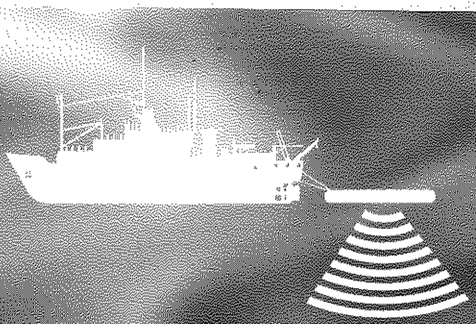
Hydrography, Surface Geology and Geomorphology of the Deep Water Sedimentary Basins to the West of Ireland



N.J. Vermeulen - *Dublin Institute for Advanced Studies*

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AIRS 1996

Atlantic Irish Regional Survey

Hydrography, Surface Geology and Geomorphology of the Deep Water Sedimentary Basins to the West of Ireland

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Abstract

This desk study involved the assembly, review and analysis of public domain and available data from an extensive deep water area offshore to the west of Ireland. All major bathymetric and sedimentary basins, in addition to associated shallow plateau and bank areas, were considered. Particular emphasis was placed on the Porcupine Seabight and Rockall Trough as these were considered to be the main areas of interest for the proposed 1996 AIRS (Atlantic Irish Regional Survey) project. Only relatively brief summaries are given for the Hatton Basin, Hatton Bank and the area further west. Also, as the GLORIA side-scan sonar system used in the project is effective only in deeper waters (continental slope and abyssal depths), a considerable portion of the shallow shelf has been ignored.

The primary goal of this study was to assemble a large existing data base on the above areas and to present this in a concise format. An introduction for each area describes the geological location and bathymetric characteristics. This is followed in each case by a description of the hydrography, in particular the characteristics of the water column and bottom current dynamics. Finally, an overview of the main geological and geomorphological features is given. Little reference will be made to the pre-Pleistocene geology of the region, with the focus of the project being on the modern sediments.

The water column over much of the study area is seen to be highly stratified, with a number of distinct layers of various origin evident. Vigorous bottom currents are also clearly present in many areas, often at significant depth, and undoubtedly have an influence on seafloor sedimentation patterns.

Sediment influx related to the cessation of the last glacial cycle has had a profound influence on the sea bed geomorphology. In a number of areas, massive sediment drifts or accumulations are evident, in addition to large scale mass-wasting and slope failure features which determine slope and basin floor character. Vigorous early post-glacial sea bed currents probably determined the distribution of much of the glacial sediment, but currents capable of transporting fine sand to silt grade sediments have been recorded and are still active today.

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Introduction

In August 1996, the most significant and comprehensive sea floor survey of the deep water basins to the west of Ireland to date was undertaken. The AIRS (Atlantic Irish Regional Survey) used GLORIA (Geological Long Range Inclined Asdic) side-scan sonar equipment together with a 3.5 KHz sub-bottom profiler. An area of approximately 200,000 km^2 was covered resulting in the acquisition of a large data base of high quality images of the sea floor and shallow sediments.

In preparation for this month-long survey, a feasibility study was undertaken with a number of particular objectives in mind. One of these was the production of a comprehensive literature review of existing knowledge on the extensive study area. The review showed that the bathymetric basins west of Ireland are today, and have been in the past, an area of dynamic sea bed sedimentation, rather than simply experiencing pelagic fallout from suspension. Secondly, the literature review facilitated the fine tuning of the initial proposed cruise path. Time limitations meant that the entire deep water area could not possibly be surveyed. As a result, it was necessary to select and focus on the most geologically, geomorphologically and biologically interesting and informative areas.

Although no previously unpublished data are presented here, the study still formed an important part of the 1996 AIRS survey and will set the framework for the interpretation of the results of the project.

Porcupine Seabight Basin

Introduction

The Porcupine Seabight Basin (Figure 1) has dimensions of approximately 320 km by 240 km and consists of a north-south trending amphitheatre-shaped bathymetric low, the Porcupine Seabight, which slopes gently south, swinging to a northeast-southwest trend. This bathymetric depression opens westwards onto the Porcupine Abyssal Plain. The Porcupine Seabight Basin, is underlain by up to 10 km of Upper Palaeozoic-Cenozoic sediments. This basin is bounded by three shallow, steep-sided platforms composed of Precambrian and Lower Palaeozoic metamorphic rocks (McCann *et al.* 1995). To the east, the Irish Continental Shelf forms a continuous border, with the Slyne Ridge and the Porcupine Bank and Porcupine Ridge closing the Porcupine Seabight to the north and west respectively. The Goban Spur bathymetric high borders the Seabight to the south. Water depths in the basin range from 200-400 m on, and adjacent to, the shelf areas, to approximately 2,000 m in the south of the Seabight. The Seabight then slopes away southwest to the Porcupine Abyssal Plain where water depths exceed 4,000 m.

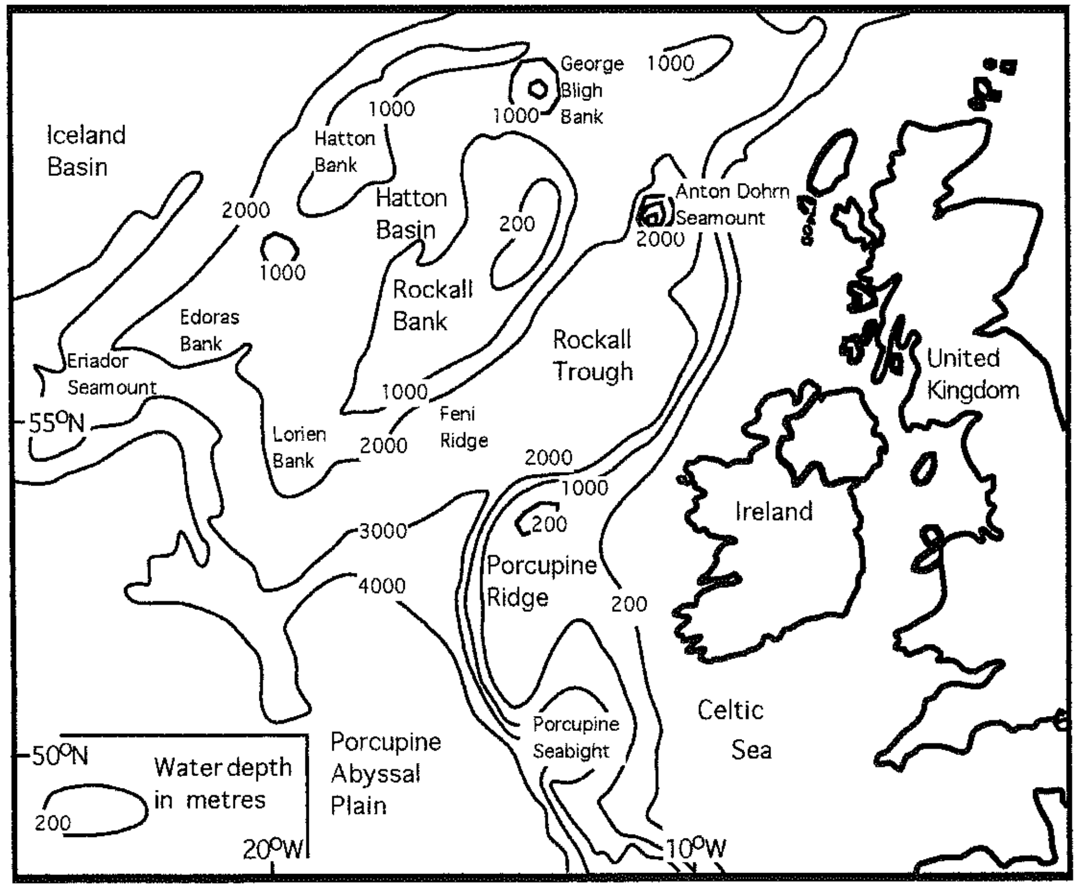


Figure 1: Bathymetry of the major deep water sedimentary basins to the west of Ireland (after Naylor and Shannon 1982).

Hydrography

Water stratification is well developed in the Porcupine Seabight. East North Atlantic Water, a water body on the eastern side of the North Atlantic, is present extending to 750 m water depth, overlying Mediterranean Water which displays a salinity maximum and oxygen minimum at 950 m water depth. Below this, Labrador Sea Water with a salinity minimum and oxygen maximum at 1,700 m is seen. A minor salinity maximum was recorded at 1,900 m due to the presence of Norwegian Sea Water (Rice *et al.* 1991).

A permanent thermocline exists at 600-1,400 m water depth, where the temperature falls from 10° C to 4° C. A seasonal thermocline is typically also present at approximately 50 m depth (Rice *et al.* 1991).

Both bottom and intermediate nepheloid layers have been recorded from the Porcupine Seabight. Nepheloid layers are distinct layers of water which have reduced optical transmittance, often due to the presence of large quantities of suspended or dissolved fine-grained solids of either terrigenous or biological origin (Thorpe and White 1988), typically in the size range 8-40 μm (Rice *et al.* 1991). These layers commonly display associated elevated turbulence. Bottom nepheloid layers, due to sea bed erosion by internal waves and tides or currents, may become detached from the sea bed to form discrete water layers with clear water above and below. Such layers are termed intermediate nepheloid layers. One such intermediate nepheloid layer, recorded at 700-800 m depth within the Porcupine Seabight and at the Seabight mouth (Figure 2), can be traced laterally to a detached bottom nepheloid layer on the Porcupine Ridge (Rice *et al.* 1991).

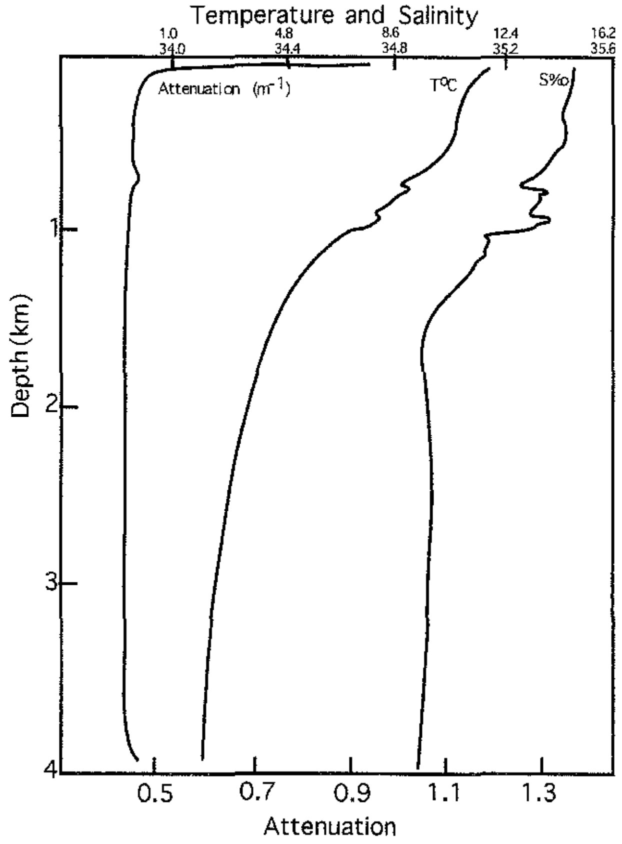
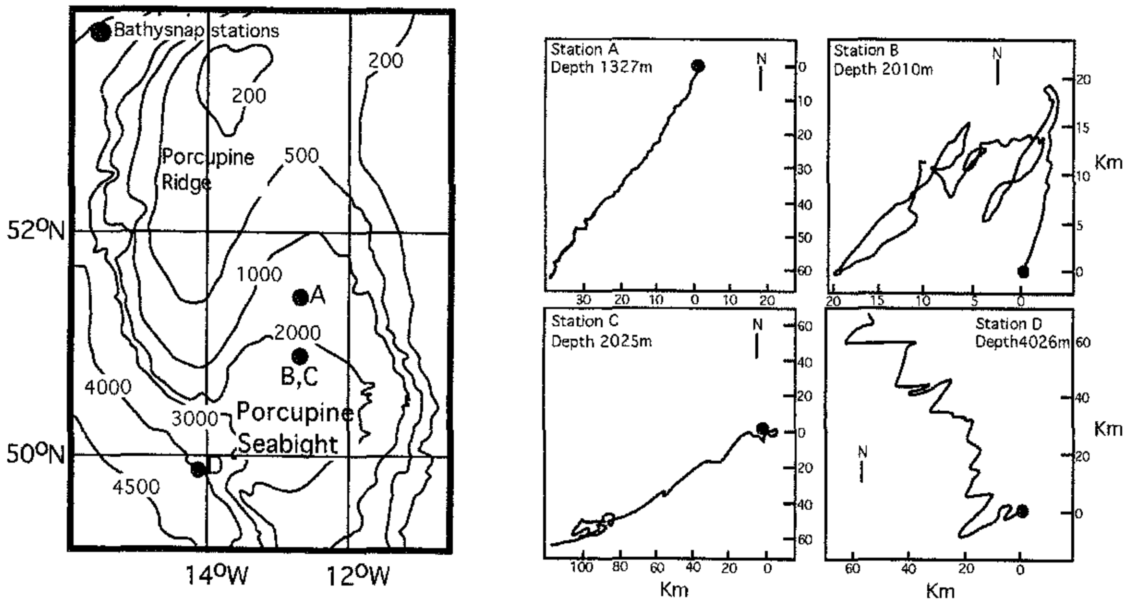


Figure 2: Temperature, attenuation and salinity depth profiles at the mouth of the Porcupine Seabight (after Rice *et al.* 1991).

A north flowing boundary current running parallel to the slope contours, with superimposed tidal currents, has been recorded at the Seabight mouth, but it is unclear whether the current enters the Seabight proper (Rice *et al.* 1991). Four Bathysnap deployments in the area failed to resolve this question (Figure 3). Two deployments in the northwest of the Seabight and at the mouth of the Seabight displayed an along-slope flow sense, while current meters deployed in the centre of the Seabight did not support this conclusion. This current is a component of the anticlockwise deep water circulation pattern recorded in the Rockall Trough which will be described in more detail later.



(a) **(b)**

Figure 3: **(a)** Location of the four Bathysnap deployments in the Porcupine Seabight Basin. **(b)** Progressive vector plots for the above four Bathysnap deployments (both after Rice *et al.* 1991).

Measurements of current speeds have been made in the region of the mouth of the Seabight in water depths of 4,025 m (Rice *et al.* 1991). More than 30% of the recorded velocities were in excess of 1.6 cm.s^{-1}, while the velocity profile was seen to change from less than 1.6 cm.s^{-1} to 6-10 cm.s^{-1} in the space of 2-3 hours, with an associated change in the current direction. Current speeds in the Seabight as a whole do not appear to exceed, or even reach, the bedload transport threshold for silt or fine sand grade sediment. In support of this, photographs taken in the area show a bioturbated, pockmarked sea floor with no evidence for current smoothing or the formation of organised sedimentary bedforms. Currents on the western side of the Porcupine Ridge are significantly greater than those seen in the Porcupine Seabight, with 25% of all currents in the former area in excess of 10 cm.s^{-1}.

Geology and Geomorphology

The pre-Pleistocene geological development of the Porcupine Basin is summarised by McCann *et al.* (1995) and Moore and Shannon (1995). The geological development can be broadly divided into three tectono-sedimentary divisions, the classic pre-rift, syn-rift and post-rift of a steer's head type basin. The pre-rift succession is composed of Devonian clastics overlain by Lower Carboniferous carbonates. Upper Carboniferous clastic deltaic deposits follow deposited in an east-west trending Carboniferous basin. Three post-Carboniferous syn-rift extensional episodes have been defined at Triassic to early Jurassic, Tithonian to mid-Valanginian and mid-Aptian to Albian times respectively. The Cretaceous signals the onset of the main post-rift thermal subsidence phase of basin development.

The RRS "Discovery" Cruise 123, in August and September 1981, covered much of the eastern and southern zones of the Porcupine Seabight. The acquisition of a relatively large data base of moderate to good quality GLORIA imagery data facilitated the mapping of the major geological and geomorphological features of the Irish Continental Shelf and Slope within the survey area (Kenyon 1987).

A major channel system (Figure 4), previously recognised by Berthois and Brenot (1966), was fully mapped with the aid of the GLORIA data. This channel system, named the Gollum Channel System after Kenyon *et al.* (1978), consists of sinuous, typically flat-floored channels, 100-280 m deep and up to 1.5 km wide, with flanking terraces (Kenyon *et al.* 1987). The darker tone of the channel floors suggests a coarser grained sediment fill than in the surrounding overbank areas. Sediment at the surface in the interchannel zones consists of coccolith-foraminiferal marl with steamship clinker, glacial dropstones and associated material, with a clearly visible down-slope decrease in sedimentary grain size (Rice *et al.* 1991). Channels, generally separated by uneroded slope, trend east-west from the Irish Continental Slope to the mouth of the Porcupine Seabight, and are seen to amalgamate to form one major, structurally-controlled (P. Croker *pers. comm.*) channel feature that continues west possibly onto the Porcupine Abyssal Plain. It is unlikely that the channels in the north of the Seabight, where slopes are in the range 1.5-2.5°, are active at the present day (Kenyon 1987), as channels in this area tend to be poorly defined and appear to be totally or partially covered by prograding recent sediments. To the south, where the mean slope increases to 2.5-3°, three deeply eroded channel systems are present. Associated with the channels, on the undissected parts of the slope, are along-slope ridges up to 25 m high and approximately 1.5 km apart. These are identified as slump folds and associated features formed by down-slope sediment creep into the Porcupine Seabight. The channels in the south of the area appear to be periodically active, with a distinctive coarse-grained sediment fill. Their initial development was almost certainly related to erosion and sedimentation from Pleistocene fluvial systems on the Irish Continental Shelf, when large volumes of terrigenous sediment were transported to the shelf edge during glacial sea level lowstands (Kenyon *et al.* 1978). Rice *et al.* (1991) suggest that these channels may be active on a regular basis, as there appears to be evidence for constant erosion on the channel floors. A major decrease in overall sedimentation rates is recorded at the glacial/Holocene transition, in the form of a fall from 13 cm.1000 yr^{-1} to 3.5 cm.1000 yr^{-1} (Rice *et al.* 1991), and probably coincides with reduced activity in the channels as sea level rose, flooding sediment provenance areas.

There is no sediment fan evident on a detailed bathymetric map from the Seabight mouth (Rice *et al.* 1991), where the channel system opens out onto the Porcupine Abyssal Plain. This suggests that either the volume of sediment supplied into the system was relatively small or that the sediment has been redistributed over a wide area by vigorous sea floor currents. The absence of numerous large channel features on the Porcupine Ridge and Rockall Bank slopes is probably a reflection of the low sediment budget in both areas, leading to reduced scouring by turbidity currents (Rice *et al.* 1991).

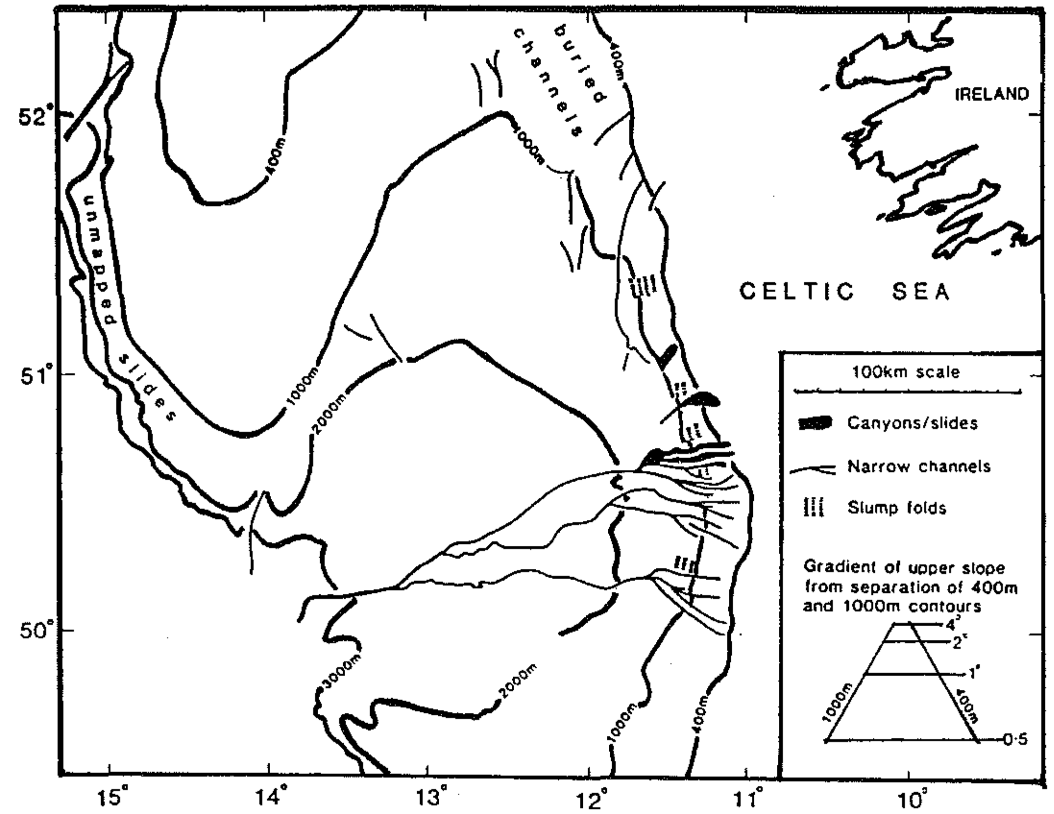


Figure 4: The Gollum Channel System, Porcupine Seabight Basin (after Kenyon 1987).

There is clear evidence for Pleistocene floating ice on the Irish Continental Shelf and on the Porcupine Ridge, where characteristic patterns of glacial scour marks are recorded from sonar data, in water depths of approximately 140-500 m. Scour marks are typically 20 m wide, with a maximum of 100 m, and 2 m deep, with a maximum of 10 m. The longest recorded feature was 5.5 km in length (Belderson *et al.* 1973). The Porcupine Ridge examples, generated during the last glacial or late glacial period (Belderson *et al.* 1973), represent the most southerly occurrence of such features in the North Atlantic (N. H. Kenyon *pers. comm.*). Similar features are also recognised from the Rockall Plateau surface.

Hovland *et al.* (1994) describe groups of sea bed mounds from the Porcupine Seabight between 52° 30'-52° N and 12-13° W. These features are often greater than 1 km in diameter and over 100 m high with total thickness of up to 255 m (Figure 5). Approximately 31 separate mounds have been described, located in water depths of 650-1,000 m. Sediment sampling has confirmed the presence of light grey to light brown oxidized clays and ahermatypic coral (*Lophelia* sp.) and shell debris on the mounds, with uniform, partly bioturbated, olive brown sandy clay in the offmound areas.

These knoll features tend to be concentrated in areas where north-south trending normal faults in Tertiary and Upper Cretaceous strata die out, possibly due to the presence of east-northeast strike slip faults. Such features, if present, would penetrate deep into the sedimentary succession facilitating fault plane seepage of light hydrocarbons from depth. Interstitial gas sampled from the mound structures is overmature thermal methane, with no biogenic component evident (Hovland *et al.* 1994). Thus, the development and location of the organic rich mounds may be closely related to the focused seepage of thermally generated light hydrocarbon fractions from the subsurface, leading to localised eutrophication or fertilization of the lower part of the water column, providing nutrients for bacteria. These organisms, in turn, act as a food source for colonial, cold water ahermatypic corals. Dating results tentatively indicate an Upper Pleistocene age (12,000-13,000 years BP) for the end of mound development (Hovland *et al.* 1994). It should be noted that these features were previously recorded by the GLORIA instrumentation during the RRS "Discovery" 123 cruise in 1981 (Kenyon 1987).

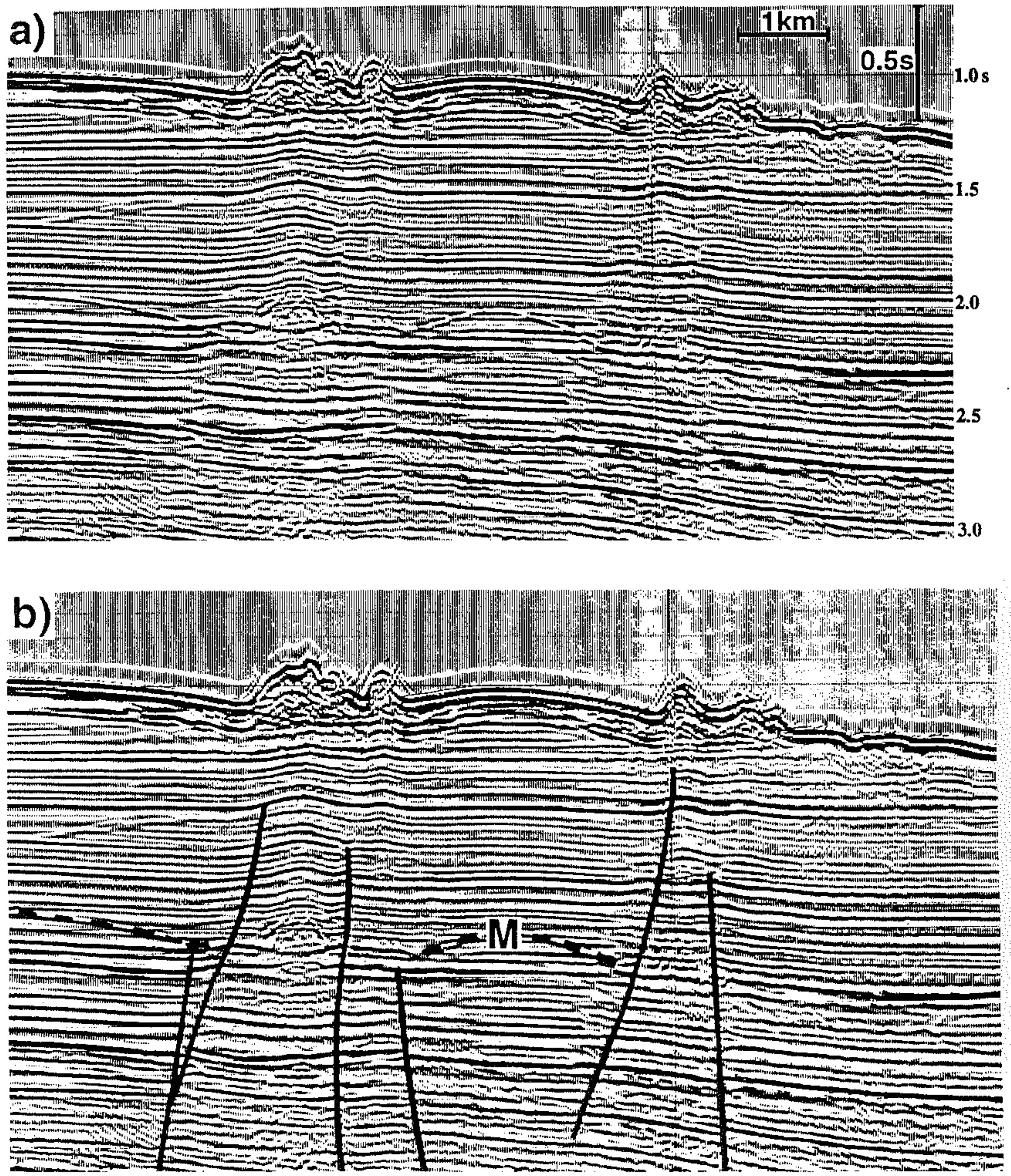


Figure 5: Sea bed knolls from the Porcupine Seabight Basin. Note the close relationship between these features and subsurface fault traces (from Hovland *et al.* 1994).

Porcupine Ridge and Porcupine Bank

Introduction

The Porcupine Bank is defined as the northern section of the Porcupine Ridge where water depths are less than approximately 200 m. This bank is a relatively small, northeast-southwest trending feature which slopes away steeply to the northwest into the Rockall Trough, and more gently to the Porcupine Seabight in the southeast. It continues northeastwards into the Slyne Ridge and south into the Porcupine Ridge proper. The Porcupine Ridge (Figure 1) is a steep sided, north-south trending, elevated plateau area which constitutes the western margin of the Porcupine Seabight Basin. This feature marks the transition from moderate water depths of up to 1,000-2,000 m on the Irish Continental Shelf and in the Porcupine Seabight to the east, to abyssal depths which sometimes exceed 4,000 m in the deep water Rockall Trough to the west.

Hydrography

A weak, but very large, deep intermediate nepheloid layer has been described from a northeast-southwest profile extending south from the southwestern margin of the Porcupine Ridge (Thorpe and White 1988). This layer is located adjacent to the Porcupine Ridge Continental Slope, in a water depth of approximately 2,550 m, and extends off-slope for more than 16 km and along-slope for more than 100 km (Figure 6). The layer is a benthic nepheloid layer when in contact with the sloping Porcupine Ridge, but it becomes detached from the Irish Continental Slope due to advection of sediment off the slope along density surfaces, and is subsequently an intermediate nepheloid layer. This benthic nepheloid layer is approximately 350 m thick when in contact with the slope, but at a distance of 8 km off-slope the corresponding intermediate nepheloid layer is found between 2,360 m and 2,790 m water depth. Although there is no direct evidence for the source of the intermediate nepheloid layer, the benthic nepheloid layer, and the associated intermediate nepheloid layer, appear to be closely linked to the Norwegian Sea Overflow salinity maximum. The depth of both layers is significantly below the Shelf Break, so it is unlikely that the source of the sediment is erosion of Continental Shelf sediments by wave action. Mean current vectors at the depth of the intermediate nepheloid layer are to the northwest, along the Porcupine Ridge slope, with recorded velocities in the range 1-6 cm.s^{-1}. A current meter deployed in a water depth of 2,478 m (1,009 m above the sea bed) for six days recorded a mean velocity of 2.0 cm.s^{-1} towards 339°. This mean velocity is clearly significantly less than the approximate current velocity of 15cm.s^{-1} required for bedload transport of silt to fine sand grade sediment.

A second intermediate nepheloid layer has been described along the southwestern edge of the Porcupine Ridge and at the mouth of the Porcupine Seabight at approximately 700-800 m water depth (Thorpe and White 1988, Rice *et al.* 1991), while a transmittance minimum at 50 m water depth appears to be associated with the concentration of planktonic marine organisms at the seasonal thermocline (Figure 6, Thorpe and White 1988).

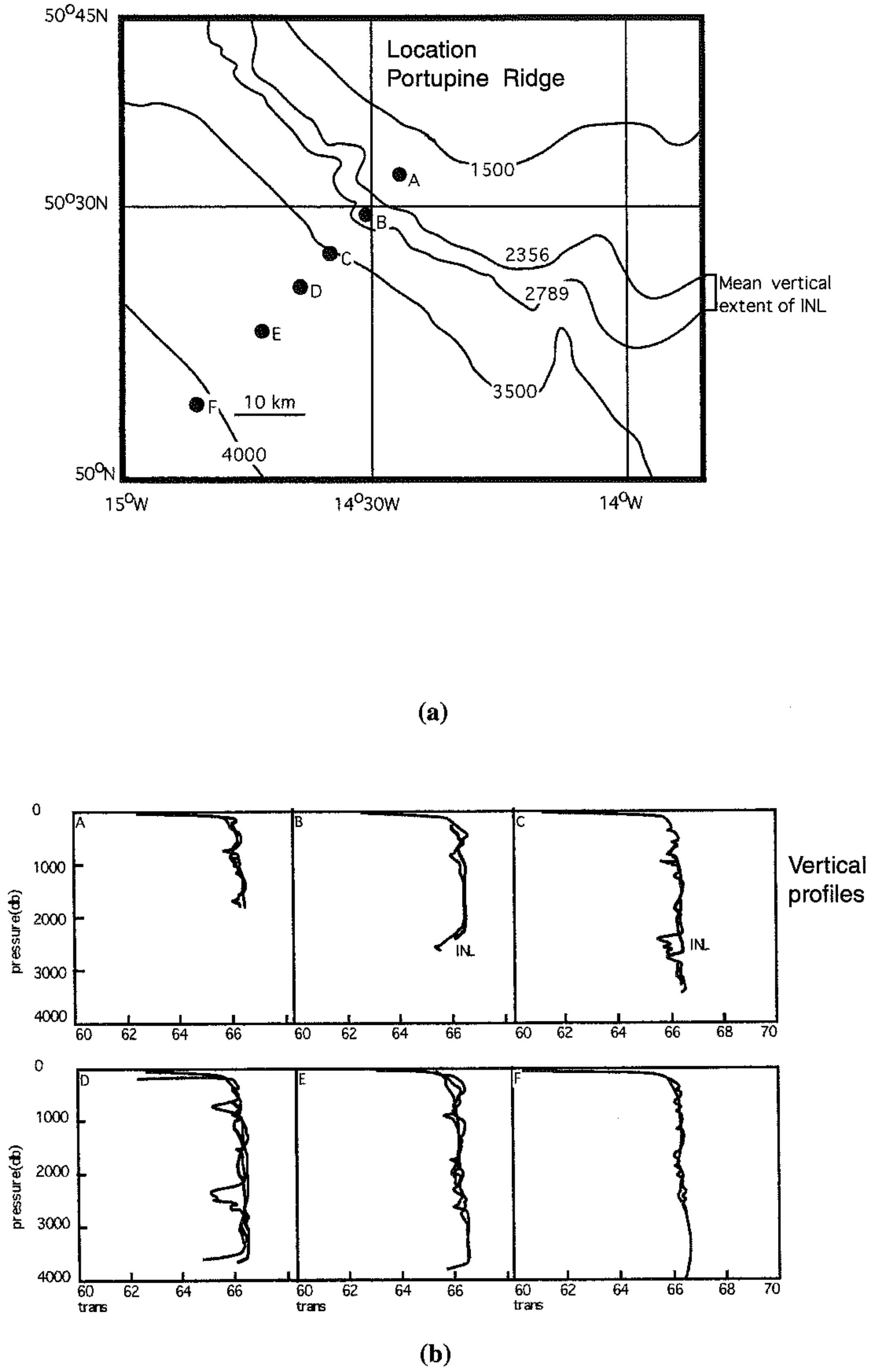


Figure 6: **(a)** Location of study area. **(b)** Vertical profiles of percentage light transmission (both after Thorpe and White 1988).

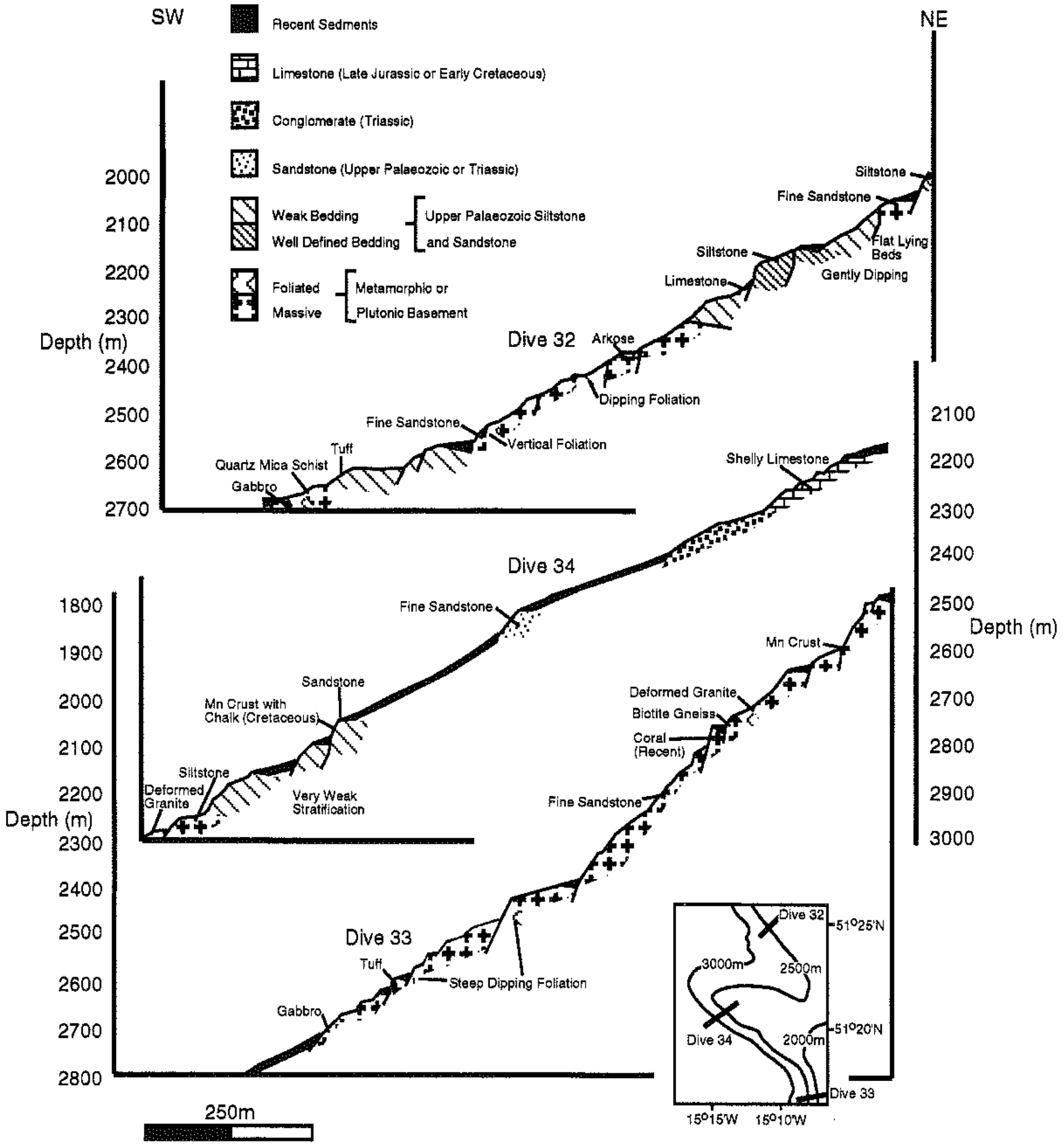


Figure 7: Geological cross sections of the western slope of the Porcupine Ridge. Arrows show sample locations: underlined samples are in place, those not underlined are possibly in place (from Masson *et al.* 1989).

Geology and Geomorphology

As mentioned previously, the basement platforms bordering the Porcupine Basin are comprised of Precambrian and Lower Palaeozoic metamorphic rocks which include metasediments, leucogranites, granodiorites, quartz syenites, granulites, charnockites and epizonal schists (McCann *et al.* 1995).

There is little control on the morphology of the Porcupine Ridge although previously acquired GLORIA imagery data highlights a number of slump structures on the eastern side. The results of three dives on the western slope of the Porcupine Ridge, at coordinates 51° 17' N, 51° 21' N and 51° 25' N, are available (Figure 7). The western slope of the Ridge is characterised by steep slopes of 30° or more between 1,500 m and 3,000 m water depth, and generally consists of rock outcrops, meters to tens of meters in height, separated by less steep sediment covered terraces. The recent sediment cover is sparse, possibly due to the north flowing currents on the eastern margin of the Rockall Trough, giving 50-80% total rock outcrop. Sampling recorded the presence of basalts and gabbros, metamorphics, Upper Palaeozoic sandstone and siltstone, Mesozoic sediments and Tertiary sediments and manganese crusts from the western slope of the Porcupine Ridge (Masson *et al.* 1989).

Porcupine Abyssal Plain

Introduction

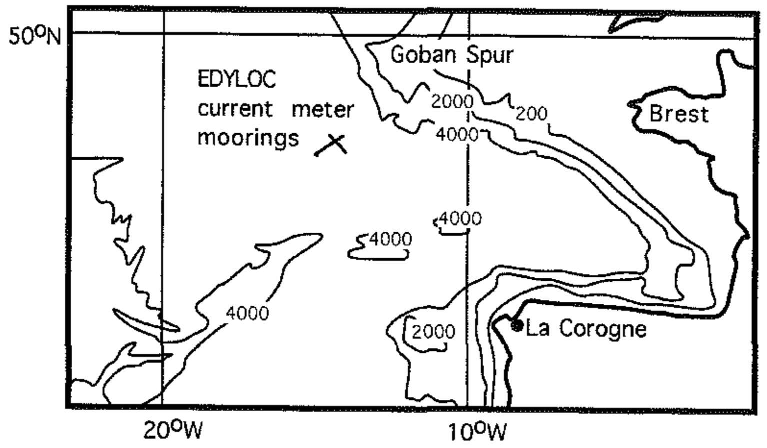
The Porcupine Abyssal Plain is a flat-bottomed area located to the west of the Porcupine Seabight and Goban Spur and to the south of the Rockall Trough, in up to and over 4,500m water depth. This area is underlain by oceanic rather than continental crust, in contrast to the other areas described in this study. There are data for the sea bed current dynamics in this area but little data exist in relation to the sea bed geology and geomorphology, although mass wasting features basinward of the steep slopes that mark the western boundary of the Goban Spur might be expected.

Hydrography

The hydrography of the Porcupine Abyssal Plain is similar to that of both the Rockall Trough and the Porcupine Seabight, with Northeast Atlantic Central Water to approximately 500 m depth underlain by Mediterranean Water. Labrador Sea Water is present below this with a Norwegian Sea Water contribution obvious at approximately 2,300 m water depth. Finally, a layer of Northeast Atlantic Bottom Water, with a distinct silica maximum, is present and is thought to have an Antarctic origin (Vangriesheim 1988).

The EDYLOC 81-82 experiment (Figure 8, Vangriesheim 1988) was carried out in order to examine the spatial and temporal scales of deep current variation on the Porcupine Abyssal Plain and to constrain the active sedimentary and hydrographic processes in that area. Six moorings were deployed on a flat sea bed in order to eliminate topographic effects, at 47° N and 14° 30' W in 4,780 m water depth. The study was particularily concerned with the benthic boundary layer, a non-turbulent logarithmic layer in close proximity to the sea bed. In theory, the current speed in this layer will decrease in a logarithmic manner to reach zero at the sea bed. Optical scatterance was measured, in addition to current dynamics, in order to determine the presence or absence of a bottom nepheloid layer.

Two current meters were deployed at each mooring (Table 1), one 10 m above the sea bed and a second 800 m above the sea bed. Current observations recorded a velocity maximum of 12.4-14.4 cm.s^{-1} for current meters deployed 800 m above the bottom, and 14.4-16.3 cm.s^{-1} for the current meters 10 m above the sea bed. The mean velocity for an eleven month period was determined to be 1.26 cm.s^{-1} 800 m above the bottom and 1.50 cm.s^{-1} 10 m above the sea bed. In addition to absolute velocities, velocity variance was also studied for an east and north component. The results of this survey indicate that a westerly flow vector dominates in the mean circulation patterns more than previously recorded, with the northerly component less distinct than expected. This may however be a seasonal variation rather than indicating a fundamental change in the deep water current circulation patterns over time.



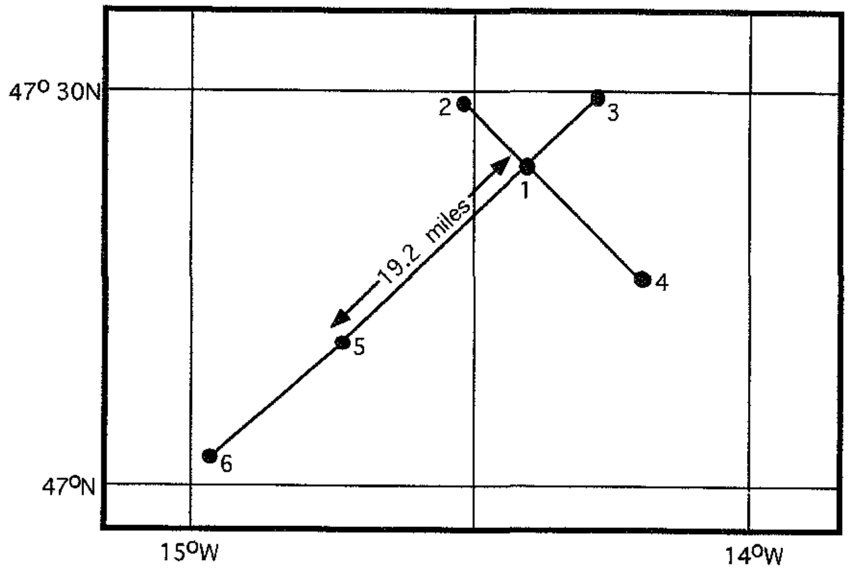


Figure 8: Location of current meter moorings during the EDYLOC 81-82 experiment (from Vangriesheim 1988).

Table 1: Current measurements from the Porcupine Abyssal Plain (after Vangriesheim 1988).

Height above sea bed (m)	East-directed flow component velocity	North-directed flow component velocity
800 m	-12.9 to 12.7 cm.sec^{-1}	-14.1 to 12.5 cm.sec^{-1}
10 m	-15 to 14.6 cm.sec^{-1}	-12.8 to 14.1 cm.sec^{-1}

The negative values above indicate a flow direction opposite to the east and north flow vectors; i.e. to the west and south respectively.

Major optical scatterance was recorded at the top and the bottom of the water column with homogeneous transmittance in the central part of the water column. The near surface attenuation is almost certainly due to the presence of planktonic organic matter, while the attenuation at the bottom of the water column can be directly linked to the presence of a nepheloid layer of 500-750 m thickness, which is developed despite the very flat sea bed topography. In other parts of the Atlantic, a similar bottom nepheloid layer appears to be closely linked with the north directed flow of Antarctic Bottom Water (Vangriesheim 1988), but the link may be more tentative for the example shown here. This layer appears to contract in areas where the flow velocity increases. Vangriesheim (1988) proposes that the nepheloid layer may be a series of stacked flows all moving on density contrast surfaces. If this is the case, it will have implications for sea bed features especially in areas with topography, as low velocity shadow zones may be present on the leeward side of topographic features, promoting the deposition of sediment in suspension in the nepheloid layers.

In conclusion, the EDYLOC 81-82 data clearly indicates the presence of bottom currents in the Porcupine Abyssal Plain area, with a well developed bottom nepheloid layer or series of such layers. It is likely that the currents periodically exceed velocities required for bedload transport of silt or fine sand (approximately 15 $cm.s^{-1}$). This will have two consequences. Primarily, it means that current moulding of the sea bed is likely, possibly leading to the formation of organised sedimentary bed forms. In addition, the presence of nepheloid layers implies that any fine sediment shed into the abyssal plain region may remain in suspension in the lower levels of the water column, be transported by the north or northwest flowing sea bed currents and finally be deposited at a point far removed from the zone of sediment input.

Geology and Geomorphology

As mentioned previously, the Porcupine Abyssal Plain is a flat-floored area in water depths of over 4,000 m. It is unlikely that significant topographic features are developed, although the presence of unmapped seamount structures cannot be ruled out. Some sea bed relief might be expected on the eastern margin of the Abyssal Plain, adjacent to the steep scarp slopes of the western Goban Spur area. The channelised and canyoned nature of the Goban Spur and its continuation to the southeast, the Trevelyan Escarpment, suggest that turbidite deposits or sediment lobes may be developed at the downslope extremities of these features. However, the elevated nature of the Spur, and it's current position away from any major sediment source possibly suggest that recent sediment flux off the Spur will be minimal. As slide features are seen on slopes of less than 1° on the continental slope to the north, slope failure features and their associated deposits might be expected to extend westwards out onto the Porcupine Abyssal Plain.

Goban Spur

Introduction

The Goban Spur is a fault-bounded, east-west trending, elevated plateau area located on the continental margin to the southwest of Ireland, immediately to the east of the continent-ocean transition. The general structure is in the form of a series of horsts, grabens and tilted fault blocks, developed in water depths between 500 m and over 4,000 m and stepping westwards in a down-to-the-basin fashion. The steep, fault controlled western margin of this feature trends roughly northwest, extending to the mouth of the Porcupine Seabight, while the northern margin slopes away steeply into the deepest part of the Porcupine Seabight. The Spur itself is a smooth, flat topped platform, underlain by Variscan granites and is thought to be the western extension of the Cornubian Platform (Dingle and Scrutton 1979). For much of the later stages of its geological history, the Goban Spur has been sediment starved due to the elevated position of the Spur crest, resulting in little down slope sedimentation and poorly developed continental rise sedimentary prisms. The top surface of the Goban Spur is characterised by a smooth west- dipping slope, cut by some canyon features, and terminating at the Pendragon Escarpment, which has relief of up to 2,000 m. This escarpment is not canyonised to the same extent as the Trevelyan Escarpment, which forms part of the north Biscay continental slope to the southeast of the Goban Spur.

Hydrography

The hydrography of the deeper parts of the Goban Spur feature, at the foot of the Pendragon Escarpment, is expected to be very similar to that seen in the Porcupine Abyssal Plain area, with Northeast Atlantic Water underlain by Mediterranean Water which is, in turn, followed by Labrador Sea Water, Norwegian Sea Water and possibly Northeast Atlantic Deep Water at abyssal depths. The hydrography of the crest of the Goban Spur is most likely dominanted by Northeast Atlantic Water, with a possible Mediterranean Water influence at deeper levels.

Geology and Geomorphology

Dingle and Scrutton (1979) described the margin southeast of the Goban Spur as being excavated by deep canyons and gullies which cut into the sedimentary succession, while Kenyon *et al.* (1978) also described the Trevelyan Escarpment to the west of the Celtic Sea as being deeply canyoned and gullied. In this area, the steepness of the Continental Slope appears to be the dominant factor in determining slope morphology. Canyons and gullies in this region are almost certainly related to incision of the Celtic Continental Slope to the south of the Goban Spur which could be attributed to the action of Pleistocene turbidity currents. One such gulley is recorded from the spur in 2 km water depth at coordinates 49° 40' N and 13° 25' W.

A core of Variscan granite has kept the Goban Spur buoyant for much of its history, limiting the thickness of the sedimentary succession and exposing the Spur to vigorous submarine erosion events. Dingle and Scrutton (1979) also recognised that nepheloid suspension and similar near bottom current generated sediment sources would have had little effect on depositional processes on the top of the Goban Spur or the steep marginal flanks. However, slope instabilities on the steep western margin are expected to be a factor influencing sedimentation.

The major Mesozoic rift event in this region imparted a general horst and graben topography with a down-to-the-basin fault pattern, as mentioned earlier. There appears to have been little or no fault movement since this period of rifting with overall limited subsidence dominating the post-rift developmental history of the Spur (Dingle and Scrutton 1977). Major scarps, such as the Pendragon Escarpment, are present, generally trending northwest-southeast parallel to the dominant structural grain. Pautot *et al.* (1976) describe a steep southwest sloping granite cliff in the region of 48 °N and 12° W, with dip reaching at least, and probably much more than, 30°. This steep gradient, together with the very straight base of the slope, led the authors to conclude that the feature is a fault scarp up to 1,000 m high. The foot of the scarp is seen at approximately 4,150 m water depth with the top at approximately 3,150 m. Once again the trend is northwest-southeast parallel to the Pendragon Escarpment. The steep slopes recorded in the region of the Goban Spur will almost certainly have an influence on the morphology of the Glacial to post-Glacial sediments, with slumps recorded on slopes of less than 1° in the region to the north of the Spur. Large slump blocks and slump folds are recorded from interchannel areas on the North Biscay Continental Slope, with similar features expected from the Goban Spur slope (Kenyon *et al.* 1978).

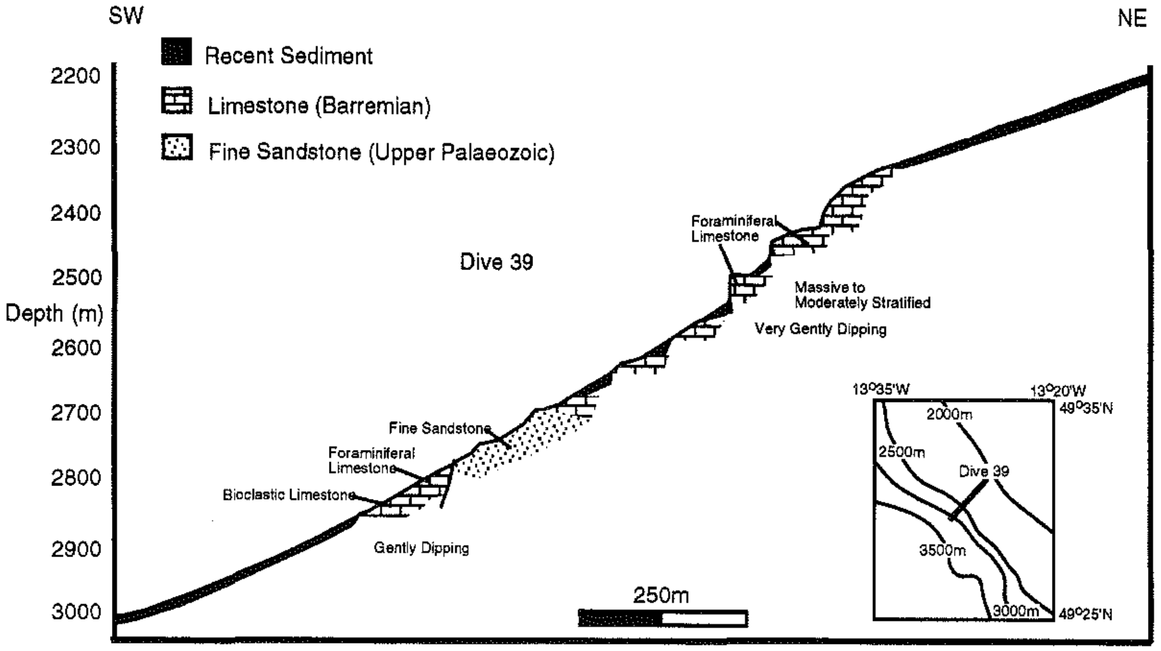


Figure 9: Geological cross section of the western slope of the Goban Spur. Underlined samples are in place, those not underlined are possibly in place (from Masson *et al.* 1989).

Data on a number of geological traverses are available for the Goban Spur. These are largely concerned with the western edge of the Spur, as defined by the Pendragon Escarpment, which has a mean slope of 45° from 2500-3000 m. A Cyaporc Cruise research dive near the northern end of the Goban Spur at 49° 30' N recorded recent sediments covering more of the slope than on the Porcupine Bank, with outcrop over only about 40% in this case (Figure 9). This outcrop typically occurs as steep slopes or cliffs, meters to tens of meters in height, separated by less steep, sediment covered terraces. The samples from the Pendragon Escarpment include igneous rocks and high grade metamorphics, Palaeozoic strata, Barremian to Cenomanian sediments and Tertiary sediments (Masson *et al.* 1989).

The northern Biscay continental slope, in particular the Trevelyan Escarpment, is essentially a continuation of the Goban Spur slope. Kenyon *et al.* (1978) described the continental slope to the west of the Celtic Sea and the Armorican Plateau as deeply canyoned, gullied and slumped with some undissected remnants on a slope of 5-9°. Individual canyons are often entrenched, with a dendritic pattern described by channel axes that vary from straight, to sinuous with sharp turns. The interfluves are either sharp crested aretes or undissected continental slope. Undissected interfluves tend to be convex up due to lateral gravity creep of sediment towards the canyon axes, and often contain slump folds. The positions of the canyon heads is again related to the position of Pleistocene rivers, which supplied large amounts of coarse terrigenous sediment to the shelf edge during the period of glacial meltwater production and sea level lowstands.

Belderson and Kenyon (1976) noted that canyon trends on the northern Biscay continental slope are quite oblique to the slope and that their similarity to fluvial drainage patterns is striking. The distinct oblique trend may be due to structural control on the drainage patterns.

Rockall Trough

Introduction

The Rockall Trough is a 250 km wide bathymetric basin, bordered by steep faulted continental crust to the east (Irish Mainland Continental Shelf and Slope), west (Rockall Bank) and north (Wyville-Thomson Ridge). This basin ranges in depth from 1,000 m in the north to over 3,000 m in the south before it opens out southwards into the Porcupine Abyssal Plain, in water depths of over 4,000 m. This major feature, which has a northeast-southwest trend, formed after rifting of the Rockall Bank-Irish Mainland Continental Shelf continental crust in pre-Jurassic times (Shannon *et al.* 1995). Rockall Trough has long acted as a settling basin for pelagic and terrigenous sediments and a flow path for North Atlantic bottom currents (Lonsdale and Hollister 1979). Rockall Trough is underlain by severly attenuated continental crust (O'Reilly *et al.* 1995).

Hydrography

Lonsdale and Hollister (1979) described the hydrography of the basin in some detail (Figure 10). Immediate similarities to the Porcupine Abyssal Plain are evident, with the presence of a strongly stratified water column. North Atlantic water, which comprises the surface layer, is underlain by Gibraltar Water at 800-1,200 m depth, with a distinct salinity maximum and oxygen minimum evident in this lower layer. This, in turn, is underlain by oxygen depleted, high salinity Labrador Sea Water, extending from 1,200 m to 2,000 m depth. The basal water layer is the Northeast Atlantic Deep Water which has a deep salinity maximum at the top due to the presence of the Norwegian Sea Overflow component.

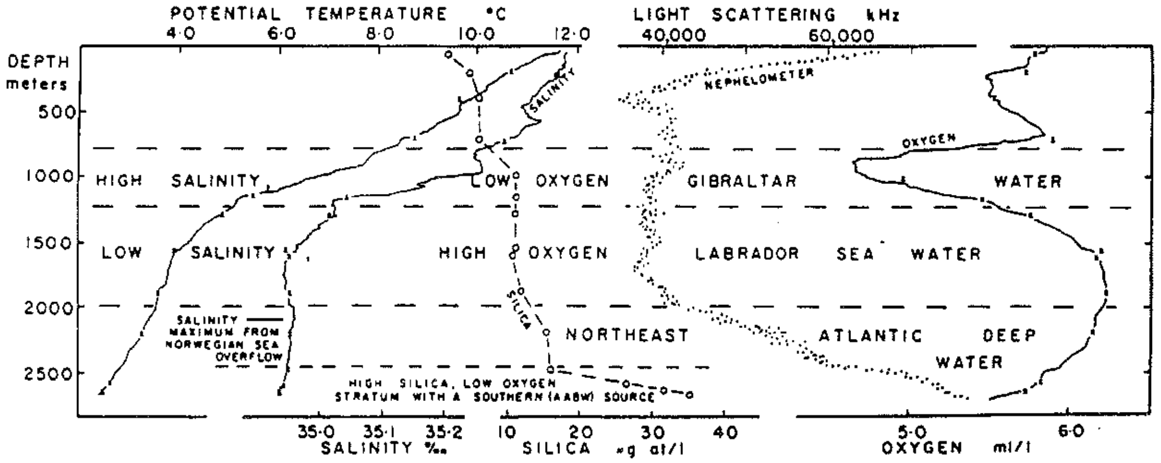


Figure 10: Hydrographic profile of the Rockall Trough (from Lonsdale and Hollister 1979).

Velocities of over 80 cm.s^{-1} within the Norwegian Sea Overflow were recorded on the Wyville-Thomson Ridge. The lowest sub-layer is the silica rich Antarctic Bottom Water layer. Ellett *et al.* (1983) slightly modified this overall structure on the basis of the results of the JASIN 1978 project in the Northern Rockall Trough. The water structure in this case consists of two upper layers. North Atlantic Water, seen in the south of the trough, with fresher modified North Atlantic Water in the north and west, is underlain by North Atlantic Water in contact with Sub-Arctic Intermediate Water. At greater depths, a distinction can be made between water from the south, water with a Norwegian Sea Overflow input and water with an Arctic component from the Faeroe-Shetland Channel.

Lonsdale and Hollister (1979) described the main sedimentary features and current dynamics of the Rockall Trough. Both the eastern and western margins display current ripples, with the eastern margin characterised by a fast, narrow, erosive flow of Labrador Sea Water and Northeast Atlantic Deep Water. These flows built, and are at present eroding a narrow continental rise on the eastern margin, and are responsible for the entrainment and transfer of sediment to the western margin of the trough. Thorpe and White (1988) described a deep intermediate nepheloid layer at 2,550 m depth on the continental slope of the Porcupine Ridge. A current on the lower part of the slope, 10-30 m off the bottom, reached velocities of over 15 cm.s^{-1}. Thermohaline currents were also recorded at 2,400-2,900 m depth on both margins of the Rockall Trough (Lonsdale and Speiss 1977), while significant bedload transport and reworking at 1,300-1,350 m depth was also noted. A thin (500 m) and narrow (10 km) sea bed current also enters the Trough along the eastern margin and flows in an anticlockwise loop to the western margin of the Trough where it is augmented by the southerly directed Norwegian Sea Overflow (Figure 11). This Northeast Atlantic Water is the most significant current in the Rockall Trough, determining both sediment distribution and the sea floor bedforms present. Kenyon (1986) recorded a strong northwest directed current flowing along the continental slope of the Northeast Atlantic, which is believed to be responsible for the development of longitudinal and transverse bedforms on the slope. In the vicinity of the Wyville-Thomson Ridge the current extends down to 400-600 m depth while to the west of Scotland current velocities in excess of 20 cm.s^{-1} were recorded at 90-490 m depth.

Firm evidence exists for current action on the eastern margin of the Rockall Trough at various depths. One of the most detailed studies of current dynamics in the Rockall Trough was that carried out by Dickson and McCave (1986) (Figure 12). A bottom nepheloid layer on the western margin of the Porcupine Ridge at 400-600 m depth is described. It is noted that such layers may become detached and spread along isopycnal surfaces to form intermediate nepheloid layers. In support of this, an intermediate nepheloid layer is described at 450-600 m depth, in a total water depth of 900 m. Numerous other current readings, at various depths and localities, formed the basis of this study (Table 2).

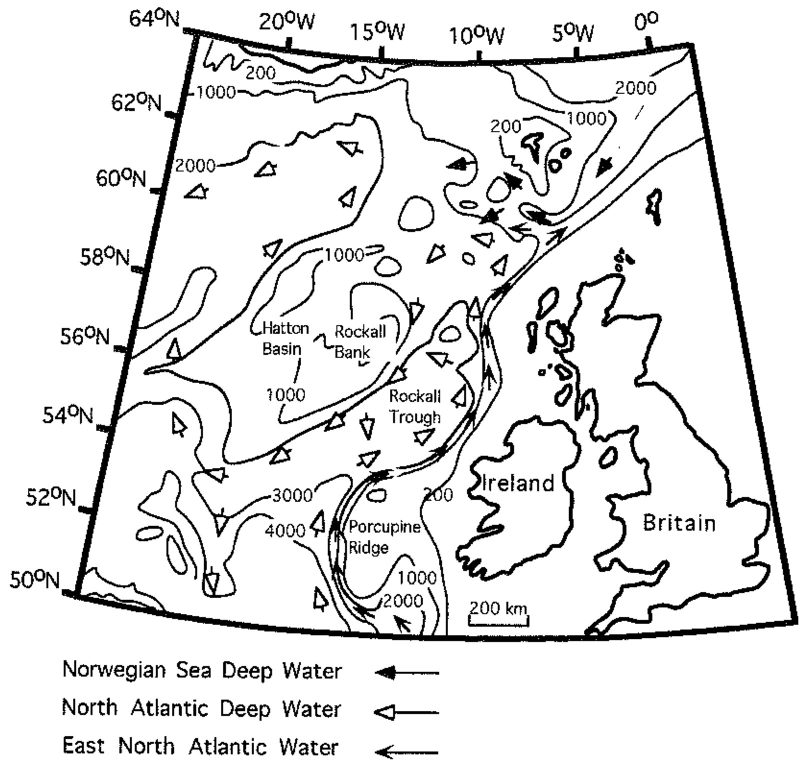


Figure 11: Present day bottom circulation patterns in the Rockall Trough, with the major water layers highlighted (after Howe and Humphery 1995).

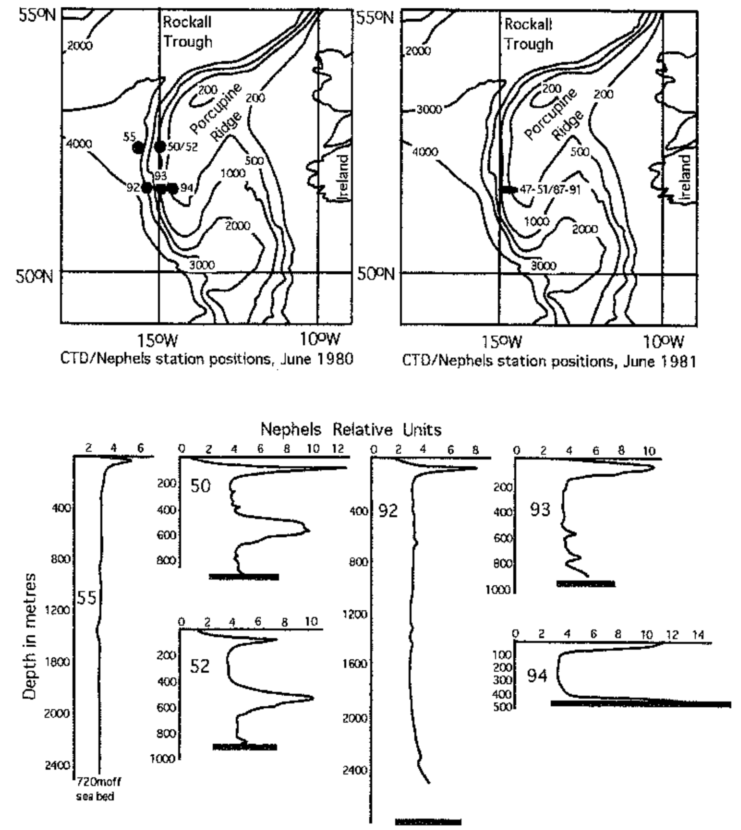


Figure 12: Location of study transects on the western slope of the Porcupine Ridge and the results of the associated nephelometer traces showing well developed intermediate nepheloid layers at a number of levels (from Dickson and McCave 1986).

Table 2: Results from a Porcupine Ridge current meter array (after Dickson and McCave 1986).

Latitude Longitude	Sounding (m)	Instrument height above bottom (m)	Duration (days)	Max. speed (cm.s^{-1})
52°30.4' N 14°44.4' W	505	54	206	37
52°30.2' N 15°25.9' W	2555	50	213	29
51°41.8' N 14°57.3' W	778	50	90	37
51°41.1' N 15°12.7' W	1537	50	90	27
51°42.1' N 15°18.8' W	2404	50	90	43
51°41.4' N 14°56.3' W	786	29	201	49
51°41.6' N 14°44.3' W	500	29	197	33
51°42.4' N 14°54.9' W	741	30	195	31
51°42.7' N 15°11.1' W	1709	30	138	40

It should be noted that the maximum speeds recorded above are all capable of suspending fine grained sediment, but there was no evidence for enhanced mean speeds or higher maximum speeds from the erosion zones. As a result, the origin of the nepheloid layers at discrete levels in the water column is slightly puzzling. One possibility is that the nepheloid layers are long-lived features initiated by higher current speeds which predate the measurements being made during this study.

Howe and Humphery (1995) recorded a north flowing slope current, at a water depth of 500-1,100 m, from the Hebrides Slope area, in the north of the Rockall Trough. This current flows north along the bathymetric contours at peak velocities of 15-25 cm.s^{-1} at depths of 1,035 m and 457 m. The origin of the current appears to lie with the East North Atlantic Water body. This current appears to be actively reworking sea bed sediments. Fine-to-medium grained siliciclastic sands, reworked as sandy contourite deposits and separated by glaciomarine hemipelagite deposits, were described from the sea bed in the study area. Associated sedimentary structures include linguoid ripples with wavelengths of 7-15 cm and amplitudes of 2-3 cm, crag-and-tail structures, scour marks, primary current lineation and current smoothing of the sea bed. It should be noted that current velocities of 20-50 cm.s^{-1} are required for the development of linguoid ripples (Howe and Humphery 1995).

Strong to moderate currents are reported from the western margin of the Rockall Trough, in 2,000-2,400 m water depth at the foot of the Rockall Plateau Continental Slope, and at 2,400 m water depth on the southeast flank of the Feni Ridge, both flowing to the southwest (Lonsdale and Hollister 1979). West-northwest currents of mean velocity 3.7 cm.s^{-1} and 3.3 cm.s^{-1} and maximum velocity of 13.5 cm.s^{-1}, were recorded by two current meters in the north of the Rockall Trough, adjacent to the western margin. Inferred velocities for the crest of the Feni Ridge at 55° N indicate bottom currents of 12-15 cm.s^{-1}, with a maximum velocity of over 29 cm.s^{-1} (Dowling and McCave 1993). Van Weering and de Rijk (1991) recorded maximum velocities of 9-15 cm.s^{-1} on the Feni Ridge with the possibility of periodic currents in the range 15-30 cm.s^{-1} near the lower Rockall Slope. Roberts (1972) reports very variable current velocities of 3 cm.s^{-1} to 45 cm.s^{-1} from the western margin of the Rockall Trough. Bottom nepheloid layers described from the foot of the Rockall Plateau and near the crest of the Feni Ridge appear to be the result of the action of the Norwegian Sea Overflow current which has a high velocity core at 2,100 m depth. Bottom nepheloid layers recorded from the lower flanks of the Feni Ridge are due to the southerly flowing North East Atlantic Deep Water current (van Weering and de Rijk 1991).

Geology and Geomorphology

A three-layer, up to 5 km thick, sedimentary succession has been recognised in the Rockall Trough (O'Reilly *et al.* 1995). The basal layer probably represents an early Mesozoic syn-rift package of Triassic and Jurassic sediments, with the upper two layers representing Cretaceous to Recent post-rift sediments.

Given the obvious range of current velocities on the eastern margin of the Rockall Trough, a variety of sedimentary bedforms might be expected to be developed. The morphology of the eastern slope of the Rockall Trough changes dramatically from south to north, as the effects of glaciation become more pronounced. A mean dip of 4° is given for the Irish Continental Slope (Lonsdale and Hollister 1979), with thin and patchy sediment cover on the upper half. Glaciomarine deposits, in the form of cobbles and rock fragments, are preferentially concentrated at the shelf edge, while just below the shelf break a 200 m scarp with a dip of 12° is described, with clear evidence for the erosional truncation of sedimentary strata. The deepest erosional incision on the eastern margin of the Rockall Trough is at 1,300 m-1,500 m at mid-slope depth, with the Labrador Sea Water high velocity jet as the agent of current erosion on the Irish Continental Slope at the present time. It is difficult to say whether current erosion or sediment non-deposition are the dominant factors at this depth. A combination of both processes is the most likely scenario. At depths greater than 1,770 m on the eastern margin of Rockall Trough, a continuous layer of unconsolidated sediment is observed, with a smooth or pockmarked surface, thickening to 400 m at 2,100 m depth and extending offslope to a depth of 2,950 m (Lonsdale and Hollister 1979). This pattern of sedimentation appears to define a distinct sediment wedge characterised by a hummocky surface and along-slope corrugations up to 30 m high and 2 km across. The deepest part of the slope, at depths greater than 2,700 m, is the site of ongoing erosion.

Howe (1995) notes the presence of sandy contourite deposits from the sea bed in the Hebrides Slope area, just south of the Wyville-Thomson Ridge. A three-stage depositional history is given for the glacial to Recent interval, based on core data. Lowered sea levels and the suppression of bottom currents during the last glacial maximum resulted in a predominance of down-slope and glaciomarine sedimentation. As bottom currents increased in strength at the end of the glacial period, along-slope processes became dominant over down-slope sediment transport, leading to the development of sandy and muddy contourite deposits. Present day currents are still dominantly along-slope reflecting post-glacial inheritance, with peak velocities of 26-48 cm.s^{-1} at 468 m and 403 m depths. The sandy contourites exposed on the sea bed at the present day are probably Early Holocene in age. The clear change from downslope dominated sedimentation during glacial times to along-slope proceses in post-glacial times is related to the reactivation of bottom current activity, which was linked to a meltwater pulse, and also climatic instability as the polar front migrated north from a position near Portugal to Iceland. On the Upper Continental Slope to the west of Scotland and Norway, Kenyon (1986) describes barchanoid sand waves which are the result of a north flowing current that extends along the Continental Slope for approximately 3,000 km. A small field of sand waves is also described form the upper Continental Slope to the southwest of Ireland. In this case the development of the sand waves is related to shelf edge effects, but an along slope current of over 40 cm.s^{-1} is required for the development and maintenance of the sand waves to the north.

Two large sedimentary fans are described from the northern part of the eastern margin of the Rockall Trough, to the northwest of the Irish Mainland (Figure 14). Flood *et al.* (1979) conclude that the Upper Tertiary sedimentary fill of the trough was evenly partitioned between the Donegal and Barra deep sea fans, located on the eastern margin of the Rockall Trough, and the Feni Sediment Drift on the western margin of the basin. Stoker (1996) suggests that the initiation of the Barra Sediment Fan was in the mid-Miocene to Holocene.

To the north, adjacent to the St. Kilda Scarp and East Rockall Scarp, Kenyon (1987) suggests the presence of slumps or rotational faults oriented parallel to the contours (Figure 13). North of St. Kilda, two notches are seen on the continental slope. The upper feature, which is 215 km long and reaches a height of 235 m in the centre and 50 m at the north and south extremities, is considered to be either a fault scarp or a wave cut platform of Oligocene age. There is a well formed bulge, up to 35 m high, at the foot of the headwall. The lower scarp is discontinuous but is thought to be between 150 m and 420 m in height. Both features slope at an angle of 10-20° and appear to pass down-slope into slides on the floor of the Rockall Trough at the southern end of the East Rockall Scarp. These slides are characterised by large areas of hummocky seafloor. Up to four slide episodes are recognised, from shallow cores, as debris flow deposits, each separated by turbidites (Faugeres *et al.* 1981). It is thought that slide frequency may have increased as a result of climatic amelioriation at the end of the last glaciation with the increase in sediment transport to the shelf edge and subsequent oversteepening of the continental slope. Lowered sea levels, leading to higher energy conditions at the shelf break, may also have promoted slope failure. Slump folds or current ridges are also reported, with wavelengths of approximately 3 km, from the south flank of the Wyville-Thomson Ridge.

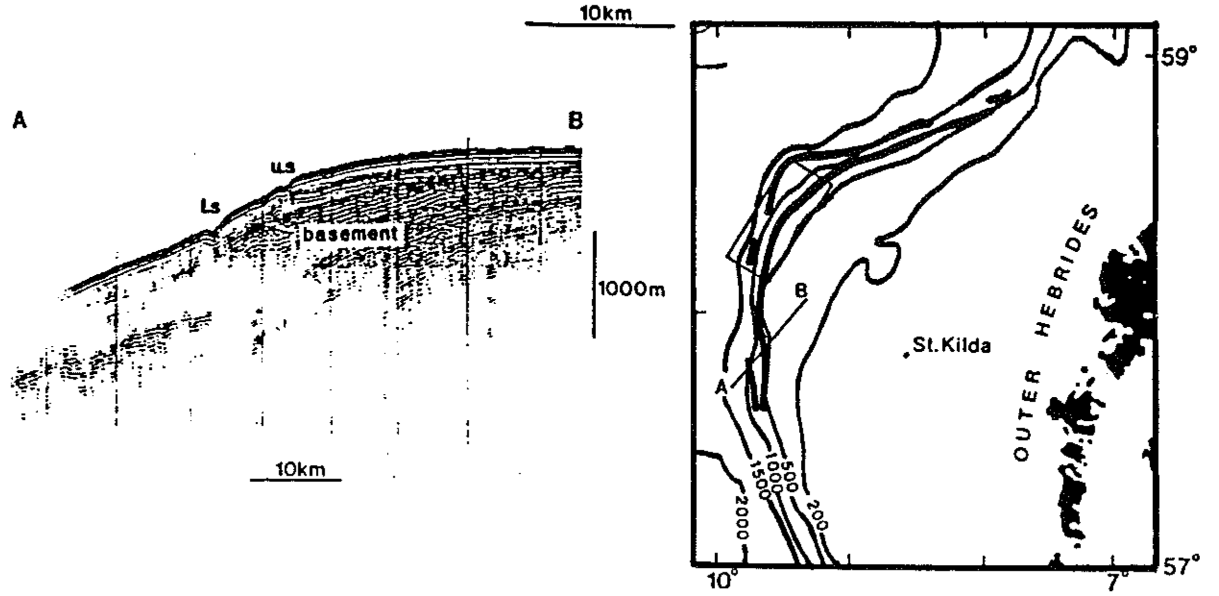


Figure 13: **(a)** Air gun reflection profile of the St Kilda slump features on the Hebrides Slope (ls = lower scarp, us = upper scarp). **(b)** Along slope trace of the above slump features (both from Kenyon 1987).

Finally, large canyons are seen at the edge of the continental shelf and on the continental slope (Kenyon 1987) to the north and west of the Porcupine Bank and north of the Slyne Ridge. These are most likely Pleistocene features and may pass down-slope into sediment lobes or fan deposits. Canyons, with characteristic v-shaped profiles, are reported from the upper continental slope extending almost as far north as the St Kilda scarps (Kenyon 1987).

Iceberg ploughmarks are reported from depths of 140-500 m on the outer continental shelf and upper continental slope on both the eastern and western margins of the Rockall Trough (Belderson *et al.* 1973). These features, formed by the scouring action of floating ice that grounded in the shallow waters of the Irish Continental Shelf, are typically 20 m wide (maximum of 100 m) and 2 m deep (maximum of 10 m) while the greatest recorded length is 5.5 km.

There appears to be little available data on the sedimentary characteristics of the floor of the Rockall Trough. Lonsdale and Hollister (1979) describe the eastern half of the Trough as a turbidite plain with the Irish and Hebridean margins as the primary source areas. Turbidites are however less extensive to the south due to the reduced terrigenous influx. It is also possible that much of the turbidite load was pirated by north-directed, anticlockwise deep circulating currents and transported to the western margin of the Rockall Trough. High Pleistocene sedimentation rates, of up to 3 cm.year^{-1} on the Feni Drift, would support this theory.

Sedimentation on the western margin of the Rockall Trough is dominated by the Feni Sediment Drift and later slump and related turbidity current deposits. Lonsdale and Hollister (1979) describe a traverse from 1,200 m water depth on the eastern slope of Rockall Bank to the marginal channel of the Rockall Trough. At depths of 1,300-1,400 m, discontinuous sheets of winnowed, rippled sediment less than 10 m thick are present, separated by rocky seafloor. On a photographic traverse from 1,315-1,345 m on the slope of the Rockall Platform, Lonsdale and Hollister (1979) also describe a field of transverse sand waves with 7-8 m wavelengths and amplitudes less than 0.5 m. The crest lines are typically parallel to the along-slope contours. A rippled seafloor of winnowed sand is also described, with the seafloor smoothed to different degrees by current action in almost all photographs. On the lower slope, the continuity of the sand sheets increases to form a sediment veneer. Rippled sand or silt deposits are associated with the drop in gradient at the foot of the slope.

The Feni Sediment Drift has been described in detail by numerous authors. It consists of one main ridge and a second, subsidiary ridge to the southeast (Lonsdale and Hollister 1979). The main ridge is approximately 600 km long (Figure 14), with a thickness of 500 m reported by both Dowling and McCave (1993) and Roberts and Kidd (1979). The maximum sediment thickness reported in the Lonsdale and Hollister (1979) profile is approximately 800 m. Growth of the ridge since the Oligocene-Miocene is related to the south directed overflow of Norwegian Sea Water (Dowling and McCave 1993). Geochemical investigations suggest that deep water production was suppressed during the last glacial maximum, with maximum bottom water production prior to and during the early part of deglaciation probably the result of changing surface water and climatic conditions.

Regular, symmetric, large scale sediment waves are described by Lonsdale and Hollister (1979) oriented subparallel to the slope contours and the dominant current vector, with amplitudes of 30 m and wavelengths of 2 km, from the Feni Ridge (Figure 15). These features, believed to have been initiated in the Late Miocene, are active at present, migrating at approximately 0.25 m.year^{-1} in a northwesterly direction. Roberts and Kidd (1979) described the same features from GLORIA data acquired during the RRS "Discovery" Cruise 84. A complex array of sediment wave fields is seen to decorate the Feni Ridge surface, with a dominant trend subparallel to the slope contours. Two sets of sediment waves are defined. Heights of 4-25 m were recorded for the inner set of sediment waves, while the outer set are up to 25-50 m high and have wavelengths of 1-4 km, with crests that can be traced for up to 26 km. These features are confined to the eastern side of the ridge, with the western side characterised by a smooth surface (Figure 16).

Richards *et al.* (1987) described the results of a shallow reflection seismic survey over a northern dune field, which covers 350 square kilometers. It is believed in this case that sediment waves were initiated in the Late Miocene in 1,080-1,180 m water depth. A threefold subdivision is recognised with a basal climbing unit, a transitional phase and an upper sinusoidal package. This developmental pattern signifies decreasing energy in the sedimentary system over time, possibly related to the waning input of glacial meltwater into the basin during deglaciation.

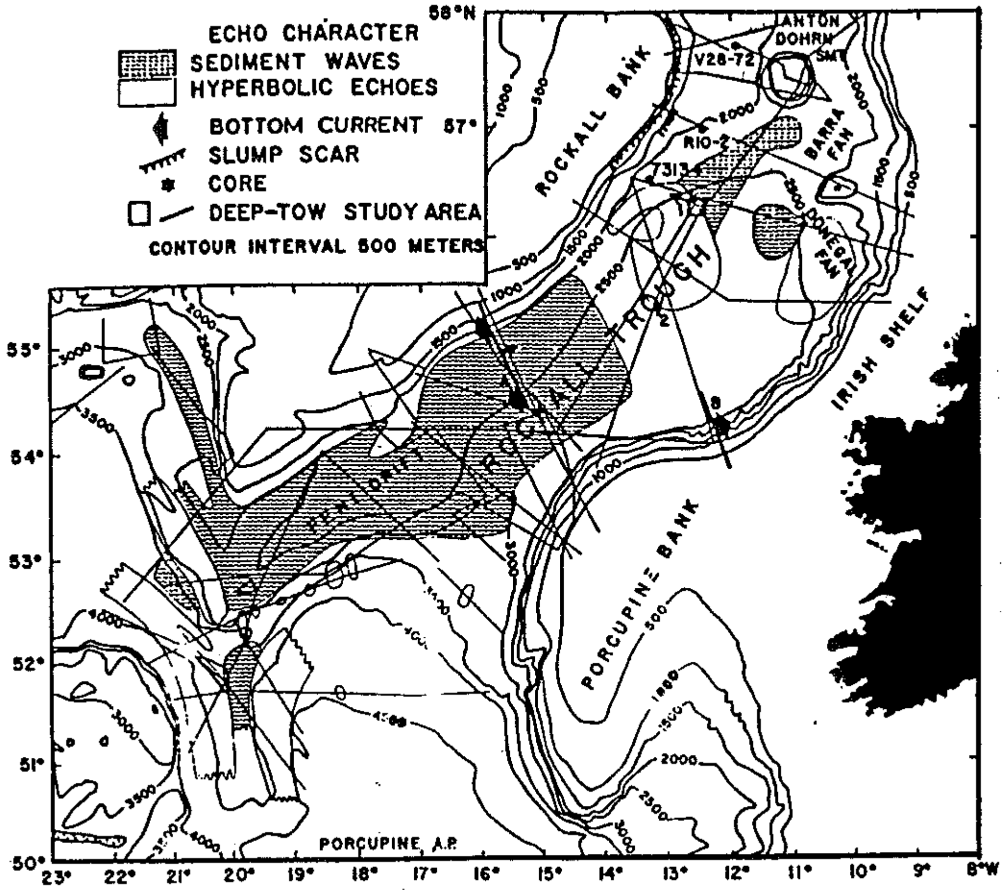


Figure 14: Bathymetric and echo character map of the Rockall Trough, with Feni Sediment Drift, Rockall Bank Slumps and Donegal and Barra sediment fans delineated (from Flood *et al.* 1979).

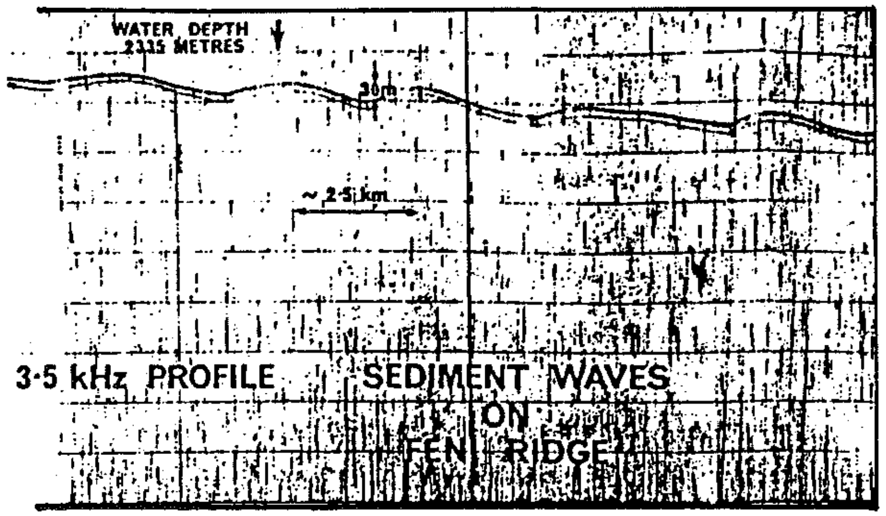


Figure 15: 3.5 kHz profile near the axis of the Feni Ridge. Wave heights are approximately 30 m, with an apparent up-slope migration direction (from Roberts and Kidd 1979).

This submarine sand dune field is the lateral equivalent of the sediment waves described from the area on the Feni Drift located further to the south.

Large slump features are also recognised from the eastern margin of the Rockall Bank (Figure 14). Roberts (1972) describes two large slumps on the upper part of the eastern slope of the Rockall Bank, the uppermost of which can be traced along-slope for 270 km (Kenyon 1987), has a mean width of 14 km and appears to be Pleistocene in age. The volume of the upper slump, which developed on a 2° slope, is calculated to be approximately 300 km^3, with an estimated minimum horizontal translation of 0.6 km and a maximum of 3 km. The depth to the base of this upper scarp is 500-800m, while a lower feature is recorded at 1,400 m depth. Kenyon (1987) calculated a headwall steepness of 6-13.5° for the Rockall Bank slump features. Slump glide planes or detachment surfaces, which have a listric geometry in cross section, are defined by two conspicuous reflectors on shallow reflection seismics (Roberts 1972). It is, however, more likely that a series of closely associated, en-echelon glide planes are present, rather than just two discrete features.

Faugeres *et al.* (1981) also confirm the presence of slumps from the Feni Ridge but noted that the slumps do not contribute a great deal to the construction of the drift. In this case, slumps are separated in time by turbidite deposits reported over a large area to the north and south of the slump deposits. In the above study, an age of 15,000-16,000 years BP was assigned to the slumps, with most of the material sourced from the Rockall Bank and Slope. High sedimentation rates of 15-18cm.1,000 $years^{-1}$ for the interval 13,400-73,000 years BP may have promoted slope failure and the development of the slump features. Associated sea level lowstands may, once again, have promoted slope instability, with higher energy conditions experienced at the Shelf edge as a result of lowered wave base. Evidence for beach conglomerates and gravels at 180 m depth on the Rockall Bank give a rough estimate of the sea levels during the last Glacial maximum (Roberts 1972). Faugeres *et al.* (1981) however suggested that loading due to sea level highstands would be more likely to promote slope failure. Flood *et al.* (1979) also described slump features from the eastern margin of the Rockall Bank. Slope failure in the interval 15,000-16,000 years BP produced debris flows and turbidity currents which have obliterated part of a field of sand waves on the northern half of the Feni Sediment Drift. It appears that the sediment wave troughs have been rapidly infilled since 73,000 years BP, suggesting a high sediment input into the basin prior to the onset of slumping. Once again, Late Pleistocene sedimentation rates on the slope floor are estimated to be approximately 18cm.1,000 yrs^{-1}, values high enough to lead to oversteepening of the Rockall Bank slope and the initiation of failure features. The slump described in this case covers approximately 11,000 km^2, originating at a depth of 2,000 m. It becomes depositional below 2,600 m depth.

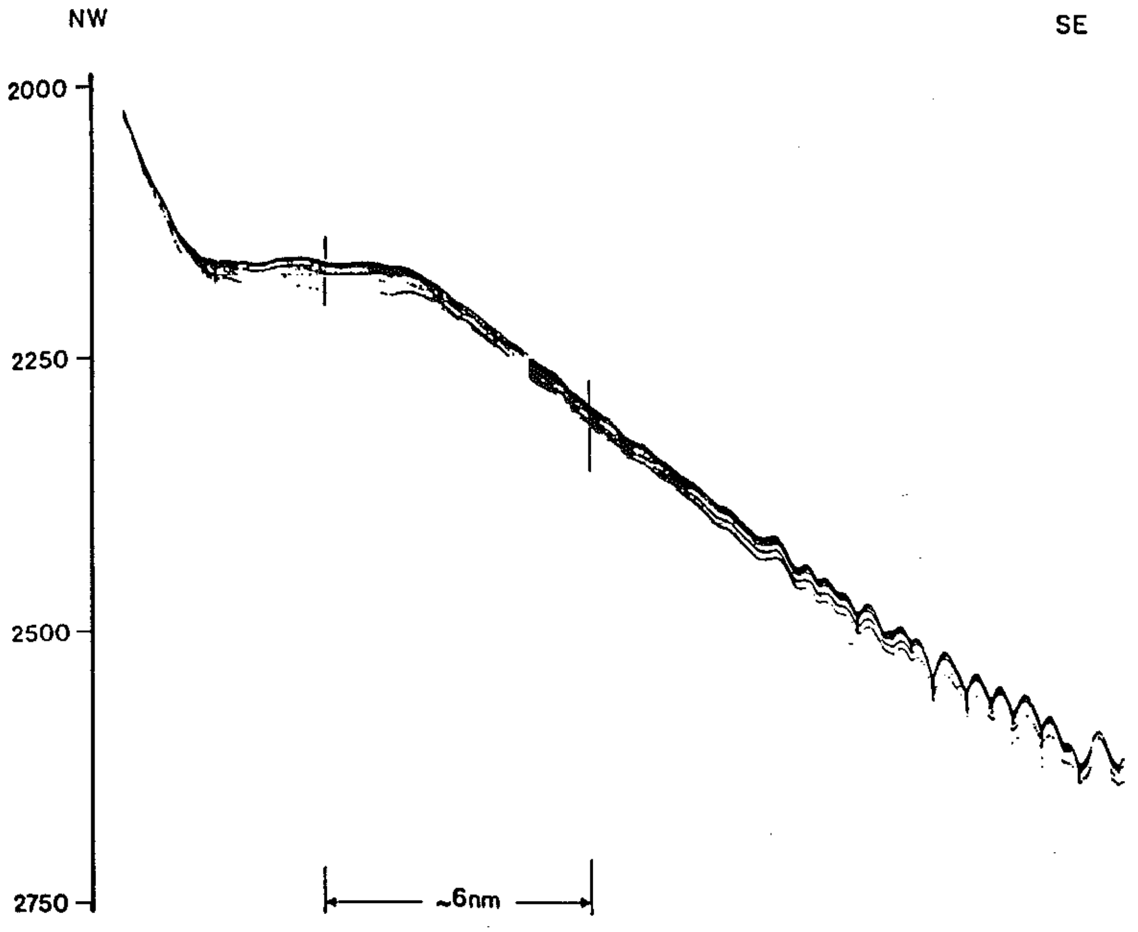


Figure 16: **(a)** 3.5 kHz profile of the northern section of the Feni Ridge, with the sediment drift attached to the Rockall Bank. Sediment waves are clearly developed on the lower eastern flank (from fter van Weering and de Rijk 1991).

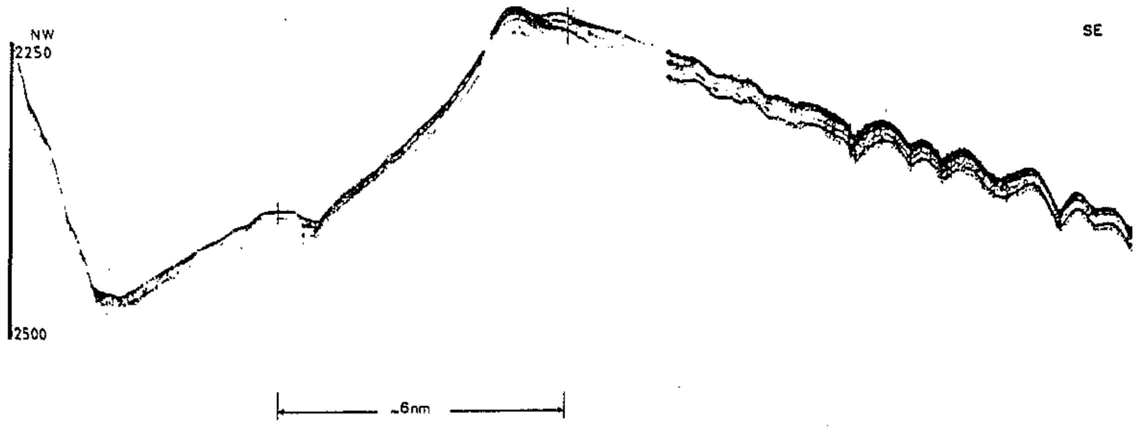


Figure 16: **(b)** Section from the southern part of the Feni Ridge. The sediment drift has detached from the Rockall Bank. The smooth western flank and eastern flank, with well developed sediment waves, are both clearly visible (from van Weering and de Rijk 1991).

Hatton Basin

Introduction

The Hatton Basin (Figure 1) is a northeast-southwest trending deep water bathymetric low, located to the west of the Rockall Bank, far from any significant present-day sediment source. The Hatton Basin is closed to the west by Hatton Bank, to the north by George Bligh Bank, to the east by Rockall Bank and extends south to the deep Atlantic Abyssal Plain. Water depths in the region range from less than 500 m on the crest of Hatton and Rockall banks, to over 1,500 m where the basin opens out to the south onto the Atlantic Abyssal Floor. Basin development is once again most likely related to rifting of the continental crust to the east of Rockall Plateau in pre-Jurassic times, followed by accentuated rifting and thermal subsidence in the Mesozoic and Tertiary (Shannon *et al.* 1995). The Hatton Basin contains up to 5 km of Late Carboniferous to recent sediments (O'Reilly *et al.* 1995)

Hydrography

Relatively little data exists on the hydrography of the Hatton Basin. It is speculated to be quite different to that of the Rockall Trough and Porcupine Abyssal Plain described in sections (5.2.) and (3.2.), due to the different geomorphological framework and elevated location on the Rockall microcontinent.

Geology and Geomorphology

The Hatton Basin, which forms the central portion of the Rockall Plateau microcontinent, is underlain by thick continental crust and, as mentioned, is located far from any significant present-day terrigenous sediment source. There is the possibility that some sediment may be sourced off the crest of the Hatton Bank to the west and the larger Rockall Bank to the east.

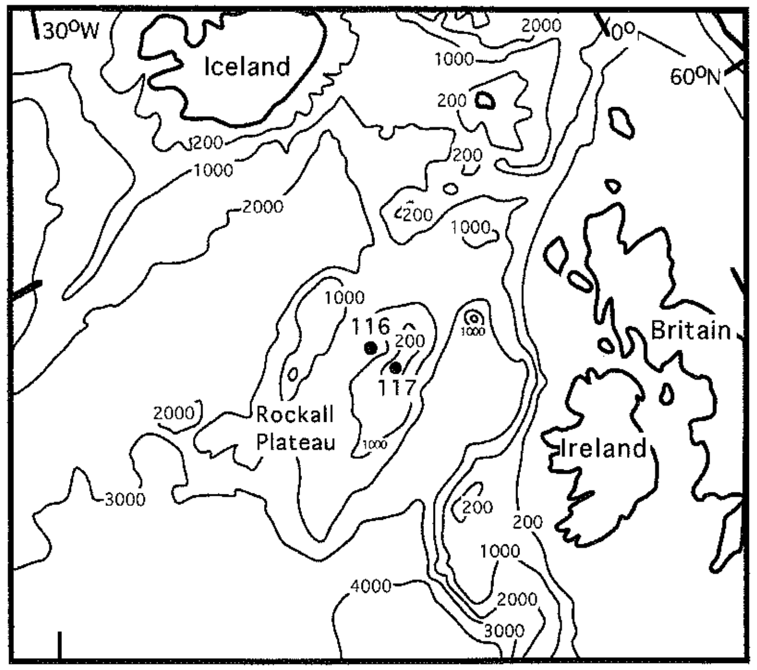


Figure 17: Location of DSDP drill sites 116 and 117 in the Hatton Basin (from *Initial Reports of the Deep Sea Drilling Project*, Leg 12, sites 116 and 117).

DSDP drill sites 116 and 117 are located in the eastern portion of the Hatton Basin, adjacent to the Rockall Bank bathymetric high (Figure 17). The recorded sediment thickness in the basin reached 2 sec TWT on reflection seismics, corresponding to an approximate mean sediment thickness of 1,400 m. There is poor seismic resolution on the adjacent Hatton Bank and Rockall Bank, suggesting the presence of crystalline basement at shallow depth. The DSDP coring results indicate foraminiferal ooze, sand and silty clay on the sea bed at site 116, with limestone, chalk and chalky ooze encountered at a depth of 71 m. However, at site 117, the foraminiferal upper layer is absent, with the limestone, chalk and ooze encountered at the sea bed. Reflection seismic profiles acquired in the area (Figure 18) by Glomar Challenger indicate the presence of sea bed features on the eastern side of Hatton Bank and also on the eastern margin of the basin, in the vicinity of drill sites 116 and 117. A pronounced erosional feature is evident on reflection section (a), on the lower levels of the eastern slope of the Hatton Bank. This appears to be a sea bed channel, with evidence for truncation of reflectors in the subsurface suggesting sea bed erosion possibly due to along-slope contourite currents. Basinward of this feature, a number of minor notches are seen on the sea bed. These may represent discrete channel features or are possibly the surface expression of faults in the underlying sedimentary succession. Up-slope from the major channel feature is a possible along-slope slump scar, with a large block of sediment appearing to detach from the Hatton Bank slope and move down-slope towards the channel axis. Thus, there is some evidence for the development of mass wasting features on the eastern slope of the Hatton Bank and in the western portion of the Hatton Basin. Section (b) is from an area to the west of the Rockall Bank, in the eastern portion of the Hatton Basin. Once again, along slope erosional sea bed features, which bear remarkable similarities to channel features described in other deep water areas to the west of Ireland, have been recorded. The two largest features are seen at the break in slope where the Rockall Bank passes out onto the floor of the Hatton Basin.

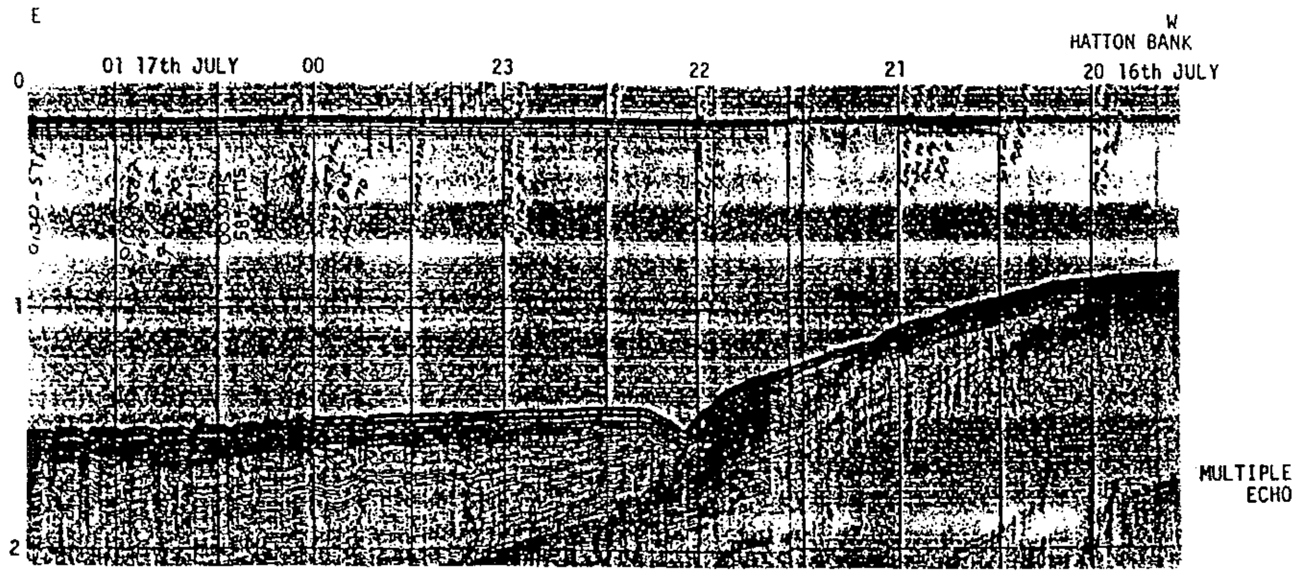


Figure 18: **(a)** Reflection seismic section from the eastern slope of the Hatton Bank, displaying possible sea bed mass wasting features (from *Initial Reports of the Deep Sea Drilling Project*, Leg 12, sites 116 and 117).

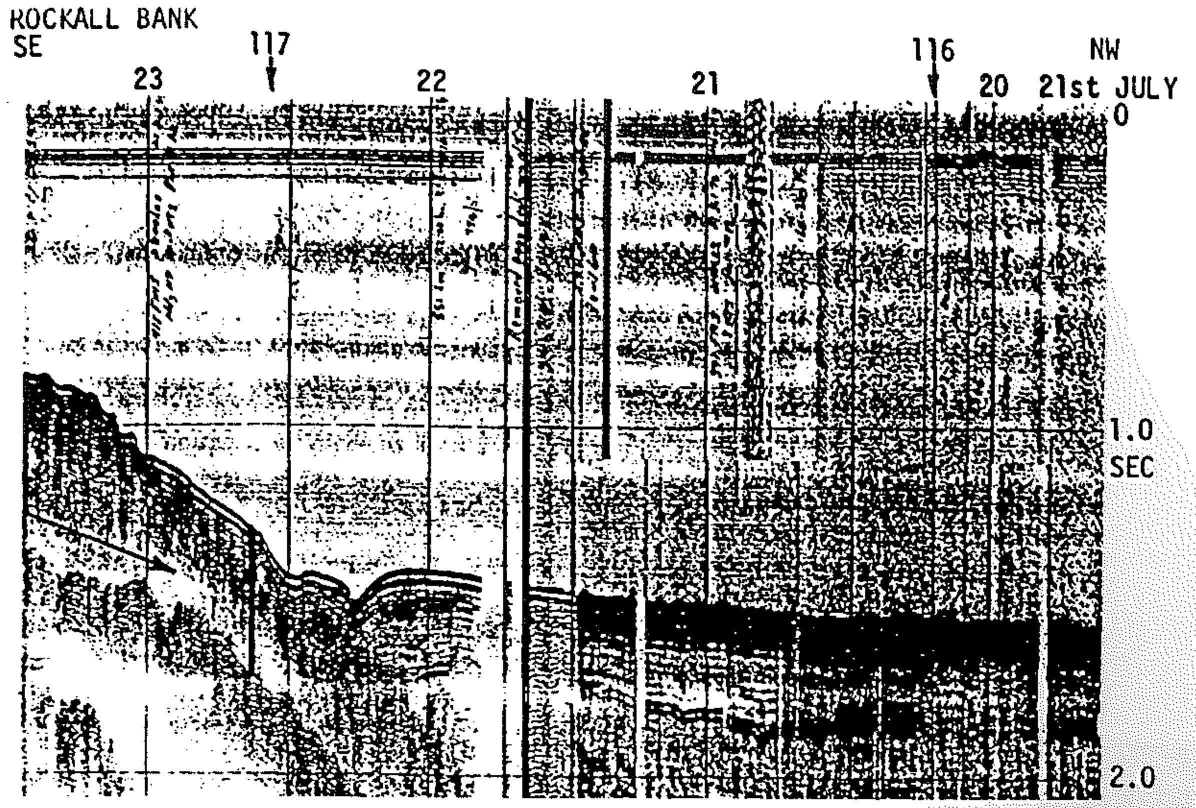


Figure 18: **(b)** Reflection seismic section from the western slope of the Rockall Bank, also displaying possible sea bed mass wasting features on the floor of the Hatton Basin (from *Initial Reports of the Deep Sea Drilling Project*, Leg 12, sites 116 and 117).

Stoker (1996) suggests that Late Eocene to mid-Miocene sedimentation in both the Hatton and Rockall basins was dominated by a vigorous bottom current regime, leading to significant lateral migration of sediment by up-slope accretion onto the flanks of both basins. This process is thought to have resulted in the development of extensive submarine sediment drift and wave features. Sedimentation in mid-Miocene to Holocene times was dominated by extensive progradation of the shelf margin clastic wedge on the Hebrides Slope and eastern margin of the Rockall Trough during the Plio-Pleistocene, due to the introduction of large volumes of glaciogenic sediment. Erosion dominated on the western margin of the Trough at this time, with the thickest sediment accumulation preserved in the Hatton Basin.

Hatton Bank and Edoras Bank

Introduction

The Hatton Bank (Figure 1) is a northeast-southwest trending plateau area located to the west of the Hatton Basin, on the Rockall Plateau, in water depths ranging from less than 500 m over the crest of the bank, to more than 1,200 m on the bank slopes. The Hatton Bank, extending south into the Edoras Bank, is flanked to the west by the Hatton Sediment Drift and to the east by the Hatton Basin.

Hydrography

The hydrography over the relatively shallow Hatton Bank feature is almost certainly dominated by the North Atlantic Water and Mediterranean Water layers, with stratification expected to be similar to the upper levels of the water column in the Rockall Trough and Porcupine Abyssal Plain.

Geology and Geomorphology

The Hatton Bank is covered by approximately 250 m of post rift sediments (White 1987), a conclusion which is derived from the poor reflection seismic resolution over the bank, suggesting crystalline basement at shallow depths. The sea bed geomorphology in this area is dominated by the major Hatton Sediment Drift, located on the western slope of the bank. It is likely that both Hatton Bank and Rockall Bank at present act as the provenance of relatively small volumes of sediment shed into the Hatton Basin, although their role in determining the hydrography and circulation patterns in the basin would be of far greater significance.

Basement of the Edoras Bank is a complex of blocks and basins with the main faults parallel to the south and southwest flanks of the bank. The Edoras Bank proper is the largest of these blocks (Bull and Masson 1996).

Hatton Sediment Drift

Introduction

The Hatton Sediment Drift, located on the western slope of the Hatton Bank, trends north-south paralleling the Rockall Plateau edge contours. To the west is the major Gardar Sediment Ridge, located just east of the Reykjanes branch of the mid-ocean ridge, on the Atlantic Abyssal Floor. The Hatton Drift sediments are clearly imaged on reflection seismics (White *et al.* 1987, Figure 19), while indirect evidence of depositional ridges or ocean basin hills, which have been recorded from other deep marine sediment drifts including the Gardar Ridge, also exists (Johnson and Schneider 1969).

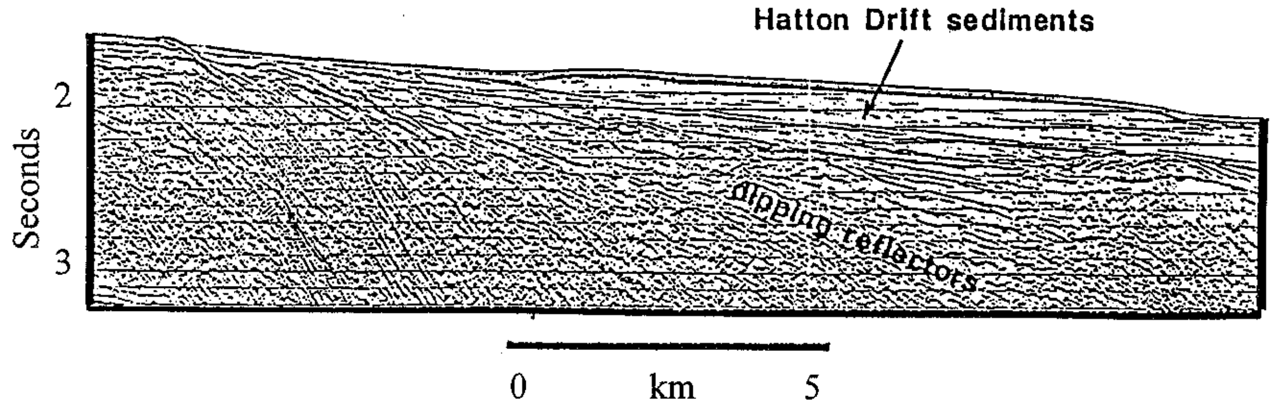


Figure 19: Reflection seismic section from the Hatton Bank to the Atlantic Abyssal Floor. The Hatton Sediment Drift is clearly imaged as a broad, low amplitude high on the sea bed (after White *et al.* 1987).

Hydrography

The present morphology of both the Hatton and Gardar sediment drifts is almost certainly related to the overflow of Norwegian Sea Water. Flow of this water body over the Iceland-Faroe Ridge, to the southeast of Iceland, was calculated at 5.4 m $m^3.s^{-1}$ (Johnson and Schneider 1969). Mean flow velocities of 7-15 $cm.s^{-1}$ are also recorded over both the Hatton and Gardar sediment drift crests, in abyssal water depths (Dowling and McCave 1993). Lonsdale and Hollister (1979) described a steady flow of 14 $cm.s^{-1}$, with a velocity maximum of 22 $cm.s^{-1}$, at the foot of the Hatton Drift. Lonsdale and Speiss (1977) reported long crested, low energy current ripples in 3,000 m water depth, from the Hatton Drift. Flow velocities in this case were up to 21 $cm.s^{-1}$, with a mean velocity of 13.8 $cm.s^{-1}$, and are believed to be the direct result of thermohaline currents. The change in surface topography of the Gardar Sediment Drift, from current smoothed in the north to hummocky and uneven in the south, is almost certainly related to the decrease in flow velocity of the Norwegian Sea overflow water from north to south.

Geology and Geomorphology

As mentioned, the Hatton Sediment Drift is a north-south trending topographic feature located to the west of the Hatton Bank. Growth of this feature is almost certainly related to post-glacial contourite currents which became dominant over downslope currents after the last glacial maximum, with the Norwegian Sea Overflow being the most likely sediment transport mechanism in this case. The Hatton Drift lies far from any present sediment source, with the exception of the Faeroe Plateau. Sediment supply is possibly related to the last glacial maximum approximately 18,000 years BP, and the associated sea level lowstand and increased meltwater production (Dowling and McCave 1993) although a post-glacial sediment input would seem to be the more likely scenario. The presence of winnowed sediment on the Feni Drift to the east, implies the production of deep circulating water bodies in the region during glacial-deglacial intervals which almost certainly influenced sedimentation patterns and supply on the Hatton Drift.

Bull and Masson (1996) also recognised the latest Early Miocene-Late Miocene as a period of pronounced sediment drift accumulation in the area to the south of Edoras Bank. In this area the sea bed typically has an undulating surface with a maximum relief of 150 m at the crest of the sediment drift between the Edoras Bank and the Rohan Seamount. Sediment waves with wavelengths of 2-5 km mark the top of the drift. Seismic reflection data shows that the sediment drift deposits overlie an Eocene prograding fan deposit marking the transition from down-slope detrital sedimentation to pelagic sedimentation.

Conclusions

This study represents a compilation and synthesis of much of the existing published literature on a large region to the west of Ireland and presents a regional framework in which the 1996 AIRS (Atlantic Irish Regional Survey) Project was planned and carried out. It provides a synopsis of the geological setting, modern day sedimentology and hydrography for each of the major physiographic areas in the Atlantic waters west of Ireland. Areas of interest with regards to slope instability, sediment erosion, transport and deposition are highlighted. The study helped to provide important background data for the planning stages of the 1996 AIRS Project.

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