PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Morphology of the Continental Margin

A. S. Laughton and D. G. Roberts

*Phil. Trans. R. Soc. Lond. A* 1978 **290**, 75-85
doi: 10.1098/rsta.1978.0073

*Phil. Trans. R. Soc. Lond.* A. **290**, 75–85 (1978) [ 75 ]
*Printed in Great Britain*

# Morphology of the continental margin

By A. S. Laughton and D. G. Roberts
*Institute of Oceanographic Sciences, Wormley, Godalming, Surrey GU8 5UB, U.K.*

[Plate 1; pullouts 1 and 2]

The continental margin is the surface morphological expression of the deeper fundamental transition between the thick low density continental igneous crust and the thin high density and chemically different oceanic igneous crust. Covering the transition are thick sediment accumulations comprising over half the total sediments of the ocean, so that the precise morphological boundaries often differ in position from those of the deeper geology.

Continental margins are classified as active or passive depending on the level of seismicity. Active continental margins are divided into two categories, based on the depth distribution of earthquakes and the tectonic régime. Active transform margins, characterized by shear and shallow focus earthquakes, result from horizontal shear motion between plates. Active compressional margins are characterized by shallow, intermediate and deep earthquakes along a dipping zone, by oceanic trenches and by volcanic island arcs or mountain ranges depending on whether the margin is ocean–ocean or ocean–continent.

Passive margins, found in the Atlantic and Indian Oceans, are formed initially by the rifting of continental crust and mark the ocean–continent boundary within the spreading plate. They are characterized by continental shelf, slope and rise physiographic provinces. Once clear of the rifting axis, they cool and subside. Sedimentation can prograde the shelf and load the edge leading to further downwarping; changes of sea level lead to erosion by wave action and by ice; ocean currents and turbidity currents redistribute sediments; slumps occur in unstable areas.

The passive and sediment-starved margin west of Europe is described where the following factors have been significant: (*a*) faulting related to initial rifting; (*b*) infilling and progradation by sediments; (*c*) slumping; (*d*) contour current erosion and deposition; (*e*) canyon erosion.

## Introduction

The continental margins of the world, comprising the continental shelves, slopes and rises, cover $74 \times 10^6$ km$^2$, or a total of 15 % of the Earth's surface (Menard & Smith 1966). In the context of this discussion meeting it is neither possible nor desirable to review comprehensively all the complexities of margin morphology. It is more appropriate to consider those aspects of morphology that are likely to be relevant to the needs of ocean engineers as the exploitation of natural resources moves progressively from the shelf into deeper water.

Rather than limit the discussion to a straight description of the shape, features and texture of the margin, we review the underlying geological processes which have moulded the margins, with especial emphasis on those of the northeast Atlantic, because of the national interest. It is convenient to consider first the initial evolution of the margins and the development of the large-scale morphology, and then to examine the secondary processes that have sculpted the intermediate and small-scale features.

## Evolution of the large scale morphology of margins

Plate tectonics (Le Pichon, Francheteau & Bonnin 1973) can account very satisfactorily for the splitting and separation of continents and the evolution and destruction of oceanic crust† during the past 200 Ma. The continental (or oceanic) margins reflect the transition between the thin and dense igneous crust and the thicker, less dense and chemically different continental or intermediate crust. Isostatic balance between the two crusts, modified by subsequent sedimentation or erosion, creates a major step in the seabed at the boundary, of which the continental slope is the prime expression.

Continental margins can be divided into passive and active types based on their seismicity. Passive margins lack earthquakes and widespread volcanism, unless very young, and are typically comprised of a continental shelf, slope and rise. In contrast, active margins like those that border the Pacific Ocean are associated with a trench, volcanism, mountain building and earthquakes that extend down to a depth of as much as 700 km along a dipping zone. The active margins are often associated with island arcs, marginal seas and interarc basins.

The division into active and passive types is a fundamental one that can best be understood in terms of the plate tectonics hypothesis in which the tectonic and seismic activity of the upper layer of the Earth is related to the interaction of a number of large rigid plates whose boundaries are the seismic belts of the world. These plates are diverging, converging or shearing past each other.

Active continental margins mark the boundaries between two plates which are either converging or sliding past each other with deformation or destruction of crust, often by subduction back into the interior of the Earth. By contrast, the passive margins are the ancient scars of the rifting and subsequent separation of the halves of a continental plate and which have migrated away from the active zone as new oceanic crust fills the gap.

This paper is concerned with reviewing the evolution of passive margins which are found throughout nearly all the Atlantic, and discussing the geological processes that have shaped their present morphology.

### *Passive continental margins*

Although many passive continental margins appear to have formed by rifting, their present structure, stratigraphy and morphology result from a number of geological processes that are a function of climate and ocean circulation as well as being variable in time and space. A better understanding of the relationship of these factors within a kinematic framework of continental margin evolution is now developing as the first results in 1976 and 1977 of the I.P.O.D.–D.S.D.P.‡ passive margin drilling programme, and the accompanying geophysical surveys, become available. From these new data, and by comparison with present-day analogue margins, we can gain a perspective within which to review passive margin evolution (Falvey 1972; Roberts & Caston 1975). The highly schematic evolutionary sequence shown in figure 1 forms the basis of the following discussion.

The evolution of a passive margin is considered to include the following phases:

(1) rifting of the continental crust;

† The term 'crust' is sometimes used to include all rocks above the Mohorovičic discontinuity and is sometimes limited, as in this paper, to the igneous or crystalline rocks only.

‡ International Phase of Ocean Drilling of the Deep-Sea Drilling Project.

(2) onset of spreading (i.e. actual separation of the continental crust and the accretion of oceanic crust in the gap between the continental blocks);

(3) post-rift evolution (subsidence of the rifted margins and shaping of the present morphology by tectonic and sedimentary processes).

Evidence for the nature of the rifting process that constitutes the initial stage of margin development is based on the analogue provided by the East African rift system. A period of regional uplift may precede or be contemporaneous with rifting and accompanied by widespread volcanism. The rifting may follow subparallel or trilete patterns exemplified by the Viking Graben of the North Sea. During this stage, the basic structural framework of the

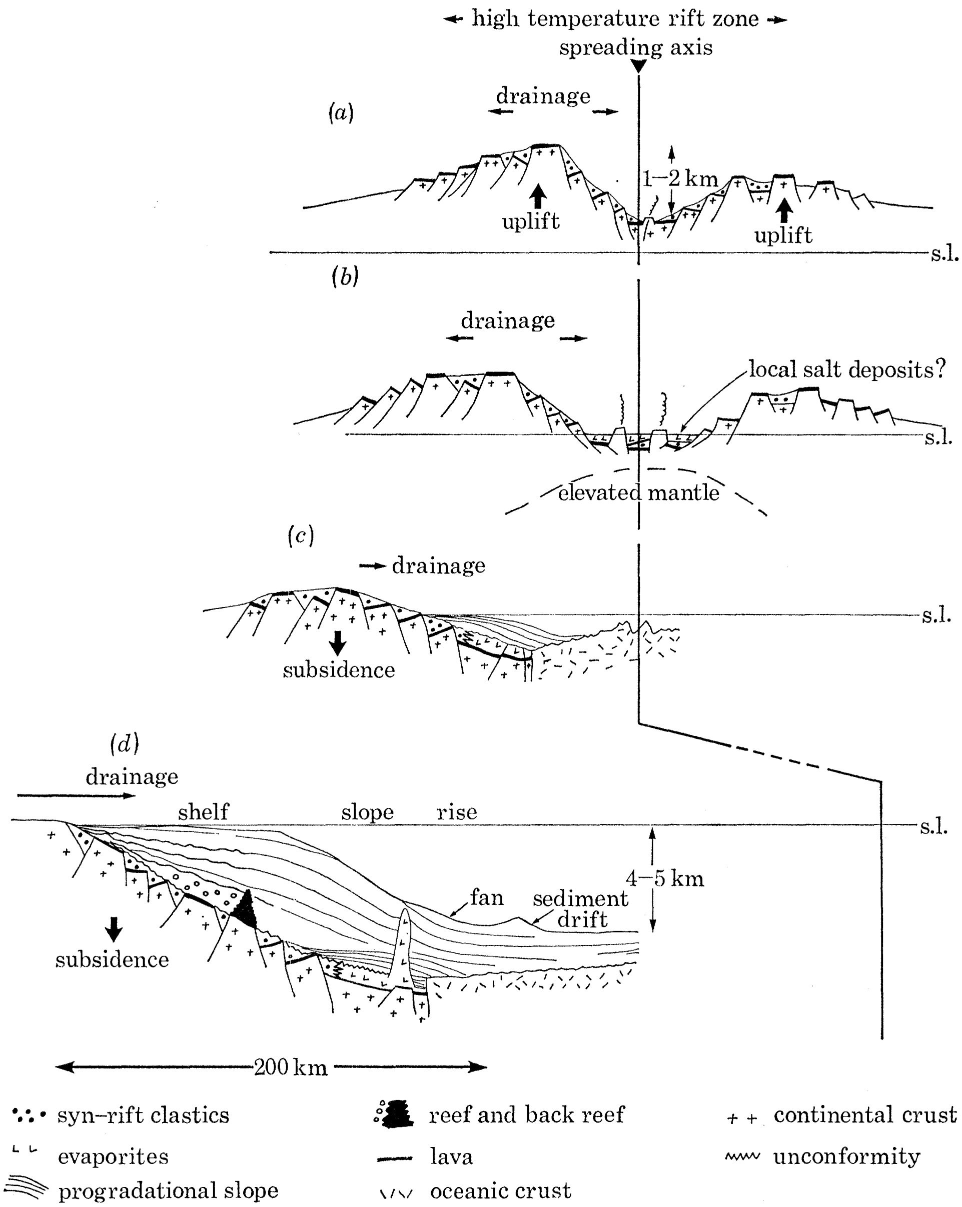



Figure 1. Stages in the evolution of a passive continental margin, showing the uplift and rifting while over the high temperature zone, and subsidence and sedimentation when it has moved away. (*a*) Rifting; (*b*) crustal attenuation; (*c*) initial spreading; (*d*) old margin. The line marked s.l. represents sea level.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

embryo margin is shaped by the rifting and fracture zone development, which is influenced by the pre-existing structural fabric of the continent. Within the rift, basic and alkaline extrusives may be intercalated with, and thickly covered by, contemporaneous coarse clastic continental sediments. An effect of uplift is to direct the drainage away from the rift valley restricting the supply of clastic sediment. In other cases, the rifting may take place in an epicontinental sea, creating a deep (*ca.* 2 km) rift basin.

As the rift widens, the continental crust may stretch or fracture, and thus become thinner, allowing mantle rocks to rise. Eventually partial melts from the mantle penetrate the continental crust and oceanic crust begins to accrete at the edges of the separating blocks. The nature of the change from rifting to spreading and accretion, and thus the geology of the continent–ocean boundary or transition formed at this time, is not well understood, but may be related to a major change in the thermal régime of the margin. During rifting, the continental crust is extended but remains joined and close to the heat source. In contrast, during spreading, the young margin migrates away from the heat source as new crust accretes at the ridge axis.

Cooling and subsidence (downwarping) of the margin thus begins at the end of rifting and onset of spreading. Recent results from I.P.O.D. Leg 48 (Montadert, Roberts *et al.* 1977) show that the subsidence history is apparently independent of the initial altitude of the continent. One effect of subsidence is to allow wide transgression of the sea across the margin, often shown by an important unconformity with onlap separating the faulted pre- and syn-rift sediments from the unfaulted post-rift sediments. During this early spreading stage, sedimentation may be strongly influenced by barriers formed by fracture zones or aseismic ridges. In the south Atlantic Ocean for example, enclosure of the basin by the Walvis Ridge and Rio Grande Rise may have produced an anoxic depositional environment during the Lower Cretaceous.

In the early stages of the ocean development, high evaporation rates in closed basins can lead to thick evaporite layers, as are found today in the Red Sea. As the ocean grows and the margins prograde, these deposits are deeply buried and may subsequently migrate upwards to form the salt diapirs which are known to occur below the margins of the South Atlantic.

The subsequent evolution of the margin is a function of both age and the complex interaction between subsidence, sedimentation, climate and ocean circulation. Two types of margins appear to exist. Starved margins are characterized by a thin (1–2 km thick) prograding sedimentary cover, and may be chronologically old or young. Examples include the Bay of Biscay and the East Greenland margin. Thickly sedimented margins are characterized by 10 km thick prograding sediments and are exemplified by the east margins of North America.

Factors that influence the evolution of passive margins into these types and the nature of the sediments are poorly understood. One effect of subsidence is, for example, to bury deeply the first post-rift sediments as the margin progrades seaward. In other cases, reef growth on fracture zones or marginal basement highs may keep pace with subsidence resulting in the accumulation of thick sequences of shallow-water carbonates that may themselves be buried deeply. The lithology, volume and distribution of the sediments that comprise the post-rift sequences on starved and mature margins clearly depends on the ocean environment, climate and sea level, as well as the altitude and geology of the continental hinterland. Changes in ocean basin circulation and the chemistry of seawater, have profoundly influenced the deposition of sediments along continental margins producing large hiatuses in the geological record.

Although the integrated effects of these factors are extremely complex, there may be a few


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

simple controls. For example, the lithology and volume of the sediments deposited on the margin may be strongly influenced by global changes in sea level. Such changes may reflect variations in spreading rate (Flemming & Roberts 1973) which, by altering the cross-sectional area of mid-ocean ridges and hence the ocean basin volume, may cause changes in ocean circulation and climate.

In summary, the gross morphology of the passive margins arises from (*a*) the initial rift and associated faulting and local sedimentation while the margin lay over the thermal zone and, (*b*) subsequent progradation, reefal growth, erosion, diapirism and subsidence as the margin cools and shrinks.

## Intermediate and small-scale morphology

In discussing the intermediate and smaller-scale morphology it is convenient to distinguish between the classic subdivision of the margin (Heezen, Tharp & Ewing 1959) into shelf, slope and rise since the environments and processes operating in these regions differ significantly. It is important to remember, however, that on many margins these classifications cannot be applied too rigorously as there are sometimes deeply submerged and isolated continental blocks near the margin, multiple shelf–slope sequences, enclosed basins on the slope, and very often the continental rise is either absent as a morphological feature, or can only be delineated approximately (Emery 1971).

### *Continental shelf*

The continental shelf has been extensively discussed in the literature and in many areas has been well surveyed using echo-sounding and side-scan sonar techniques. Its relatively flat surface arises from wave erosion during low sea-level stances during the last glacial period. The maximum lowering of between 70 and 140 m occurred about 15000 years ago (Emery, Niino & Sullivan 1971).

During glaciation, the land and shelf ice-sheets gouged great troughs to many hundreds of metres depth across the shelf. Although some of these troughs have been partly closed by moraines and infilled by later sediments, good examples are found along the Greenland, Labrador, Alaskan and Norwegian margins and in the North Sea as the Norwegian Trench (Holtedahl & Sellevoll 1971, 1972). Icebergs detached from the land or shelf ice have also been carried southward as far as 32° N by surface currents often to ground on the edge of the shelf and the upper slope ploughing furrows 10 m deep. Highly irregular criss-crossing patterns of iceberg plough-marks have been mapped by side-scan sonar along the shelf edge north and west of the U.K. and around the Rockall Bank further to the west (Belderson, Kenyon & Wilson 1973).

The present distribution and depositional régime of the shelf seas of NW Europe reflects the reworking of relict glacial sediments and the continued input of fresh sediments from the land areas. The bed load transport of these sediments has been related to the pattern of tidal currents by analysis of side-scan sonar records, but it is clear that wave action may also suspend the coarse fraction of the sediments (Kenyon & Stride 1970).

### *The continental slope and rise*

Four major processes are responsible for fashioning the intermediate and small-scale morphology of the continental slope and rise: (*a*) pelagic sedimentation, (*b*) mass downslope transport of sediments by slumping, gravity slide or creep, (*c*) erosion of submarine canyons, and (*d*) the distribution or redistribution of sediments by deep contour-following currents.

(*a*) *Pelagic sedimentation*

Clay-sized sediments transported in suspension from the higher energy environment of the shelf to the quieter depths beyond are slowly deposited to mantle the slope and rise. These terrigeneous sediments are mixed with biogenic sediments largely composed of the calcareous and siliceous tests of the plankton populating the oceanic surface waters. Upwelling of nutrient-rich water over the continental slope may increase the plankton population and hence the proportion of biogenous sediments. Pelagic sediments cover by far the greater part of the continental slope and rise province which is characterized on the scale seen in seabed photographs by featureless unconsolidated sediments disturbed only by the burrows and tracks of benthic organisms. The cumulative effect of pelagic sedimentation is to subdue the relief of much of the slope and to contribute to the oceanward progradation of the shelf.

(*b*) *Slumps, slides or creeps*

Massive slumping and gravity sliding is now widely recognized as an important influence on the morphology and deposition of sediments in a variety of continental margin environments. The general condition for slumping of sediments deposited on a slope is that the shear strength of sediments along a potential glide plane must be exceeded by the shear stresses acting downslope. The shear strength is governed by sedimentation rate, grain size, lithology, age, degree of consolidation and the pore pressure conditions at the time of failure.

If the shear strength is exceeded gradually, the sediment may creep downslope with little visible disturbance of the surface except at the edges of the creeping mass. Slumps may occur on slopes oversteepened by deposition or may be caused by loading due, for example, to rapid deposition, previous slumping, or earthquake activity. In slumps due to collapse failure, the sediments are in a metastable condition caused primarily by loose packing of the sediments. Metastable accumulations of sediments often occur by continuous deposition at the heads of canyons or at the shelf break, though the metastability can be caused by wave action or by earthquakes.

A very large slump occurred in 1929 on the continental slope south of the Grand Banks off Newfoundland as a result of a nearby earthquake (Heezen & Drake 1964). The slump block, 400 m thick, 100 km wide and 100 km long, moved bodily downslope for about 100 m, breaking an array of trans-Atlantic submarine telegraph cables and generating turbidity currents that flowed many hundreds of kilometres into the ocean basins at speeds of up to 25 m $s^{-1}$, breaking further cables in succession (Heezen & Ewing 1952; Heezen, Ericson & Ewing 1954). Cable breaks in other areas have indicated similar recent slumps associated with either seismic activity (Heezen & Ewing 1955; Coulter & Migliaccio 1966), or with extreme river discharge (Heezen 1956). Less recent slumps have been identified from seismic profiles of the western side of Rockall Trough (Roberts 1972), and from near bottom observations of disturbed small-scale morphology in the adjacent trough (R. D. Flood, personal communications). Since this slump apparently originated on a slope as small as 2°, slumps may be a common occurrence on steeper slopes. The triggering mechanism for the Rockall slumps is not known but is thought to be associated with vigorous wave action during lowered Pleistocene sea level. If this is so, the slopes of Western Europe are likely to be more stable now than during the Pleistocene. Slump blocks may modify the morphology in such a way as to change significantly the course of adjacent canyons, or to create a barrier behind which sediments may be trapped.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES


FIGURE 2. Sonograph views of canyons near the top of the continental slope on the Armorican margin (Belderson & Kenyon 1976). The 13 km (*a*) and 7 km (*b*) views are obtained by insonification downslope with a narrow beam sonar. Highlights indicate strong echoes. (*a*) Slope at $45\frac{1}{2}°$ N, 4° W intensely eroded by canyons. Length of trace, 54 km. (*b*) Slope at $48\frac{1}{2}°$ N, $9\frac{1}{2}°$ W with few canyons. Length of trace, 32 km.

(*Facing p.* 81)

### (c) *Submarine canyon erosion*

Submarine canyons are the most easily recognizable and most studied features of the continental slope (Shepard & Dill 1966; Shepard 1972). In places, canyon erosion dominates the morphology of the slope whereas in others, canyons are either isolated features or entirely absent. Many mechanisms have been proposed for their origin and maintenance, none of which apply universally. It is now generally agreed that submarine erosion by downslope sediment movement, either gradual in the form of bedcreep or violent as slumps and turbidity currents, is responsible for cutting and maintaining them, although the heads of some canyons which reach near the coast, such as Cap Breton Canyon in SE Biscay, may have been partly cut subaerially during lowered sea level. Some indeed, such as the Hudson Canyon east of the Hudson river, were once the outlet of present rivers.

Most canyons run normal to the continental slope, but many are deflected along structural boundaries such as the upper side of rotated slump blocks, faults (Boillot *et al.* 1974), or along the more easily eroded strata of the underlying rock. Accurate mapping of the course of canyons can reveal something of the underlying geological structure. Acoustic pictures of canyons north of Biscay (figure 2, plate 1) obtained with long range side-scan sonar (Belderson & Kenyon 1976), show several canyons with axes oblique to the regional slope which are possibly fault controlled, as well as features interpreted as slumps. These sonographs also revealed sets of secondary gullies on the sharp crested ridges between canyons often joining the canyon at angles near 90°. Sometimes these secondary gullies are left hanging above the axial gorge of the main canyon.

At the base of the continental slope, canyons debouch on to cones or fans where the rapid decrease in slope, and hence in speed of the transport mechanism, allows deposition of the sediments. On margins with many canyons, these cones coalesce into the apron of the continental rise. Submarine channels linked to the foot of canyons often are found crossing the rise and meandering across the relatively small slopes towards the ocean deeps. The canyons are usually a few tens of metres deep, a few hundred metres across and are sometimes leveed, indicating that they are caused by a sediment-laden density current mainly confined to the channel but occasionally overflowing its banks. The mechanism which allows these flows to continue for thousands of miles, as in the cases of the northwest Atlantic mid-ocean canyon (Heezen, Johnson & Hollister 1969) and the Bay of Bengal canyons (Curray & Moore 1971), is still not understood.

The small-scale morphology of the canyons is a direct result of the erosion mechanisms operating in them. Canyons which deeply incise the shelf edge can trap the coarser sediments being moved along the seabed under the action of currents. The resulting sand and gravel bodies in the canyons can creep or slump downslope along the canyon axis eroding, and even undercutting, the walls of the canyon, giving rise to steep-sided gorges (Shepard 1972), which have been explored in the top 100 m by divers and have been shown by deep submersible observations to be common also at great depths. Well sorted sands have been seen flowing as 'sand falls', akin to waterfalls, and must contribute to erosion and transport (Shepard & Dill 1966).

More violent, but spasmodic, events are turbidity currents which develop when a slump or other disturbance creates a body of dense sediment-laden water that flows downhill, gaining momentum, gaining more sediment by erosion and hence growing in density and in speed.

Speeds of many tens of metres per second have been observed for turbidity events when they reach the bottom of the slope and they can spread out hundreds of kilometres over the abyssal plains. The frequency of such events is difficult to estimate. However, the sedimentary record of the abyssal plains (e.g. D.S.D.P. Hole 118 in Laughton, Berggren *et al.* 1972) shows that they may occur at intervals between a few thousand and tens of thousands of years. Turbidity currents may be more common during lower sea level when the heads of the canyons were in a more energetic environment.

Clearly such violent processes deeply incise and erode canyons sweeping all loose sediments downslope. Underwater photographs have shown talus slopes of collapsed walls of canyons when they have been undercut by such a mechanism.

On a smaller scale, but perhaps as important in their cumulative effect, are the alternating up- and down-currents which have been observed in canyons down to depths of several thousand metres (Shepard, Marshall & McLoughlin 1974). At depths of the order of several hundred metres these have periodicities from 20 minutes to several hours and are believed to be related to internal waves (Shepard 1975), whereas in progressively deeper water the periodicity approaches that of the semidiurnal tide (Shepard 1976). Current velocities of up to 30 cm $s^{-1}$ have been measured which are capable of transporting sediment, and the data show that there is a net down-canyon flow of water and of sediment. Underwater photographs show sand ripples indicative of sediment transport.

### (*d*) *Contour current sedimentation*

Over the past decade, many studies have shown that deep ocean currents play an important rôle in fashioning, by erosion and deposition, a characteristic relief on the continental slope and rise (Hollister & Heezen 1972). In the northern hemisphere the rotation of the Earth deflects thermohaline ocean currents towards the right so that they tend to flow parallel and adjacent to contours of the major topographic features such as the continental slope. These currents are competent to transport fine sediment in suspension and sometimes to erode. These sediments are re-deposited as constructional ridges parallel to the current. Off the east coast of the U.S.A., for example, the Blake–Bahama Outer Ridge was formed by deposition from the Western Boundary Undercurrent (Heezen, Hollister & Ruddiman 1966). In the northeast Atlantic, comparable sediment ridges, some hundreds of kilometres in length and a few hundreds of metres in height, have been built up south of Greenland, east of the Reykjanes Ridge, and in the Rockall Trough (Johnson & Schneider 1969; Jones, Ewing, Ewing & Eittreim 1970; Davies & Laughton 1972; Roberts 1975).

Characteristics of sediment ridges include marginal moats adjacent to local highs, a distinctive wave-like surface (up to 2 km wavelength), ripples (down to 10 cm wavelength) and furrows (1–100 m in width). The detailed nature of these features has been studied by coring and by near-bottom towed vehicles housing sonar, photography and a high-resolution seismic profiler (Hollister, Southard, Flood & Lonsdale 1976). The waves and ripples apparently reflect constructional or mobile bedforms either parallel or transverse to the main current direction. In contrast, the furrows appear to result from erosion by helical vortices of well mixed bottom water orientated along the flow (Hollister, Southard, Flood & Lonsdale 1976).

It should be noted that the differential deposition by ocean bottom currents is pervasive and its characteristic features may be subdued by, or superimposed upon, the other geological processes that mould the slope and rise.

## The margin around the British Isles

The continental margin around the British Isles (Roberts, Hunter & Laughton 1977) includes the broad epicontinental shelves of the North Sea, Irish Sea, English Channel and Celtic Sea, the narrower Irish, Malin, Hebrides and West Shetland shelves, partly separated from the Irish Shelf by Porcupine Seabight, the 2000 m deep Rockall Trough and the associated 1000 m deep Faeroe–Shetland Channel, the almost submerged Rockall Plateau and the insular shelf of the Faeroes. To the northwest, the Iceland and Norwegian Basins, underlain by oceanic crust, are separated by the oceanographically important sill of the Iceland-Faeroe Rise which was created by the excessive magma production from the Iceland hotspot.

In this region of the northeast Atlantic, the presence of these anomalously shallow plateaux, separated by troughs and steep gradients precludes a simple description in terms of slope and rise provinces. Indeed, the distribution and major relief of these features are primarily due to the complex structural evolution of the area and their present morphology and depth to subsequent sedimentation and subsidence.

The main topographic units reflect the presence of both continental fragments and oceanic crust in the region (figure 3). The foundered Rockall Plateau, and at least part of the basement underlying the Faeroes, are fragments of continental crust. Their present distribution is a direct consequence of three distinct phases in the opening of the North Atlantic Ocean (Laughton 1975). During the first phase, in Lower Cretaceous time, the Rockall Trough and Faeroe–Shetland Channel opened, spreading the Greenland-Rockall–North American block away from Europe. In the second phase, at about 76 Ma B.P., the Labrador Sea opened, spreading the Greenland–Rockall block away from North America. In the final phase, beginning at about 60 Ma B.P., the Iceland Basin and Norwegian Basin were opened, so separating Greenland and the Rockall Plateau. The present distribution of the major relief of the margin was largely shaped by 60 Ma B.P., though the Iceland Basin has continued to widen since then.

The present morphology and physiography largely reflects the differential deposition of pelagic sediments by ocean bottom currents. The distribution of these sediments (figure 4) bears a well known and close relationship to the deep circulation of the North Atlantic Ocean (Jones *et al.* 1970; Davies & Laughton 1972; Roberts 1975). At the present, saline surface-water flows northward into the Norwegian Sea where it cools and becomes denser. This water sinks and ultimately flows back intermittently into the North Atlantic Basins over the Iceland–Faeroes Ridge, the Wyville–Thomson Ridge and through the Faeroe Bank Channel. In the Iceland Basin the overflow water, with sediment entrained in suspension, flows parallel to the continental slope south of Iceland and then parallel to the Reykjanes Ridge. Sediments deposited from this current have smoothed the irregular basement relief of the Iceland Basin and constructed the large Gardar Ridge sediment drift (Johnson & Schneider 1969; Ruddiman 1972). In the Rockall Trough, intermittent overflow across the Wyville–Thomson Ridge flowing southward along the west side of the Rockall Trough has contructed the Feni Ridge sediment drift (Ellett & Roberts 1973). The Feni Ridge has many of the typical features of sediment drifts including giant waves and possibly furrows. South of the Rockall Plateau the drift divides into a southward trending spur and another ridge that follows the contours of the Plateau to the northwest. Sediment drifts are also responsible for the physiography of much of the Rockall Plateau and have also been identified on the slope of North Biscay (Auffret, Pastouret & Kerbrat 1975).

In contrast to these areas, the physiography of the continental slope to the north, west and southwest of the British Isles has been closely controlled by the volume of sediments transported outward across the shelf and from the land areas. North of the North Sea, the continental slope is very gentle and underlain by thick sediments and there are no canyons. However, in the Faeroe–Shetland Channel strong currents may have eroded the sediments or prevented deposition. The slope west of Scotland and Ireland is steep with little sediment cover and only very few canyons. The sediment transport paths on the adjacent shelf lie mainly parallel to the shelf edge so that little sediment may be carried across the margin into the Rockall Trough (Kenyon & Stride 1971). However, in the eastern part of the Trough, fans comprised of terrigenous sediments are present and may have been supplied by sediments transported across the shelf between the Outer Hebrides and Ireland (Roberts 1975).

In contrast to the more northerly margins, the margin southwest of the British Isles is deeply incised by many canyons. Sediments on the adjacent shelf are transported towards the shelf edge and into the heads of canyons. Erosion is active in the canyons, and the adjacent rise and abyssal plain of the Bay of Biscay are floored by sediments deposited from turbidity currents. Examination of seismic reflexion profiles and long-range sonographs across and parallel to the margin has shown that the tectonic fabric associated with the initial rifting has influenced the course of many canyons.

## Conclusion

Although many of the processes responsible for shaping the continental margins of the world are known in general terms, details are far from clear. In the progression of ocean engineering into deeper water, precise information will be needed on the nature and shape of the bottom, the geotechnical properties, the processes which might alter it during the lifetime of a structure and on the currents in the water above the bottom. These may vary significantly over short distances and detailed surveys will be necessary of both the morphology and the recent geological history. To give the required detail, near-bottom survey techniques will be necessary as well as narrow beam and precision surface measurements.

In this review, reference could not be made to all the papers written on continental margin morphology and its evolution. But four important books should be mentioned which could provide the reader with either reviews of the field or important collections of papers recently published following symposia (Heezen & Hollister 1971; Burk & Drake 1974; Woodland 1975; Vanney 1977).

## References (Laughton & Roberts)


Auffret, G. A., Pastouret, L. & Kerbrat, R. 1975 *Abstr. 9th Int. Congress Sedimentologie, Nice* 1975, Theme 6, 1.

Belderson, R. H. & Kenyon, N. H. 1976 *Mar. Geol.* **22**, M69–M74.

Belderson, R. H., Kenyon, N. H. & Wilson, J. B. 1973 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **13**, 215–224.

Boillot, G., Dupeuple, P. A., Hennequin-Marchand, I., Lamboy, M., Lepretre, J.-P. & Musellec, P. 1974 *Rev. Géogr. phys. Géol. dyn.* **16**, 75–86.

Burk, C. A. & Drake, C. L. (eds) 1974 *The geology of continental margins*. New York: Springer-Verlag, 1009 pages.

Coulter, H. W. & Migliaccio, R. R. 1966 *U.S. geol. Surv. prof. Pap.* 542-C, 35 pages.

Curray, J. R. & Moore, D. G. 1971 *Bull. geol. Soc. Am.* **82**, 563–572.

Davies, T. A. & Laughton, A. S. 1972 In *Initial reports of the Deep Sea Drilling Project* (A. S. Laughton, W. A. Berggren *et al.*), vol. 12, pp. 905–934. Washington, D.C.: U.S. Government Printing Office.

Ellett, D. J. & Roberts, D. G. 1973 *Deep Sea Res.* **20**, 819–835.

Emery, K. O. 1971 In *The geology of the east Atlantic continental margin*, I.C.S.U./S.C.O.R. Working Party 31 Symposium, Cambridge, 1970 (ed. F. M. Delaney), vol. 1 (General and economic papers), pp. 3–29.

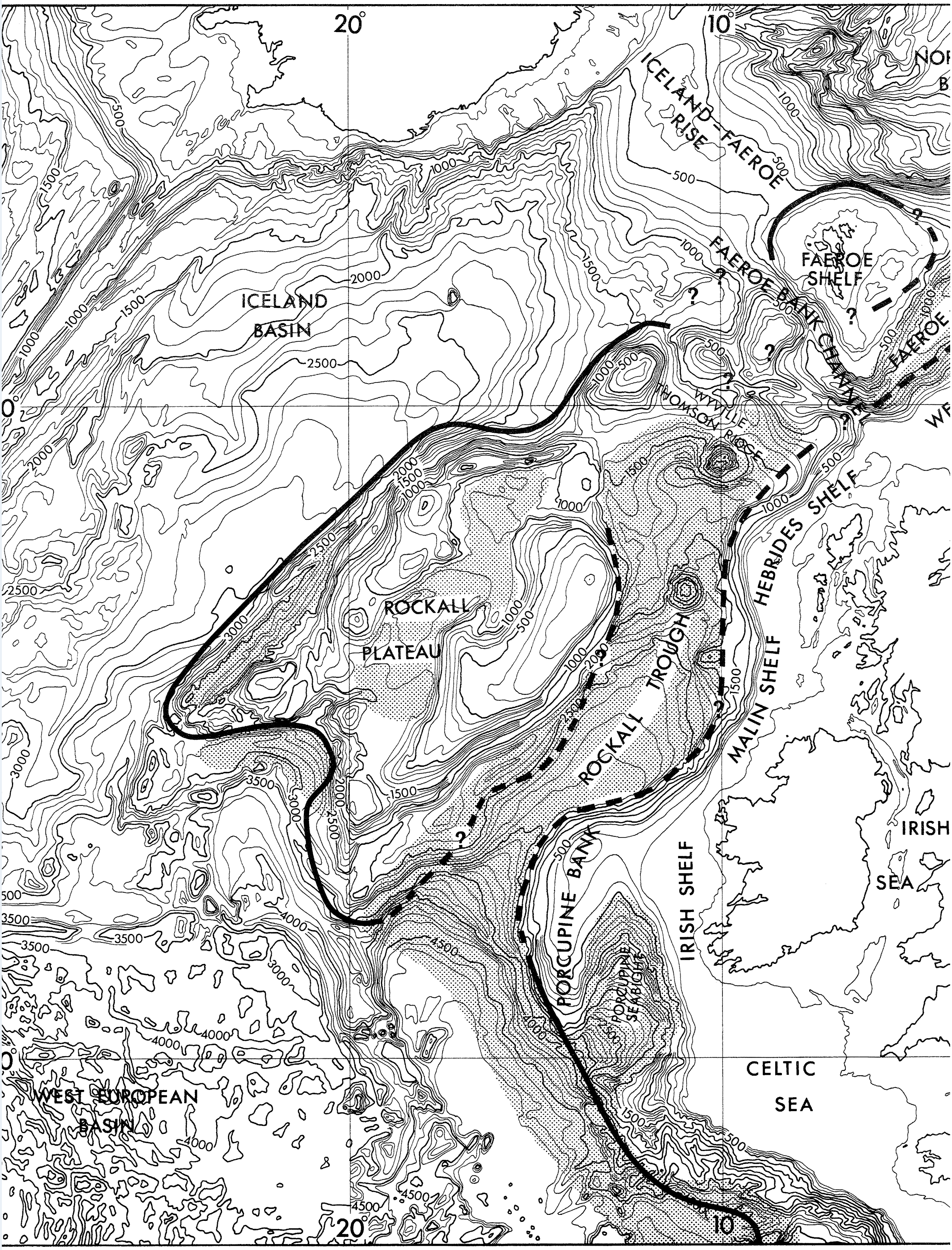
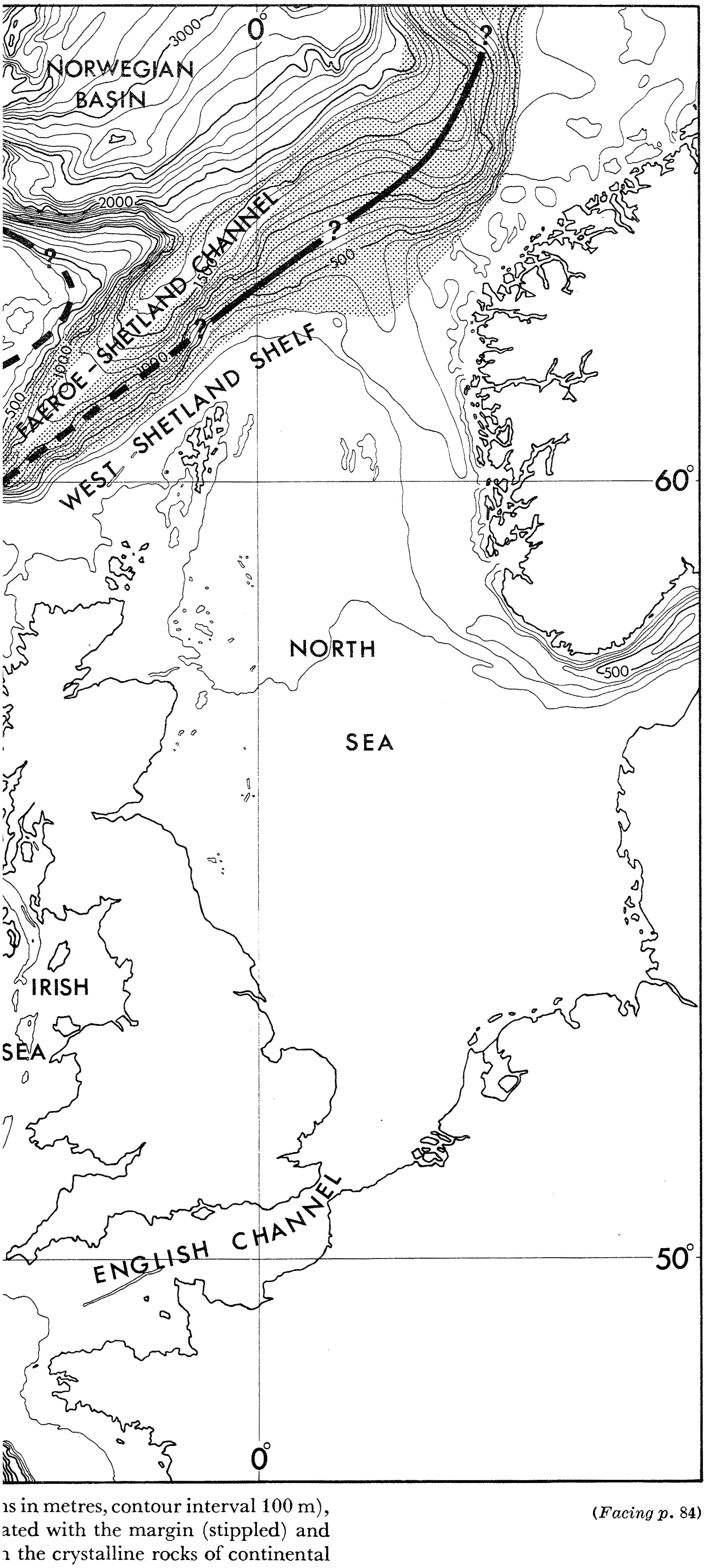



FIGURE 3. Bathymetry of the continental margin around the British Isles (depths in metre
showing the approximate extent of the major sedimentary basins associated with
the estimated position of the underlying boundary or transition between the crys
and oceanic origin (solid or broken line).



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES




ıs in metres, contour interval 100 m),
ated with the margin (stippled) and
ı the crystalline rocks of continental

(*Facing p.* 84)

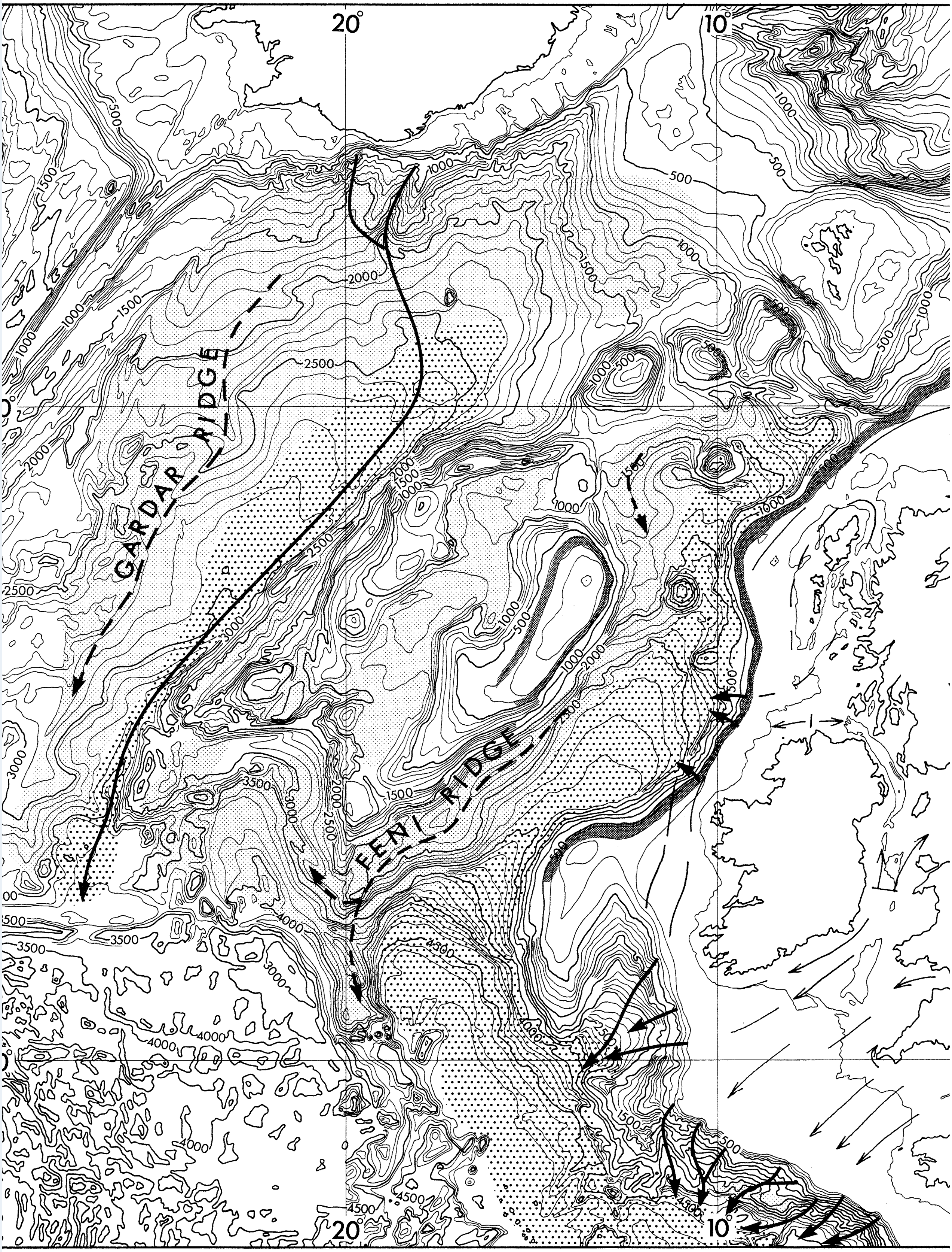
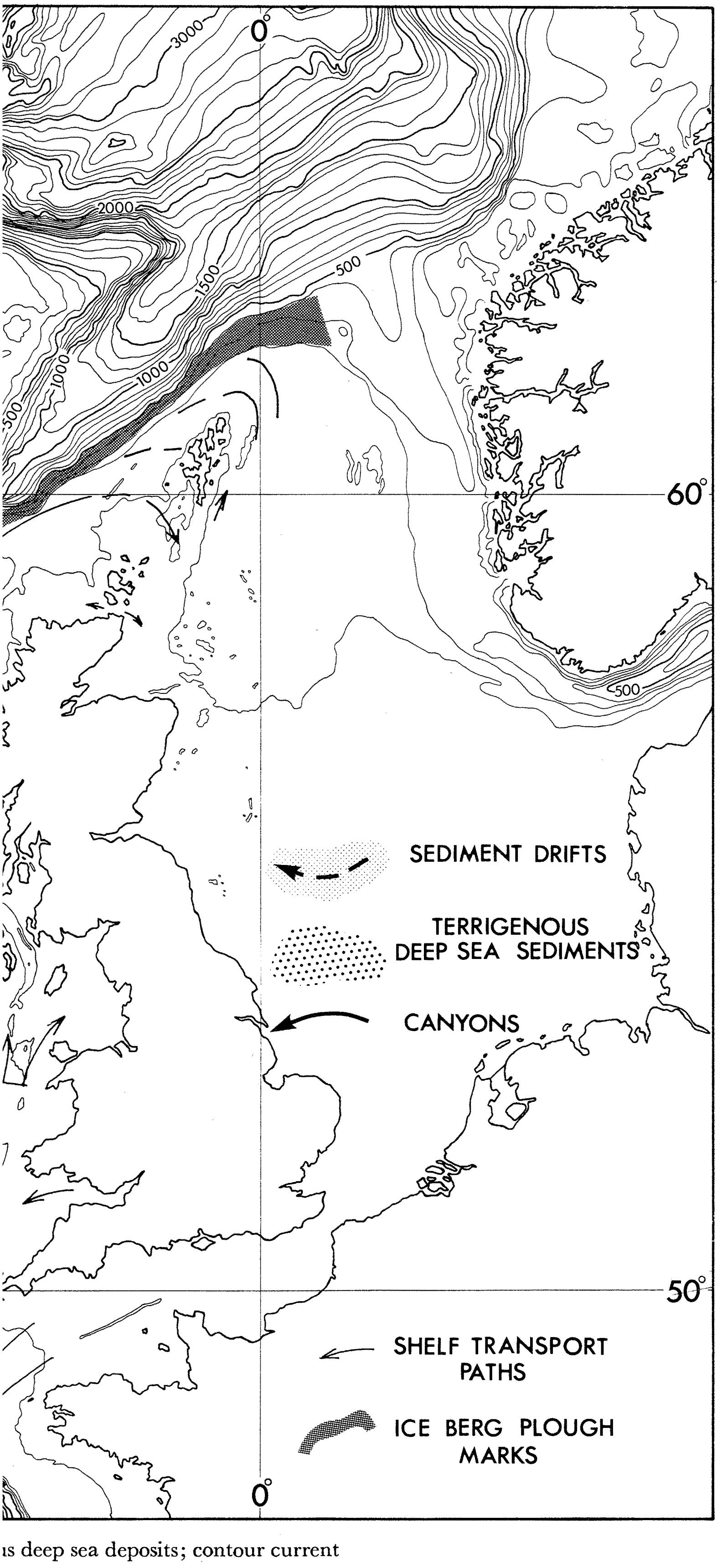



FIGURE 4. Sediment transport on the shelf and through canyons to terrigenous deep sea drifts; iceberg plough marks.




ıs deep sea deposits; contour current

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Emery, K. O., Niino, H. & Sullivan, B. 1971 In *The late Cenozoic glacial ages* (ed. K. K. Turekian), vol. 14, pp. 381–390. Yale University Press.

Falvey, D. A. 1972 *Aust. Petr. exp. Ass. J.* **12**, 86–88.

Flemming, N. C. & Roberts, D. G. 1973 *Nature, Lond.* **243**, 19–22.

Heezen, B. C. 1956 *Boln Soc. geogr. Colombia* **51/52**, 135–143.

Heezen, B. C. & Drake, C. L. 1964 *Bull. Am. Ass. Petrol. Geol.* **48**, 221–233.

Heezen, B. C., Ericson, D. B. & Ewing, M. 1954 *Deep Sea Res.* **1**, 193–202.

Heezen, B. C. & Ewing, M. 1952 *Am. J. Sci.* **250**, 849–873.

Heezen, B. C. & Ewing, M. 1955 *Bull. Am. Ass. Petrol. Geol.* **39**, 2505–2514.

Heezen, B. C. & Hollister, C. D. 1971 *The face of the deep*. London: Oxford University Press, 659 pages.

Heezen, B. C., Hollister, C. D. & Ruddiman, W. F. 1966 *Science, N.Y.* **152**, 502–508.

Heezen, B. C., Johnson, G. L. & Hollister, C. D. 1969 *Can. J. Earth Sci.* **6**, 1441–1453.

Heezen, B. C., Tharp, M. & Ewing, M. 1959 *Geol. Soc. Am. spec. Pap.* **65**, 122 pages.

Holtedahl, H. & Sellevoll, M. A. 1971 In *The geology of the east Atlantic continental margin*, I.C.S.U./S.C.O.R. Working Party 31 Symposium, Cambridge 1970 (ed. F. M. Delaney), vol. 2 (Europe), pp. 32–52. Inst. Geol. Sci. rep. no. 70/14.

Holtedahl, H. & Sellevoll, M. 1972 *R. Swed. Acad. Sci. Ambio spec. Rep.* **2**, 31–18.

Hollister, C. D. & Heezen, B. C. 1972 In *Studies in physical oceanography* (ed. A. L. Gordon), vol. 2, pp. 37–66. New York: Gordon and Breach.

Hollister, C. D., Southard, J. B., Flood, R. D. & Lonsdale, P. F. 1976 In *The benthic boundary layer* (ed. I. N. McCave), pp. 183–204. New York: Plenum.

Johnson, G. L. & Schneider, E. D. 1969 *Earth planet. Sci. Lett.* **6**, 416–422.

Jones, E. J. W., Ewing, M., Ewing, J. I. & Eittreim, S. L. 1970 *J. geophys. Res.* **75**, 1655–1680.

Kenyon, N. H. & Stride, A. H. 1970 *Sedimentology* **14**, 159–173.

Laughton, A. S. 1975 *Norg. geol. Unders.* **316**, 169–193.

Laughton, A. S., Berggren, W. A. *et al.* 1972 *Initial reports of the Deep Sea Drilling Project*, vol. 12. Washington, D.C.: U.S. Government Printing Office, 1243 pages.

Le Pichon, X., Francheteau, J. & Bonnin, J. 1973 *Developments in geotectonics*, vol. 6. Amsterdam: Elsevier, 300 pages.

Menard, H. W. & Smith, S. M. 1966 *J. geophys. Res.* **71**, 4305–4325.

Montadert, L., Roberts, D. G. *et al.* 1977 *Nature, Lond.* **268**, 305–309.

Roberts, D. G. 1972 *Mar. Geol.* **13**, 225–237.

Roberts, D. G. 1975 *Phil. Trans. R. Soc. Lond.* A **278**, 447–509.

Roberts, D. G. & Caston, V. N. D. 1975 *Proc. 9th World Petroleum Congress, Tokyo*, vol. 2, pp. 281–288. London: Applied Science Publishers.

Roberts, D. G., Hunter, P. M. & Laughton, A. S. 1977 Sheet 2, *Continental margin around the British Isles*, chart C 6567. Published by Hydrographic Department, U.K.

Ruddiman, W. F. 1972 *Bull. geol. Soc. Am.* **83**, 2039–2062.

Shepard, F. P. 1972 *Earth Sci. Rev.* **8**, 1–12.

Shepard, F. P. 1975 *Mar. Geol.* **19**, 131–138.

Shepard, F. P. 1976 *J. Geol.* **84**, 343–350.

Shepard, F. P. & Dill, R. F. 1966 *Submarine canyons and other sea valleys*. Chicago: Rand McNally, 381 pages.

Shepard, F. P., Marshall, N. F. & McLoughlin, P. A. 1974 *Deep Sea Res.* **21**, 691–706.

Vanney, J.-R. 1977 *Géomorphologie des plates-formes continentales*. Paris: Doin editeurs, 300 pages.

Woodland, A. W. 1975 *Petroleum and the continental shelf of northwest Europe*. Romford, Essex: Applied Science Publishers, 501 pages.




PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

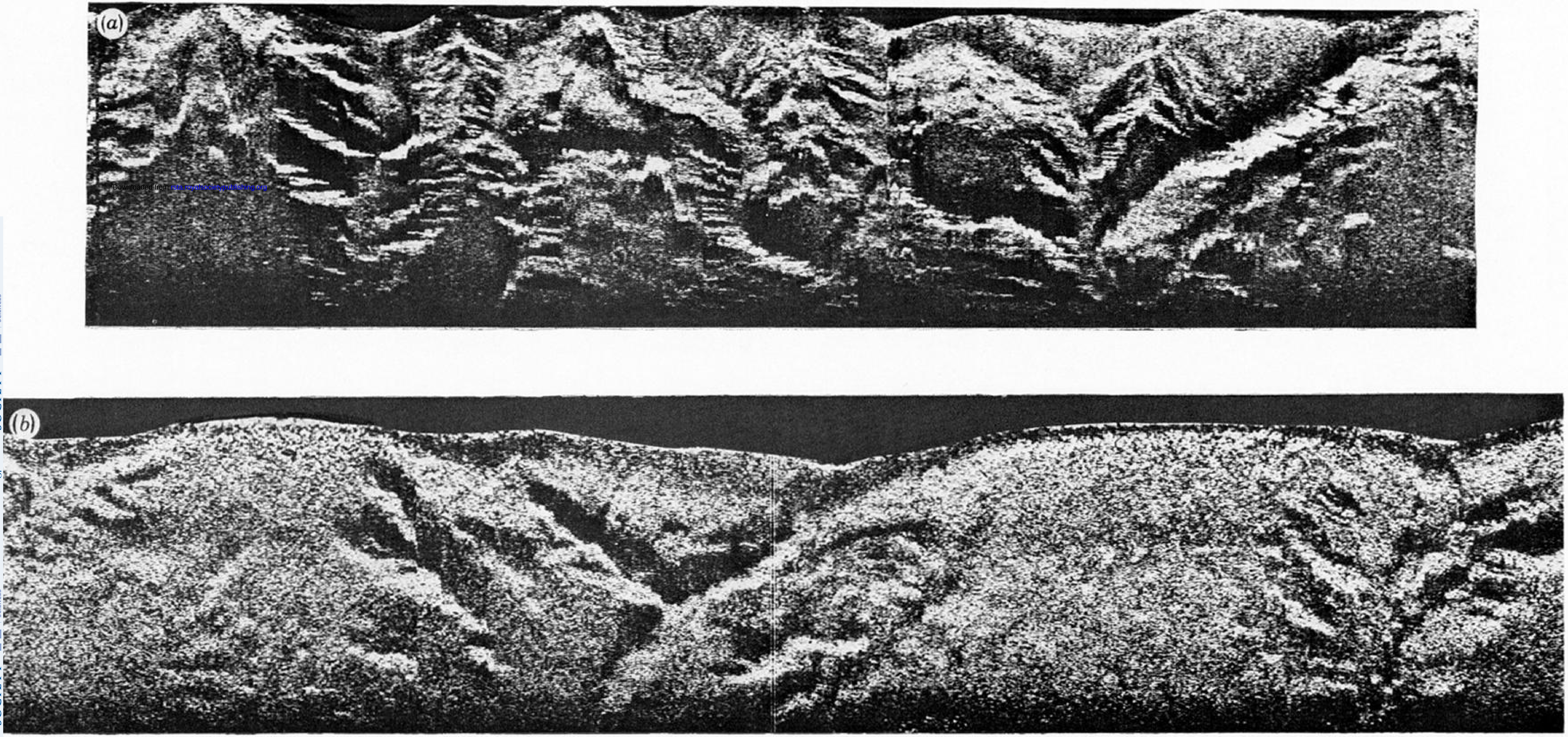





FIGURE 2. Sonograph views of canyons near the top of the continental slope on the Armorican margin (Belderson & Kenyon 1976). The 13 km (*a*) and 7 km (*b*) views are obtained by insonification downslope with a narrow beam sonar. Highlights indicate strong echoes. (*a*) Slope at $45\frac{1}{2}°$ N, 4° W intensely eroded by canyons. Length of trace, 54 km. (*b*) Slope at $48\frac{1}{2}°$ N, $9\frac{1}{2}°$ W with few canyons. Length of trace, 32 km.

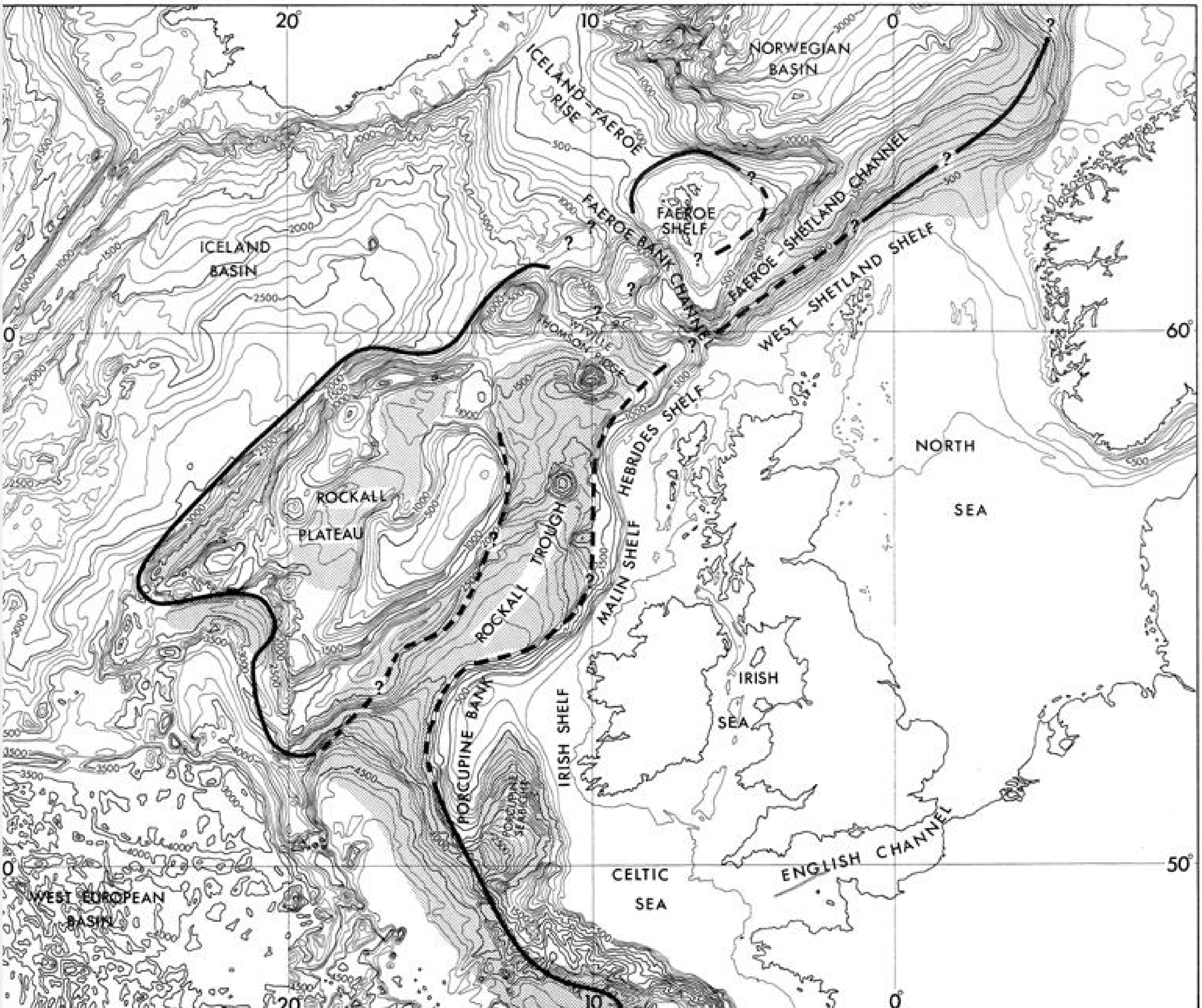



FIGURE 3. Bathymetry of the continental margin around the British Isles (depths in metres, contour interval 100 m), showing the approximate extent of the major sedimentary basins associated with the margin (stippled) and the estimated position of the underlying boundary or transition between the crystalline rocks of continental and oceanic origin (solid or broken line).

(Facing p. 84)


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

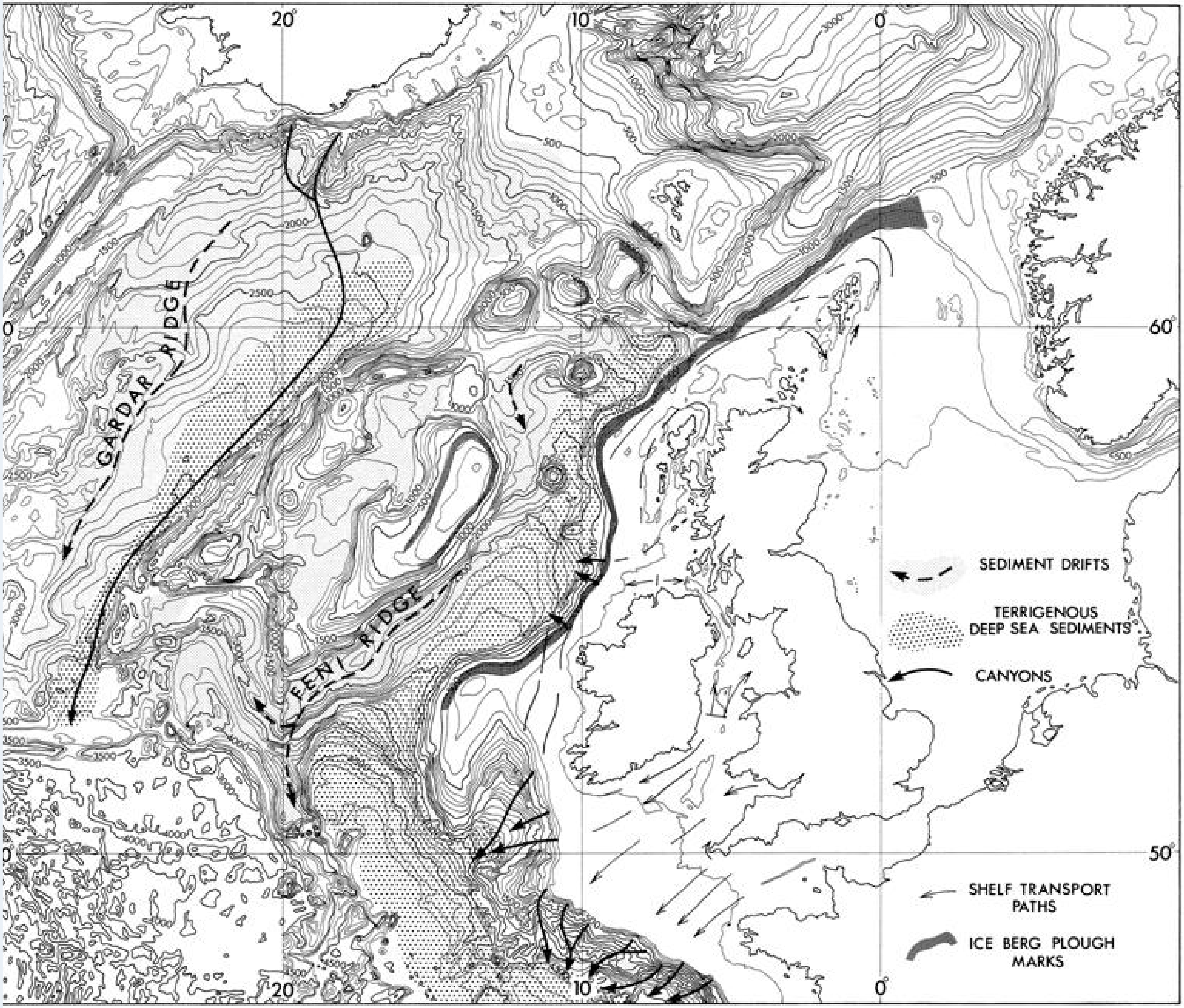



Figure 4. Sediment transport on the shelf and through canyons to terrigenous deep sea deposits; contour current drifts; iceberg plough marks.