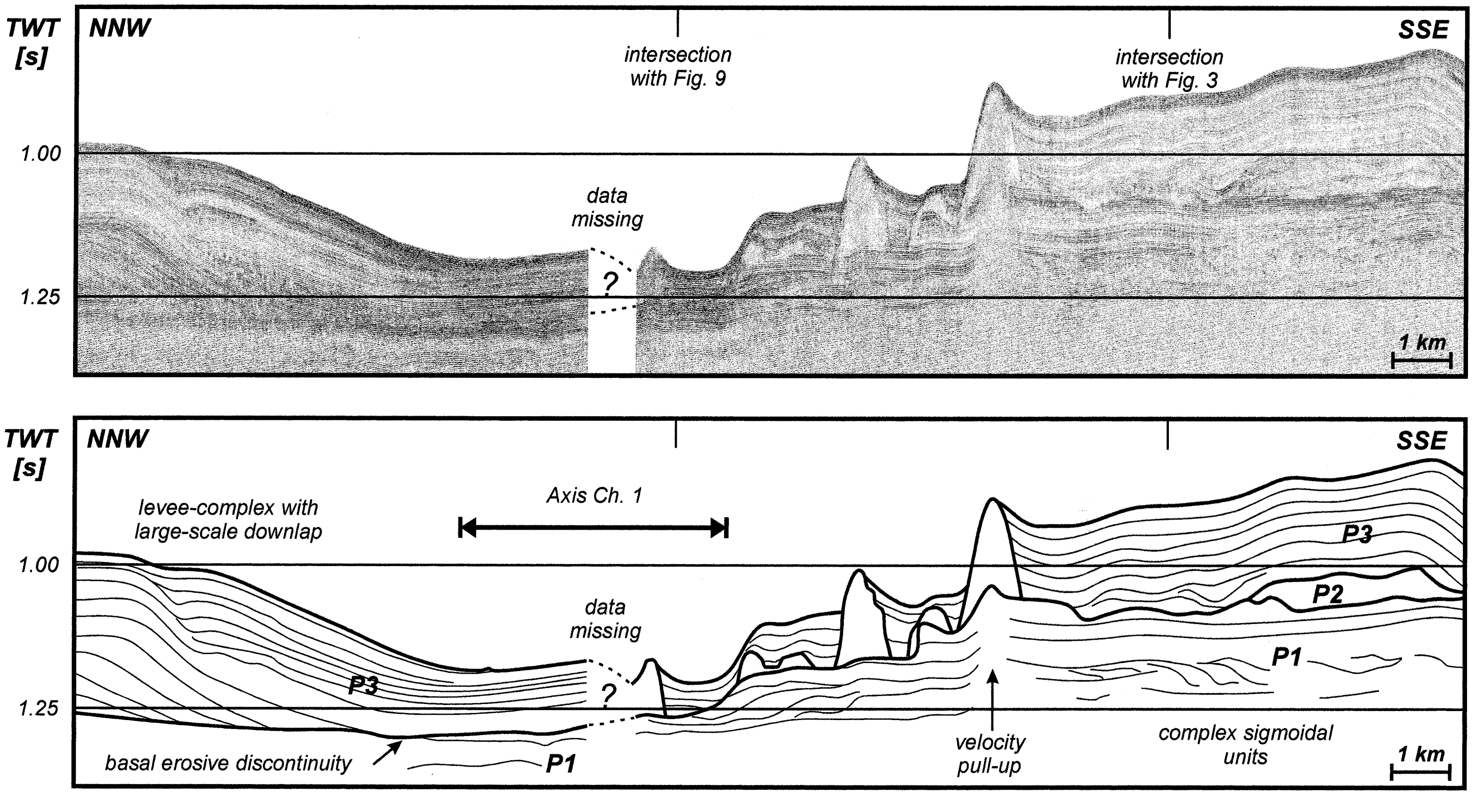


Fig. 6. NNW–SSE-oriented profiles P980552 and 53 located in the northern part of the data set. Channel Ch1 also bounds the northern limit of the Belgica mounds. In contrast to the seismic section shown in Fig. 5, which is located more to the south, the sediments of unit P3 are ponded against the SSE side of the mound. The NNW side is almost completely exposed. Note the presence of the relatively steeply dipping downlapping reflectors on the basal unconformity NNW of channel Ch1, as well as the complexity of this levee-like feature.

reflectors within P3 are parallel and onlap against the mound. To the southwest, the section is reduced in thickness and shows an upslope-migrating wavy geometry with reflectors onlapping on the mound. The uppermost reflectors even feature small moats with a width of about 100 m, suggesting the action of currents. In a NNE–SSW profile (Fig. 5), the geometry of P3 is dominated by the presence of moat structures with a width of about 1 km on both sides of the mound. These structures seem to have been present since the deposition of the lowermost P3 reflectors and probably are a transverse section through one of the many gullies flanking the mounds as observed in Fig. 2. Yet, there is a striking difference between the sediment bodies at both sides of the mound. On the NNW side, the geometry is mounded and seems to prograde gently towards the gully. Some of the lowermost reflectors do not even seem to reach the foot of the mound. SSE of the mound, the geometry is more sheeted, suggesting a more aggradational style, though a slight southward progradation is evident.

Another single mound (Fig. 8) is located NNW of the previously discussed mound. Here, the geometry of Unit P3 seems to be controlled by the distance between the steep flanks of the mound and the P2 scarp. In a previous example (Fig. 4), the distance of this passage exceeds 5 km and a sheeted geometry is found. Only minor irregularities such as downlap are found against the lower boundary. In this case (Fig. 8) however, the passage is relatively narrow (2 km or less) and the overall geometry has a mounded appearance with moats on both sides. In particular on the side of the P2 scarp, large moat-like features (width up to 500 m) are observed. The thickness of this mounded sediment body varies from 150 to 250 ms TWT. On the southwestern side of the mound, the thickness and reflector terminations are less pronounced, although subtle moats can be inferred.

Finally, it should be noted that on the upslope side of the mounds, a thick Unit P3 is always present, ponded against the mounds. On the downslope side, or on the side of the slope channel Ch1, the flank of the mound mostly remains exposed (Figs. 3 and 6).

### *5.4.3. The channels*

Ch1 is the only channel crossing the entire dataset from south to north. As demonstrated the channel cuts very deeply in the south (Fig. 7), while towards the north it broadens and shallows (Fig. 3). Furthermore, at a water depth of 1450 m, Ch1 changes from an N120° orientation to a clear south–north orientation (Fig. 1). The Belgica mound findings are restricted to the southeast of Ch1 (Fig. 6).

In the southern part of the study area, Ch1 is 370 m deep with steep flanks (up to 15°), keeping the eastern flank free of sedimentation (Fig. 7). On the other hand, on the less steep western flank (9°), wedges of Unit P3 are prograding into the channel. On the channel floor an infill up to 120 ms TWT is found with interbedded, acoustically transparent lens-shaped bodies (gravity flow deposits?).

A few kilometers to the north, Ch1 is less deep (140 m) and is less easy to define than in the south (Fig. 3). There are no clear flanks to the channel. Unit P3 is about 250 ms TWT thick to the southwest of the channel, but it is reduced to a very thin cover in the channel axis due to both pinch-out (onlap) of the lower reflectors and erosion of the upper ones (Fig. 3). Between the channel floor and the mounds, the thickness of Unit P3 seems to be reduced and the geometry features large-scale sediment waves (Figs. 3 and 4).

In Fig. 6, where the channel is seen on a NNW–SSE transect, its orientation is south–north. Here, the channel is flanked to the NNW by a large levee complex and by mounds in the SSE. Two phases in levee construction can be distinguished: a first southward-prograding stage and a second northward-prograding/aggradation phase. The channel also seems to be much less erosive here compared to its southern part (Figs. 3 and 7). Fig. 9 shows the difference in morphology between the shallow part of Ch1 and the deep part of Ch2. In the ENE, only subtle variations in reflector configuration suggest the presence of Ch1. Only the uppermost reflectors are cut by the seafloor, indicating the presence of relatively strong currents only in recent times. The observation of small diffraction hyperbolae on the supposed channel floor suggests a coarse seabed mor-

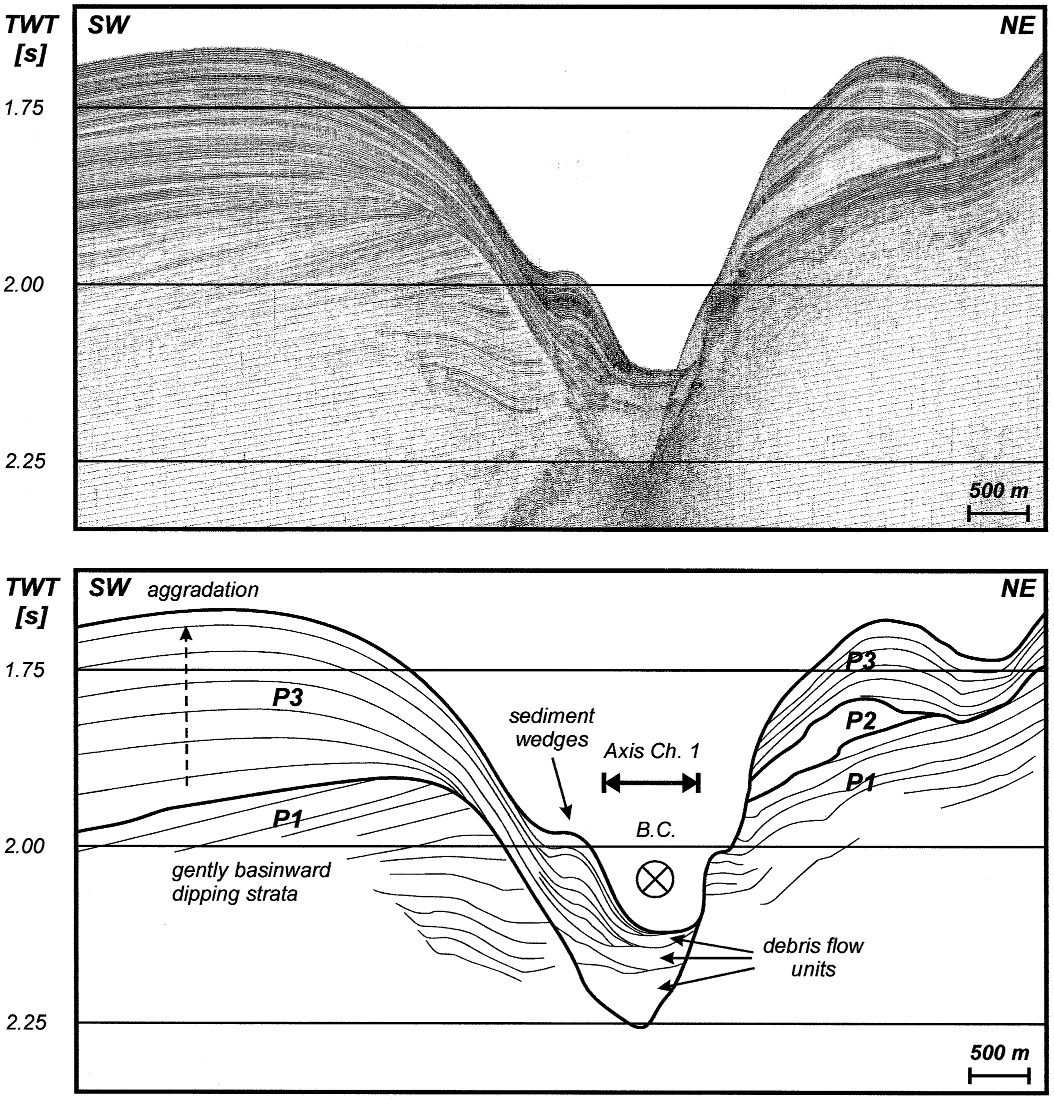


Fig. 7. Profile P970533A in the southern part of the study area showing channel Ch1 cutting deeply into P1 strata. It is filled with acoustically transparent lenses, probably mass-wasting deposits. Although sediment wedges are deposited on the southwestern side of the channel, the other steeper side is devoid of a sediment cover. B.C. = bottom current.

phology. This is confirmed by box cores and benthic sledges carried out during the Porcupine-Belgica 2000 survey, which yielded the presence of a gravel lag on this location. On the other hand, slope channel 2a on this profile acts in a similar way as Ch1 in the south, cutting deeply into Unit P1 (Fig. 9). Here, Unit P3 has the same typical seismic facies but it seems to be shaped into a mound morphology by the presence of the two slope channels. Inside this unit, the reflector configuration sometimes features a wavy configuration with sigmoidal bodies.

## 6. Discussion

The data described above indicate that the evolution of the upper eastern slope of the Porcupine

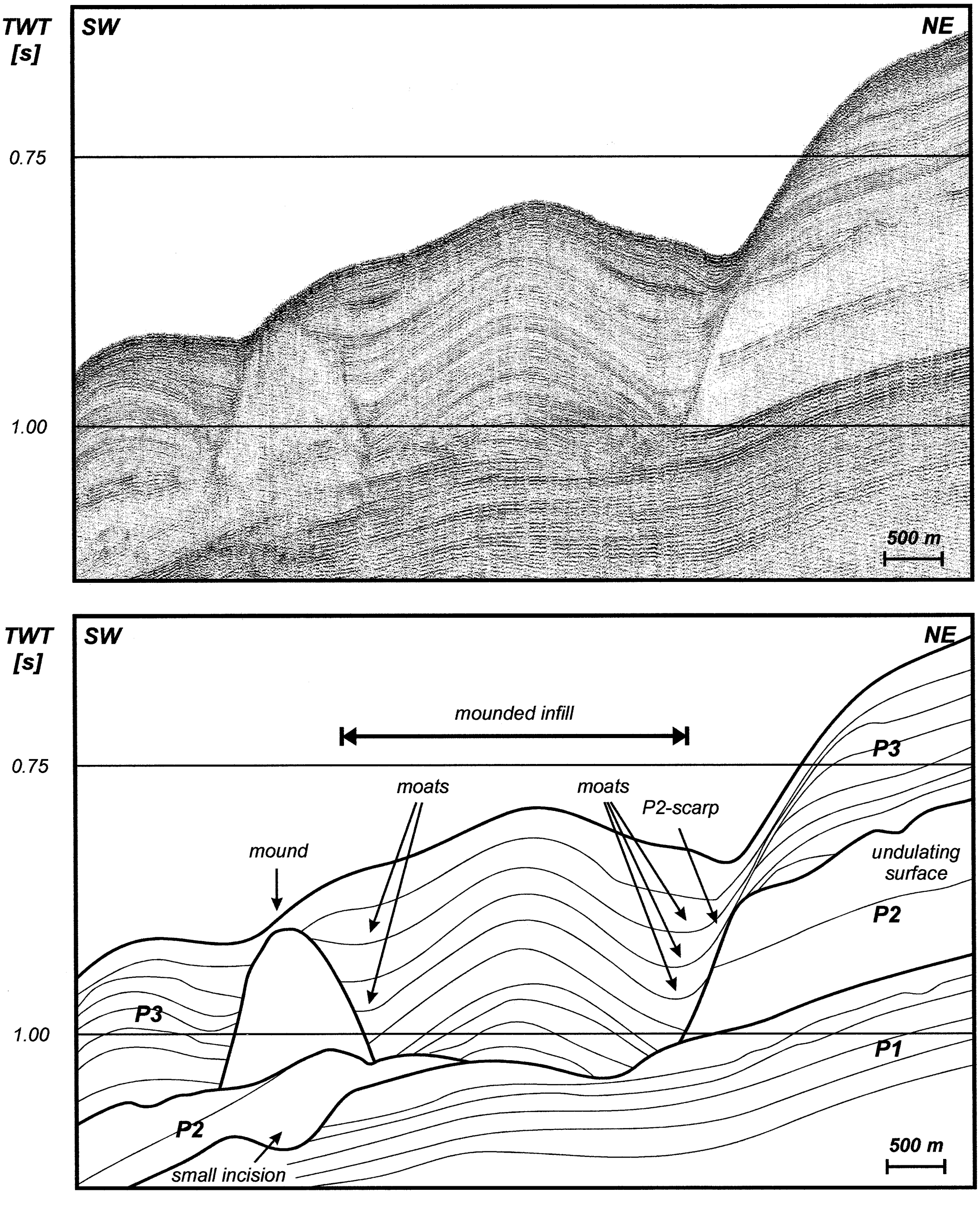


Fig. 8. Profile P970539 showing a mounded infill in a narrow passage between the steep flanks of a mound and a scarp in unit P2. In the lower part of the unit, the strata are downlapping on the basal unconformity and prograde towards the feet of the flanks. Higher in the unit, moats and onlapping reflectors are observed. Note the influence of the P2 scarp on the overlying sediments.

Seabight has been very dynamic and complex. The penetration and the very high resolution of the seismic data enable us to discuss the local stratigraphic events during Late Cenozoic times. The appearance of the mounds marks a significant change in the paleotopography, and thus probably also in the behavior of the bottom current regime. Therefore, the discussion will be subdivided into a relative chronology of pre-mound deposits (units P1 and P2) and the most recent unit (P3) will be discussed in terms of the influence of bottom currents and their interaction with the mounds.

### *6.1. A relative chronology of pre-mound deposits*

Most of the P1 strata reflect a hemipelagic sedimentary environment. In a water depth of about 600 m (upper slope), the parallel reflectors dip about 2° to the southwest. Stratigraphically equivalent reflectors on industrial seismic profiles have been interpreted as Early to Middle Miocene in age (A. McDonnell, personal communication). However, on the upper part of the slope below a paleoslope break, between 1.2 and 1.5 s TWT, upslope-migrating sigmoids appear, suggesting a local more dynamic environment. The origin of the break in the paleoslope might be related to the presence of underlying basement features (e.g. rift blocks). Although the true geometry of these irregularly stacked lenticular bodies is still unknown, they can be compared to features with similar dimensions observed on the slope of Gabon continental margin interpreted as upslope-migrating sediment waves created by landward flowing currents (Séranne and Abeigne, 1999). This implies the presence of bottom current flow on this slope section during the Early Miocene and possibly a first phase of sediment drift development. Unfortunately, most of these features are cut into by an unconformity, preventing a full understanding of the entire development of these deposits.

The upper erosional boundary of P1 is inferred to be related to an early Mid Miocene erosion event. This event was recognized in DSDP cores on Goban Spur and Rockall Trough, representing hiatuses of about 6 Myr (de Graciansky et al., 1984; Pearson and Jenkins, 1986). In the Rockall Trough, Stoker et al. (2001) recognize three main reflectors that are related to the onset and subsequent changes of bottom current activity. The second reflector, C20, may be correlated with the early Mid Miocene erosion event. According to de Graciansky et al. (1984) it is related to vigorous bottom currents due to the introduction of Norwegian Sea Water in the North Atlantic Ocean. Analogous to the nomenclature of Stoker et al. (2001), the regional discontinuity related to this event will be referred to as RD2.

The P1–P2 boundary (Fig. 3) can easily be correlated from one side of the channel to the opposite one. This implies that the sediments of Unit P2 were deposited over the entire slope and eroded later on. Although no lithological information is known about this acoustically transparent unit, its distribution and the seismic facies hint that it might contain very homogeneous sediments. The sets of internal reflectors with high amplitude might indicate some compositional changes or periods of non-deposition.

After the deposition of P2, a major change in oceanographic conditions was responsible for a large-scale erosive event along the entire slope of the Porcupine Seabight. This second erosion event removed a large part of Unit P2, as well as some P1 sediments, creating steep flanks within both units (Fig. 3). A regional Late Pliocene hiatus, found in the Rockall–Goban Spur transect, could be a possible cause for this regional discontinuity (RD1), which is interpreted in terms of the reintroduction of MOW in the NE Atlantic and the effect of glacial–interglacial events on deep water circulation (Stow, 1982; Pearson and Jenkins, 1986).

This erosion event also created the base of the slope channels, cutting sometimes very deeply into the Early Miocene deposits. The changes of the Ch1 wall geometry from south to north and the subsequent depositional patterns indicate the action of a south–north-directed bottom current. Even after this Late Pliocene erosion event this current keeps on flowing. First of all, the channel is deeper and less covered with sediments in the south (Fig. 7). This implies a vigorous current preventing deposition. The only deposits are

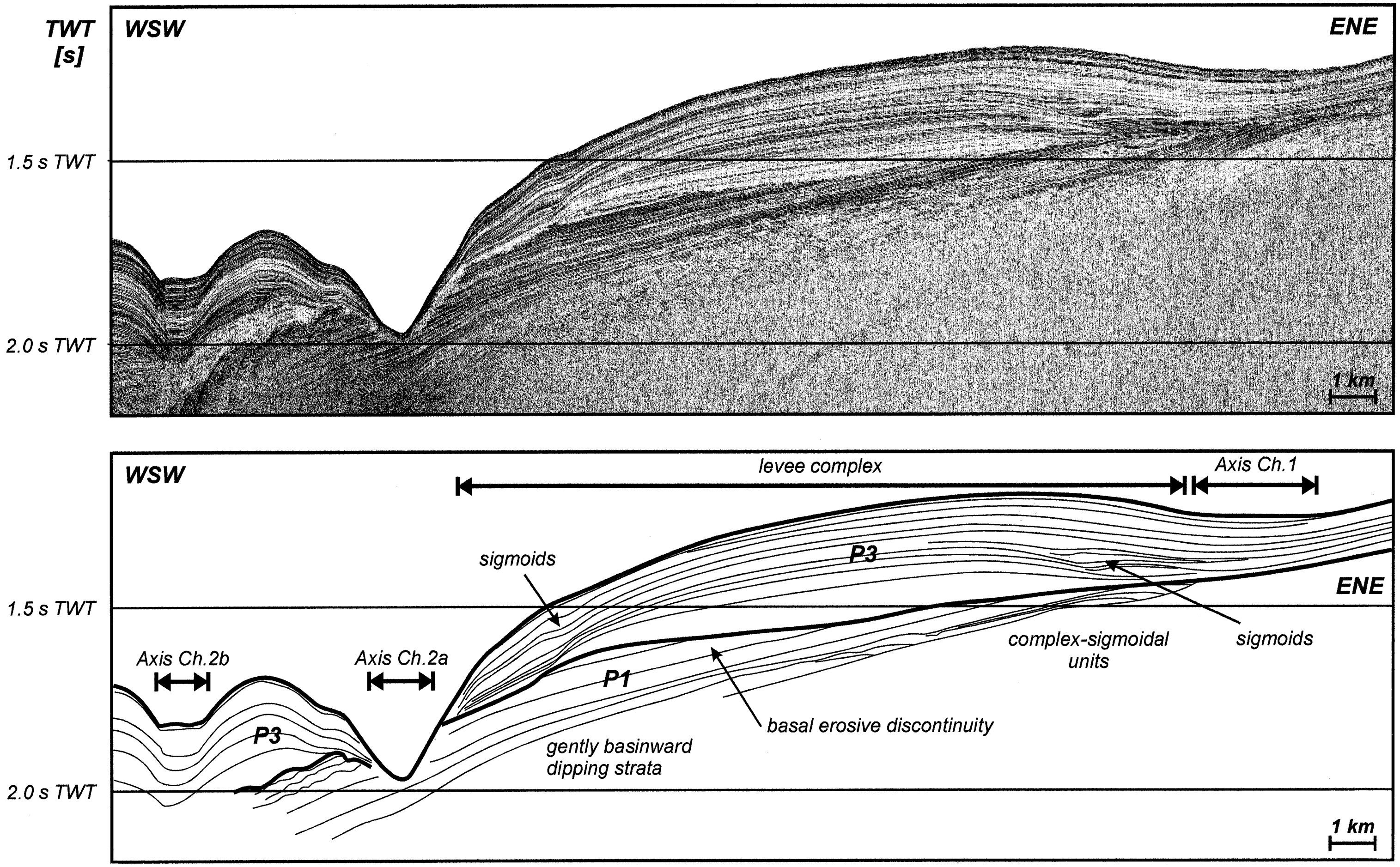


Fig. 9. This northernmost profile P000665 features the most recent unit captured and moulded between the two slope channels. Subtle changes in the thickness of unit P3 and the wavy reflection configurations clearly indicate the role of current interaction during the deposition of this unit. The shallow part of Channel 1 is less pronounced than the deepest part of Channel 2a, which is cutting down to unit P1.

probably debris flows, slumped from the steep channel walls. When following Ch1 to the north, it broadens, becomes less deep and more sedimentation has occurred (Fig. 3). The current is thus less vigorous, but still a channel is present. Eventually, the entire channel deflects gently to the north and shallows (Figs. 1, 6 and 9). The contour current is thus plastered against the eastern slope of the Porcupine Seabight, flowing towards the north, and is eventually forced to climb upslope where it will lose intensity and disappear. Nevertheless, we do not exclude the possible contribution of downslope flows.

### *6.2. Environmental controls on mound growth*

Our observations do not add much to those of De Mol et al. (2002) who interpret the mounds in the Porcupine Basin as coral banks. For this paper, however, it is interesting to briefly address the possible environmental controls on the development of the mounds. Their location on this part of the margin and their size will be of importance during the later development of the sediments surrounding these mounds. Freiwald et al. (1999) and De Mol et al. (2002) already pointed out that the builders of these coral banks, most often *Lophelia pertusa* and *Madrepora occulata*, prefer to settle on a hard substratum on an elevated position. They need strong bottom currents to get sufficient nutrients, but also to keep them free from sediment burial. So the mere presence of the mounds may already be an indicator of (strong) bottom currents after the Late Pliocene erosion.

The hydrosweep map (Fig. 2) shows that the Belgica mounds occur in a very narrow bathymetric interval between 700 and 1000 m below sea level, lined up as along-slope-oriented ridges. Most of the observations confirm that the mounds started to grow on a scarp or a topographic irregularity in Unit P1 or Unit P2, depending on the extent of the RD1 erosion event. Moreover, the sigmoidal units observed in Unit P1 and interpreted as sediment waves are located within the same slope section, exactly underneath the mounds (Figs. 3, 4 and 5). Recent models, combined with the few current meter data and the side-scan sonar imagery, indicate that the Belgica mound province nowadays is located in an area affected by enhanced currents (Pingree and Le Cann, 1989, 1990; Rice et al., 1991; Akhmetzhanov et al., 2001). So it appears this slope section may have been under the influence of enhanced bottom currents since as early as the beginning of the Miocene.

A study of the reflector terminations within Unit P3 around the mounds can yield more information about the start-up of mound growth and their relative growth rate. On most of the profiles, the lowermost reflectors onlap on the mound, suggesting that the mound was already present, though possibly not yet fully grown at the moment of deposition (Fig. 4). This implies that the mounds were built spectacularly fast, probably after and during a period of non-deposition. In some cases the lowermost reflectors do not even reach the mound (Fig. 6), which implies that the sediments of Unit P3 were prevented from deposition near the mounds.

### *6.3. The influence of bottom currents on the deposition of Unit P3*

The Late Pliocene erosive discontinuity, represented by the RD1 reflector, was created when modern oceanographic conditions were established in the North Atlantic (Pearson and Jenkins, 1986; Schnitker, 1986) and glacial–interglacial cycles started to have a pronounced effect on the production of the North Atlantic Deep Water, the Antarctic Bottom Water and the Norwegian Sea Water. These changes resulted in the variability of the thermohaline geostrophic circulation and thus affected the construction and evolution of the well-known sediment drifts along the margins of the North Atlantic (e.g. Stow, 1982; Faugères et al., 1993). The Belgica mound province, however, is located in a relatively small embayment of this North Atlantic margin, out of reach of the bottom current activity caused by deep water geostrophic circulation. Nevertheless, a complex oceanographic regime is responsible for the enhanced currents observed in recent times in a narrow zone of the slope (Rice et al., 1991). Moreover, during and after the Late Pliocene

RD1 erosion event, a few topographic features were already created under the influence of intensified bottom currents: (1) the irregular paleotopography with steep flanks with both P2 and P1 and (2) the Belgica mounds. In this section we will discuss the significance of both features and of bottom currents on the deposition of the most recent unit, Unit P3.

During the deposition of Unit P3, which according to our tentative chronology started in the early Pleistocene, after the Late Pliocene erosional discontinuity, no dramatic erosional events were observed other than the deep parts of the channels. This may indicate that no major turnovers occurred in the oceanographic regime. There are, however, more subtle changes, observed within the seismic facies of this unit. Unit P3 can be subdivided into several sections of continuous parallel or mounded reflectors, based upon changes in amplitude ranging from high to low. This might reflect subtle variations in lithology caused by subtle changes in the oceanographic regime or sediment supply controlled by e.g. glacial–interglacial cycles, although it is not easy to establish a direct link (Faugères et al., 1999). The stacking of these sections gives us the overall geometry and thickness of Unit P3 and helps in identifying depositional changes. In the eastern and western part of the studied area, the geometry of P3 features a relatively thick sheet, representing a hemipelagic sedimentary environment.

The most important modification in geometry is related to the presence of Ch1. The origin of this channel is attributed to the presence of a south–north-directed bottom current. At the western side of the channel axis, a thick levee (approximately 200 ms TWT) is built up by reflectors that progressively terminate approaching the channel axis with an onlap (Fig. 3) and downlap configuration (Fig. 6). The geometry of this contour-parallel, upslope-prograding levee shares many similarities with drift levees and associated moat channels, typical for most of the separated, elongated-mounded drifts (Fulthorpe and Carter, 1991; Faugères et al., 1999). The Faro drift, for example, features upslope-prograding trends and various seismofacies underline the depositional patterns, e.g. a shift from aggradation with continuous semi-parallel reflections to less continuous, oblique to sigmoidal reflections (progradation) towards the moat channel. Faugères et al. (1999) consider variations in geometry to be dependent on the interaction with the morphology, but also on the intensity of the current system, as is the case with Ch1 and its associated levee.

Between the channel and the mounds, the sedimentation is under the influence of bottom currents. Large-scale sediment waves (Figs. 3 and 4) with variable amplitude suggest the presence of likely contour-parallel currents sweeping the foot of the mounds. This also explains the reduction in thickness of Unit P3 at this location. On the other hand, it seems that on the NE side (Fig. 4) and SSE side (Fig. 6) of the mounds, Unit P3 is ponded against them. Here, the mounds truly act as a barrier, piling up the sediments ‘behind’ them, suggesting: (1) currents are less vigorous upslope of the mounds, (2) sedimentation is due to downslope-flowing turbidity currents effectively stopped by the mounds, or (3) sedimentation is allowed in the eastern, lee side of the mounds. The current flowing along the flank of the mound facing the channel is likely stronger. According to Faugères et al. (1993, 1999), steep slopes (in this case the flanks of the mounds) can cause an intensification of the current, which is responsible for the creation of subtle moats surrounding the obstacles (Fig. 4). In this case such a depression is sometimes evident on the southwestern (steep) side of the mounds. Furthermore, as observed on the multibeam map (Fig. 2), the mounds are flanked by gullies. Most of these gullies are rather local and only seem to influence the seabed morphology close to the mounds. A hint of the true nature of these gullies is given by the along-slope profile presented in Fig. 5. The NNW gully is flanked by a small, mounded and slightly prograding levee-like feature which could very well be a turbidite levee (Faugères et al., 1999). This, however, is not observed on the SSE side of the mound, where only aggradation is observed. We suggest these gullies are minor turbiditic channels with only a very local character (Fig. 10). When inferring turbidite currents, the build-up of a levee on its right-hand side is expected due to the deflection by the Coriolis force in the northern hemisphere (Faugères et al., 1999). Here, the presence of a mound at this side might be one of the restraining factors for the construction of a levee. However, we cannot exclude any influence of a northward-flowing bottom current in the creation of the gullies on the southern side of the mounds. Also, these bottom currents can explain the local character of these small turbidite channels. At the lowermost part of these gullies, the energy of the northward-directed bottom currents might be stronger, taking up the downslope-transported material and smoothing the seafloor at the foot of the along-slope-running ridges.

Not only the mounds, but also the scarps created in Unit P2 during the Late Pliocene erosion event participate in the shaping of Unit P3 (Fig. 8). In this case, Unit P3 is deposited within a narrow passage between the steep flank of a mound and a P2 scarp. The geometry and the reflector configuration of this sediment body suggest that (1) the mounds were already present before the deposition of Unit P3 and (2) mounds were large and steep enough to intensify currents at their foot and the P2 scarp since the start of the deposition of Unit P3. In this way, the first deposits of P3 are only observed in the center of this passage from where they progressively prograded through time towards the flanks, creating a mounded geometry with remarkable downlap on both sides. After the passage became filled up the reflectors started to onlap, but currents (still active, though possibly reduced in strength) created moats on both sides. This change is also accompanied by discontinuities on other seismic profiles. In a way, this drift can be compared to mounded confined drifts as e.g. the Louisville drift (Carter and McCave, 1994) and the Sumba drift (Reed et al., 1987) as defined by Faugères et al. (1999). Confined drifts appear similar to elongate drifts, but are deposited in passageways between tectonic or volcanic relief, and are confined by boundary channels on both sides. In the Belgica mound province however, the dimension of this mounded drift is relatively small (between 2 and 5 km) and it does not occur in a morphotectonically unusual area such as the Louisville drift (Carter and McCave, 1994). In this case, the narrow passage is constructed by (1) an erosion event creating a scarp and (2) a coral bank. Nevertheless, confined drifts remain very rare and this example confirms their occurrence in unusual areas, but demonstrates that they do not need to be unusual in a purely morphotectonic way.

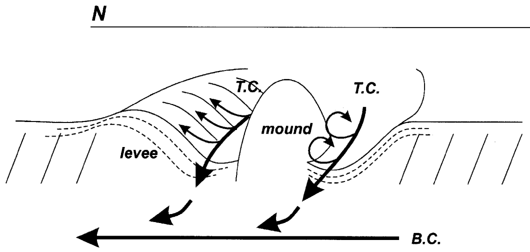


Fig. 10. Sketch illustrating the possible function of the gullies flanking the mound (based upon Fig. 5). T.C. = turbidite current; B.C. = bottom current at the foot of one of the along-slope-running ridges.

## 7. Conclusions

In this paper we present evidence of bottom current-controlled deposits on the eastern slope of the Porcupine Seabight, possibly since the Early Miocene. The stratigraphic evolution is illustrated in Fig. 11.

(1) The Early to Middle Miocene is summarized in Fig. 11A. The sediments of this first unit were deposited in a relatively calm environment on a slope of approximately 2°. Downslope of a break in the paleoslope and in a narrow zone of constant depth, however, a continuous set of lenticular bodies can be interpreted as upslope-migrating sediment waves, suggesting the presence of bottom current flow. In the lower Middle Miocene, the introduction of the Norwegian Sea Water into the North Atlantic Ocean was responsible for a margin-wide erosion event recognized in the study area as reflector RD2.

(2) After this first erosion event, an acoustically transparent unit, with as yet unknown lithology, was deposited over the entire slope (Fig. 11B) and subsequently eroded in the Late Pliocene. This large-scale erosion was responsible for the removal of a large part of Unit P2 and has cut very deeply into Unit P1.

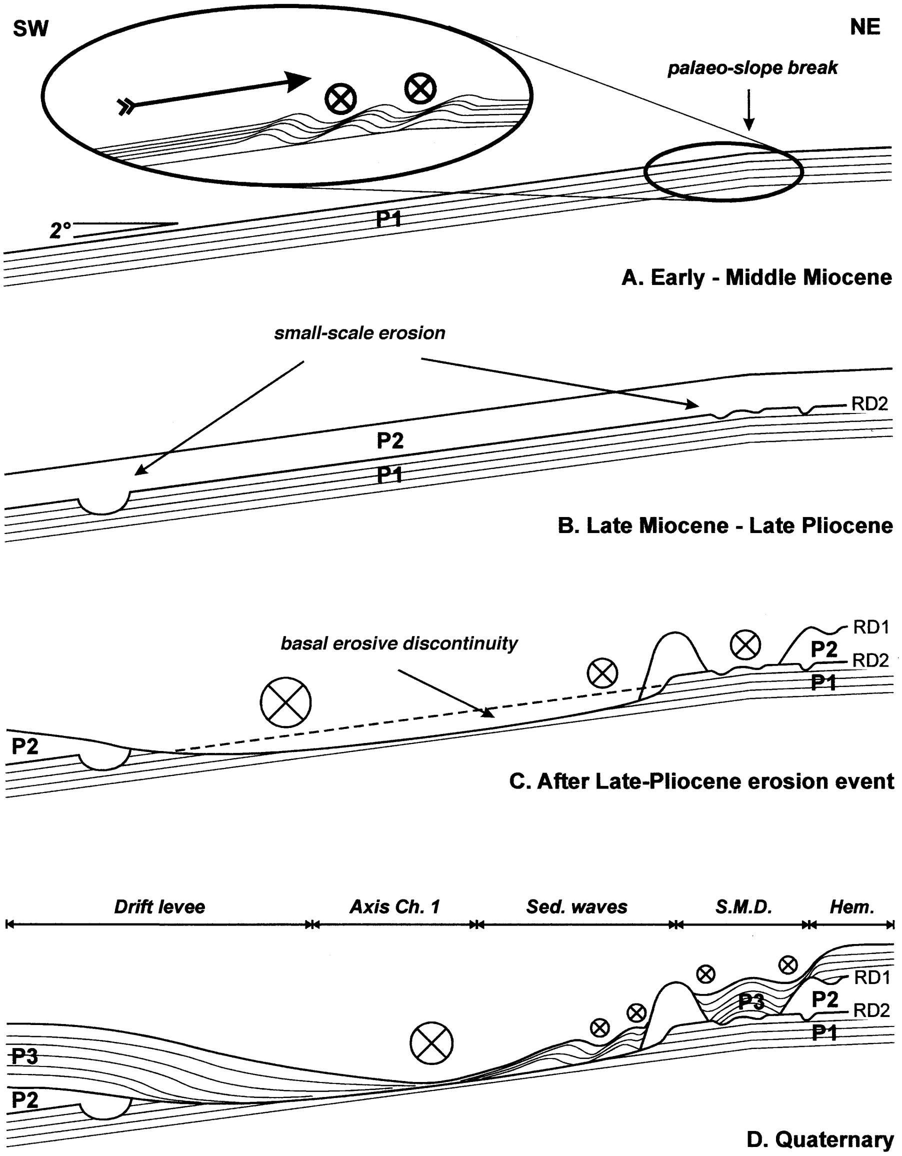


Fig. 11. Reconstruction of the depositional history in an ideal NE–SW profile. S.M.D. = small mounded (confined) drift; Hem. = undisturbed hemipelagic sedimentary environment.

(3) The basal erosive discontinuity (Fig. 11C), represented by reflector RD1, marks the onset of the modern oceanographic regime, the start of glacial–interglacial cycles and their effects on deep water circulation. The basis of the channels, Ch1 and Ch2, was created during this last erosion event by a strong south–north-directed contour current. These channels remain the pathway of this current during the Quaternary, fostering the construction of a sediment drift body on this part of the slope. Subsequent to the RD1 event, corals began to settle on topographic irregularities in the paleobathymetry. The coral banks were built spectacularly fast, in a period when the adjacent areas experienced non-deposition. The mounds are located in a zone within the influence of a

complex system of enhanced currents, also resulting in a net northward-flowing current.

(4) The Quaternary unit (P3) has similarities with some of the well-known sediment drift types reviewed by Faugères et al. (1999) and Rebesco and Stow (2002). However, these so-called drift types are only end-members of a continuous spectrum. The unique geographic and hydrodynamic setting of the study area is responsible for the creation of a contourite system, built from two sediment drift bodies (Fig. 11D). A first drift body is bounded at its right-hand side by Ch1 and displays the typical aggradation–progradation of a drift levee towards the channel, located at the foot of the slope. Between the channel and the mounds, large-scale sediment waves suggest that the action of the likely along-slope contour current is locally enhanced by the presence of the steeper mound ridges. The Belgica mounds themselves are also embedded in the contourite system that includes a number of small mounded drifts when sediment is deposited in narrow passages between the Late Pliocene paleobathymetry and the mounds. Here, an interaction of bottom currents and turbidity currents is observed, creating short turbidite channels at the southern and northern flanks of the mounds (Fig. 10).

Within this relatively small embayment in the NE Atlantic margin, the usual features diagnostic of sediment drifts are encountered. However, the key elements allowing the construction of this contourite system are unique because of the interaction between a complex oceanographic regime and obstacles in the (paleo)bathymetry, located in a relatively narrow zone of the slope. Unfortunately, not all factors contributing to the construction and evolution of the Belgica mound province are known, which calls for further research and drilling.

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