Tectonic Evolution of the Northeast Atlantic Ocean; a Review

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The hypotheses of sea floor spreading and plate tectonics enable the evolution of ocean basins to be understood provided that there are adequate data on the present and past plate boundaries from the magnetic anomaly patterns and some geological control of the nature and age of critical parts of the ocean floor. From such data, the following main phases of evolution of the north-east Atlantic from a Triassic unrifted continental mass have been identified.

1. Early Jurassic (80 my). Initial split of Africa from North America bounded to the north by a sinistral transcurrent fault from Newfoundland to southern Spain.

2. Early Cretaceous (120 my). The Iberian peninsula, rotating anticlockwise, started to split from the Grand Banks of Newfoundland and from the Celtic Sea opening the margin of the NE Atlantic and the Bay of Biscay. This was accompanied by shearing along the North Pyrenean fault. Spreading between Newfoundland and Spain may also have been coupled, via a transform fault NE of Newfoundland, to the separation of Rockall Plateau from Greenland to form the proto–Iceland basin and from Europe to form the Rockall Trough.

3. Late Cretaceous (80 my). Biscay spreading ceased as Spain stopped rotation with respect to Europe. At about this time spreading started in a new direction along a new axis running NW from Biscay to the Labrador Sea along the old transform fault.

4. Palaeocene (60 my). A change in stress pattern below the plates resulted in a split between Greenland and Rockall Plateau to the east of the Cretaceous trough axis, which grew into the Reykjanes Ridge, and further NE into the Aegir and other ridges north of the Faeroes. At this time the Vøring Plateau became separated from the Greenland margin, and volcanoes and dykes appeared in E. Greenland and N.W. Scotland. A triple junction developed south of Greenland, which now became a separate plate.

5. Middle Eocene (45 my). Spreading in the Labrador Sea virtually ceased and Greenland joined the North American Plate. The northward movement of the Iberian plate, once more moving independently of Europe, resulted in the compression phase of the Pyrenean orogeny, the subduction beneath Spain of some of the Bay of Biscay, the uplift of the central region of Biscay and possibly the formation of King's Trough further west.

6. Middle Oligocene (30 my). North of the Faeroes, the axis of spreading shifted from the Aegir Ridge to a position along the east coast of Greenland separating off a sliver of continent now preserved as the Jan Mayen Ridge.

7. Miocene (15 my). At about this time, Iceland began to appear as an area of abnormal magma output related to the development of a mantle plume, although the existence of the transverse ridges either side of Iceland suggests that abnormal activity in this region may have occurred throughout the Tertiary.

8. Present (0 my). Spreading continues along the Mid-Atlantic Ridge and the Reykjanes Ridge, separated by the Charlie–Gibbs Fracture Zone. North of Iceland, the Kolbeinsey Ridge is the site of asymmetrical spreading since the Late Miocene, and this connects northwards with the Mohns and Atka Ridges.

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Introduction

The theory of sea floor spreading and the subsequent global theory of plate tectonics have enabled the oceans and continents to be studied in an entirely new way, and now allow precise statements to be made about the stage by stage evolution of the oceanic crust and lithosphere. The widespread success of these theories in explaining the main features of the oceans, as well as in providing a rational basis for understanding orogenic processes on the continents leaves little doubt that in their essentials the theories are correct.

In the oceans, reversals of the earth's magnetic field through the Mesozoic and Tertiary have imprinted magnetic patterns on the upper layers of the crust during sea floor spreading and where these have been mapped, the crustal ages can be deduced by comparison with the reversal time scale (Heirtzler et al. 1968, Larson & Pitman 1972). Thus isochrons can be mapped wherever adequate magnetic data exist.

In the northeast Atlantic many surveys of magnetic anomaly patterns have been carried out and sufficient age identifications have been made to enable a fairly detailed sequence of plate movements to be deduced. Many of these age identifications have been confirmed by direct sampling of sediments overlying the basement rocks, or by sampling reflecting horizons in a sediment sequence which can be traced to basement contacts.

To reassemble the continents into their pre-split configuration, it is also necessary to determine the position of the edges of the continental blocks and to locate any continental fragments which may have subsided following the break-up of the main continental mass.

On the assumption that major distortions have not occurred within plates, palaeogeographic reconstructions for any age can be prepared by removing all younger crust, and by closing up the plates in the directions dictated by the fracture zones until the continental edges are adjacent. The process becomes one of geometry on a spherical earth, bearing in mind always that the plates that are moved have another edge usually outside the area being described, and that there may be constraints there on their motion.

Morphology of the northeast Atlantic

For the purposes of this paper, the northeast Atlantic lies north of a line from southern Spain to the shelf south of Newfoundland. It includes, therefore, the Labrador Sea, the Bay of Biscay, the Norwegian Sea and the Greenland Sea (Plate 1).

The mid-ocean ridge is the dominating morphologic feature in the area running approximately north from the Azores Plateau as part of the mid-Atlantic Ridge. It is offset westwards by a series of east-west oriented fracture zones of which by far the longest is the Charlie Gibbs Fracture Zone which can be traced from 22°W to 47°W along 52°N. The mid-ocean ridge (in this place called the Reykjanes Ridge) runs northward to 57°N and then bends to the northeast as a remarkably linear ridge as far as the southwest corner of Iceland. Iceland is entirely volcanic, having been derived from differentiation of the mantle in the same way as the ocean ridges, but it is anomalous in that the quantity of magma produced exceeds that of a normal mid-ocean ridge by a factor of three or more (Piper 1973). A spreading axis can be identified in Iceland although in central and northeast Iceland it is offset eastwards from the line of the Reykjanes Ridge and its northward continuation.

North of Iceland the morphology of the sea floor becomes considerably more complex. The axis of present spreading lies along the Kolbeinsey (or Iceland–Jan Mayen) Ridge as far north as Jan Mayen Island. The Jan Mayen Fracture Zone offsets the spreading axis eastwards from the Kolbeinsey Ridge to the Mohns Ridge and then continues to the Atka Ridge, west of Spitsbergen. The Spitsbergen Fracture Zone links the Atka Ridge with the Nansen Ridge in the Arctic. Earthquake epicentres lie along the axis of this mid-ocean ridge system and along the linking transform faults indicating that this is the locus of current sea floor spreading and thus identifying the present boundary between the Eurasian and North American plates.

Other older and discarded spreading axes in the Norwegian Sea, Labrador Sea, Rockall Trough and Biscay, which are indicated from the magnetic data or from the geometry of the reconstructions, often have no topographic expression and lie buried beneath thick sediments.

A major ridge crosses the northeast Atlantic through Iceland linking the Greenland continental shelf with the Faeroes shelf. Little work has been done on the western part of this ridge, but studies on the Iceland–Faeroes Ridge indicate that the crust is oceanic in character but is anomalously thick due to unusually active differentiation of basalt from the upper mantle prior to the formation of Iceland (Bott et al. 1971).

Continental boundaries

The edge of a continental block is usually assumed to be close to the base of the continental slope, since on the slope itself, continental rocks can often be sampled. However, the intitial stages of rifting which lead to a split and subsequently to the emplacement of oceanic crust, may involve a period of crustal thinning by stretching, block faulting and tilting, with subsequent downwarping or subsidence during which time the original continental edge becomes blurred. The transition from oceanic to continental crust may be buried beneath thick sediments at the foot of the slope and may be scarcely detectable by geophysical means. Prograding sedimentation on the shelf may on the one hand advance the shelf break beyond the transition, or erosion may cut it back into the continent. There is therefore a measure of doubt about the exact reconstruction of continents due to uncertainties about the true position of the original break. In the reconstructions in this paper the top and bottom of the continental slope are shown and fits are made generally using the base of the slope.

However, there are many areas where the conventional shelf, slope and rise sequence are absent and where detached and isolated continental fragments are found. East of the Grand Banks off Newfoundland, Flemish Cap is believed, from bottom samples and from geophysical data, to have a central basement area of an eroded complex of intruded and metamorphosed sedimentary rocks of late Precambrian age, covered in part by Cretaceous limestone formations, and is isolated from the Grand Banks by Jurassic faulting (Grant 1972).

450 km north of Flemish Cap, the continental fragment of Orphan Knoll was drilled on Leg 12 of the Deep Sea Drilling Project, and its subsidence from sea level to 2000 metres in the Palaeocene was determined from the sediments recovered (Hole 111 in Laughton et al. 1972). Grant (1972) believes that the deep water col between Orphan Knoll and the continental slope is also subsided continent, and that the latest possible date for the isolation of the Orphan Knoll and Flemish Cap as a result of sea floor spreading is Early Cretaceous.

Baffin Bay has been shown by seismic refraction measurements to be floored by rather thin oceanic crust in the central basin (Keen & Barrett 1972). Under the Davis Strait sill, linking Baffin Bay to the Labrador Sea, a seismic structure was found similar to that beneath Iceland, suggesting that the sill was formed by excessive outpouring of oceanic basalts.

There is little direct evidence of the crustal structure between Spitsbergen and northeast Greenland. Magnetic data and the evidence of sea floor spreading geometry suggest that the Lena Trough is a fracture zone in which some oceanic crust has subsequently developed and that the Yermak Plateau northwest of Spitsbergen is continental (Johnson & Heezen 1967, Vogt & Ostenso 1970). Certainly Spitsbergen and the Barents Shelf are continental in structure and, together with Norway, form the northeastern boundary of the oceanic crust in the Norwegian Sea (Harland 1969; Emelyanov et al. 1971).

The Vøring Plateau, off the west coast of Norway, is a sediment-filled basin bounded on the western margin by a basement high. Whereas it is generally agreed that the sediments overlie subsided or downwarped continental crust, Hinz (1972) believes that the basement high is also continental whereas Talwani & Eldholm (1972) believe it to be oceanic. Depending on which view is correct, the continental boundary either cuts through the Plateau or swings out westward from the continental slope off Norway. An accurate reconstruction of the Norwegian Sea based on a magnetic survey over the Mohns Ridge might indicate whether there was room for the outer part of the Plateau in its fit against the East Greenland shelf edge.

South of Jan Mayen Island, there is some evidence that the Jan Mayen Ridge is a continental sliver detached from the continental margin of Greenland during a mid-Tertiary shift of spreading axis (Johnson & Heezen 1967; Johnson et al. 1972; Eldholm & Talwani 1973), although towards its southern end the ridge appears to have been built up of current-carried oceanic sediments (Hinz, this volume).

Between the Vøring Plateau and the Faeroe Islands, the continental margin has been determined from seismic and magnetic data to lie along the northeast extension of the Faeroes–Shetland Escarpment on the gentle continental slope off Norway (Talwani & Eldholm 1972). Structurally this escarpment continues SW into the Faeroes–Shetland Channel and may mark the continental edge of NW Scotland. There is evidence from gravity and seismic data that continental crust underlies the Faeroe Islands (Bott et al. 1971; Casten 1973) and that this, together with Rockall Plateau is a large detached continental fragment.

Rockall Plateau is linked to the Faeroe Islands by the Faeroe Rise, a rather shoal region on which there are a number of shallow banks and which is interpreted by Bott & Watts (1971) to be continental in structure. The geophysical evidence of the continental nature of Rockall Plateau itself is clearer (Roberts 1971; Scrutton & Roberts 1971; Scrutton 1972) and this has been confirmed by direct sampling (Roberts et al. 1972, 1973; Miller et al. 1973). Data from the JOIDES drill holes showed that subsidence of Rockall Plateau occurred during the Palaeocene (Sites 116 and 117, Laughton et al. 1972).

Porcupine Bank is a spur of shoal water running southwest from western Ireland. Sampling, gravity, seismic reflection and seismic refraction data all indicate that it is continental (Stride et al. 1969; Gray & Stacey 1970; Clarke et al. 1971; Whitmarsh et al. 1974). It is not certain, however, whether the crust underlying Porcupine Sea Bight separating it from the continental shelf is oceanic or subsided continental, and thus whether the Bank can be closed into the shelf during a reconstruction (Scrutton et al. 1971).

Finally, Galicia Bank and the smaller Vigo Seamount off the northwest coast of Spain have been shown by dredging and by seismic and gravity measurements to be fault-bounded and subsided continental blocks (Black et al. 1964).

We have, therefore, a number of more or less totally submerged continental fragments that must have become detached from their parent landmasses during or after the split of the North Atlantic and which subsequently subsided. In any reconstruction these pieces have to be included in the geometry. However, apart from Rockall Plateau (see below), there is little or no geological control to suggest how far they have moved horizontally or in what direction since they have become detached. On a somewhat arbitrary basis in the predrift reconstruction Porcupine Bank has been rotated back to close Porcupine Sea-bight, and Orphan Knoll, Flemish Cap and Galicia Bank have been moved northward in order first to allow the Iberian continental slope to lie adjacent to that off the Grand Banks, and second to fill in a gap between Ireland and Labrador.

Palaeogeographic reconstructions

In deriving palaeogeographic reconstructions it is necessary to start from the present, identifying active plate boundaries from the epicentres. An older plate boundary is determined from the magnetic data and the new oceanic crust is removed from the map by rotating the plates together towards the active centre using the fracture zones or trends in the anomaly pattern to determine the direction of relative movement. Although there appears to be a general tendency for spreading directions to be perpendicular to the spreading axis (or perhaps more significantly, for the spreading axes to become perpendicular to the spreading directions), nevertheless, in the North Atlantic there are many clear cases of oblique spreading, of which the Reykjanes Ridge is the best documented (Talwani et al. 1971).

A reconstruction thus derived must then undergo the same treatment to go back another stage, bearing in mind that features such as segments of fracture zones which appeared to be unrelated before the first stage may now show a clear relationship to guide the second stage of reconstruction, and that spreading axes or poles may have changed during the evolution.

This stage by stage reconstruction is possible so long as the magnetic anomalies are clearly identifiable or until continental edges collide. Unfortunately, near to the continental edge, the magnetic anomalies are often ill-defined, weak or absent. Various theories have been put forward to explain this magnetic quiet zone (Vogt et al. 1970; Larson & Pitman 1972; Poehls et al. 1973) some of which state that at the time of formation of these marginal regions (in the middle to late Cretaceous between 110 and 85 my ago) there were no reversals of the earth's magnetic field, whereas others attribute the lack of anomalies to the downwarping of the oceanic crust under the influence of marginal subsidence and sediment accumulation, and the consequent higher temperatures which may exceed the Curie point or at least speed the thermally induced decay of magnetisation. The Cretaceous history is therefore more speculative although the size of the step from the better determined Late Senonian (78 my) reconstruction to a pre-split configuration is not too large.

In the region between Labrador, Greenland, Iceland and U.K. several detailed magnetic surveys have been made both by air and by sea. The magnetic anomalies identified from these surveys and which are used in the subsequent set of reconstructions are shown in Fig. 8. The major part of the data from Iceland southwards across the Reykjanes Ridge to the southern side of Rockall Plateau are derived from USNOO data (Avery et al. 1969; Ruddiman 1973; Vogt & Avery 1974). Additional data on the Reykjanes Ridge are from Heirtzler et al. (1966), Godby et al. (1968), Fleischer (1969, 1971), Herron & Talwani (1972) and Johnson & Egloff (1973). In the Labrador Sea and south of Greenland data are from Godby et al. (1966), Mayhew (1969), Mayhew et al. (1970), Le Pichon et al. (1971) and Laughton (1972). On the Iceland–Faeroes Ridge magnetic surveys have been carried out by Fleischer (1971), Bott et al. (1971) and Johnson & Tanner

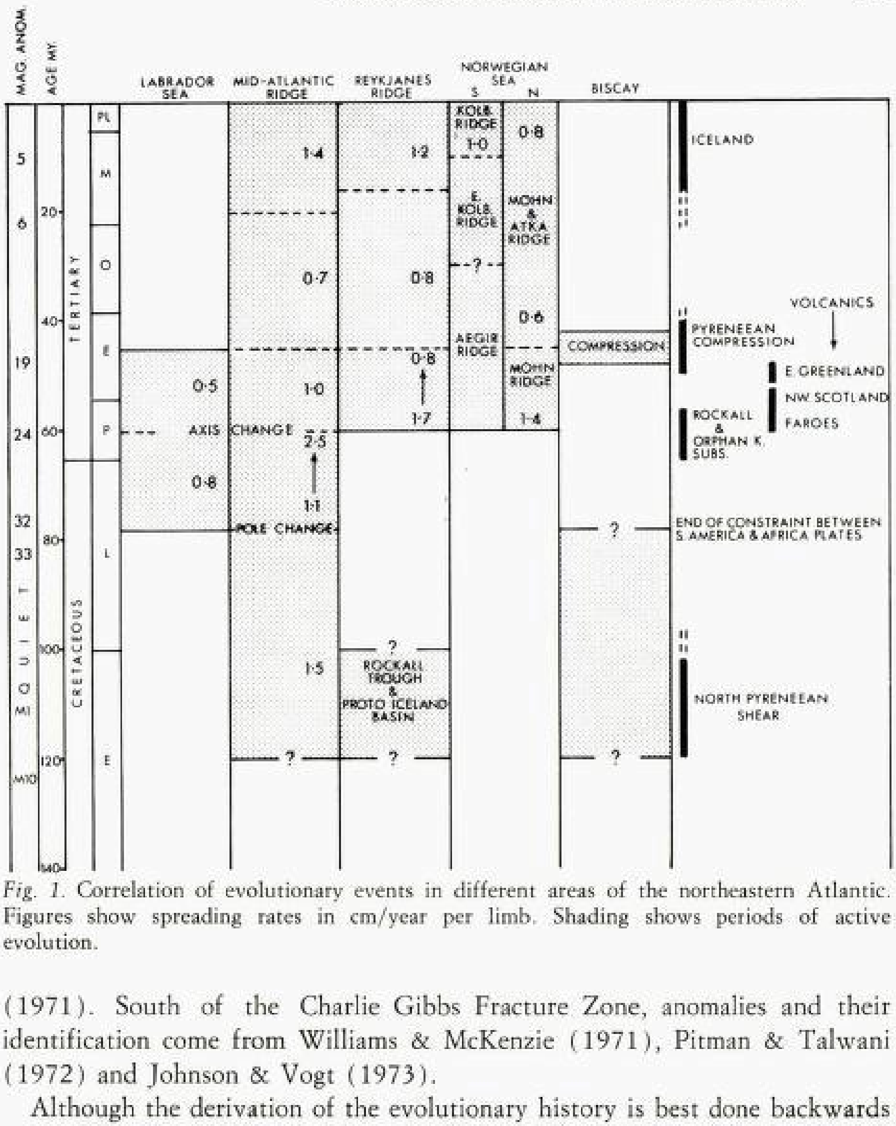

Fig. 1. Correlation of evolutionary events in different areas of the northeastern Atlantic. Figures show spreading rates in cm/year per limb. Shading shows periods of active evolution.

(1971). South of the Charlie Gibbs Fracture Zone, anomalies and their identification come from Williams & McKenzie (1971), Pitman & Talwani (1972) and Johnson & Vogt (1973).

Although the derivation of the evolutionary history is best done backwards in time, the telling of the history is perhaps clearer starting from the pre-split configuration and working towards the present. It is impossible here to elaborate all the data and the arguments that have determined this history. These will be found throughout the literature cited. But I will attempt to relate the stages of evolution as they occur with tectonic events in and around the relevant plates. In Plate 2, the isochron map summarises the results of the palaeogeographic reconstructions shown in Figs. 3 to 8 for the area south of Iceland, using as far as possible the plate boundaries derived from the magnetic surveys, and links them with isochrons in the Norwegian and Greenland Seas and the Arctic derived from the literature. The geometrical consistency between the plate movements south and north of Iceland has not, however, been tested. In Fig. 1, the activities in the various parts of the North Atlantic are related to the geological and magnetic polarity time scales, and to some important geological events.

Pre-split palaeogeography

The reconstruction shown in Fig. 2 represents the closest assemby of continental margins and fragments that can be made by the removal of all known or hypothesised oceanic crust. The closure of Biscay by the rotation of Spain has been made in accordance with the proposal of Le Pichon et al (1971). Rockall Trough and the proto–Iceland Basin have been closed by the translation northwestwards of the European Plate. The position of Africa shown is only approximate and does not take into account the relative movements of the Moroccan and Oranaise plates of northwest Africa described by Dewey et al. (1973).

The reconstruction can be tested by relating major pre-split orogenic features across from one side to the other. In Labrador, the Grenville Front marks the northern boundary of the Grenville orogeny of about 950 my ago. On Rockall Bank, rocks of Grenville (990 my) and Laxfordian (1600 my) age have been sampled (Miller et al. 1973) and it has been suggested that these straddle the eastward extension of the front, which may also be associated with an E–W magnetic lineament and with the E–W scarp bounding the SW edge of Rockall Plateau (Roberts et al. 1973).

The continuity of the Acadian–Caledonian orogenic belt has been extensively discussed (see many papers in Kay 1969), but the rather large separation of the mapped regions of the Acadides and Taconides in Newfoundland, and the Caledonides in Ireland and Scotland make it difficult to use this feature as a test of the correctness of this reconstruction. The continuation to the northeast of the Acadide structure is obscured by a Mesozoic–Tertiary basin of sediments running along the outer edge of the Labrador continental shelf (Grant 1972). The basin is bounded on the land side by a major fault. However, it is cut by NE–SW faults which may result from the reactivation of old Acadian fault lines in the underlying basement. On the European side, uncertainties about the nature of Porcupine Bank prevent any detailed studies of the southwest extension of the Caledonides.

The Hercynian (Variscan) orogeny is found in southern England and Ireland, and in western France. Cogné (1971) and Bard et al. (1971) have discussed the continuity of Hercynian structures into the Iberian peninsula prior to the opening of Biscay. The structures are not, however, clearly seen in the continental margin west of France (Montadert et al. 1971) and may have been obscured by Mesozoic and Tertiary folding and sedimentation. Bard et al. (1971) link the Hercynian folding in Iberia with that of northwest Africa. The Hercynian system can thus be traced as a sinuous zone on the reconstruction of Fig. 2 from France to Africa. The Hercynian Front, which is well mapped in southern Ireland and England but which is not seen in Newfoundland, must therefore run across the Grand Banks and lie subparallel to the continent shelf edge SE of Newfoundland.

Associated with the Front in Wales and southern Ireland, there are high grade anthracites. On Orphan Knoll, Jurassic sandstones of non-marine or

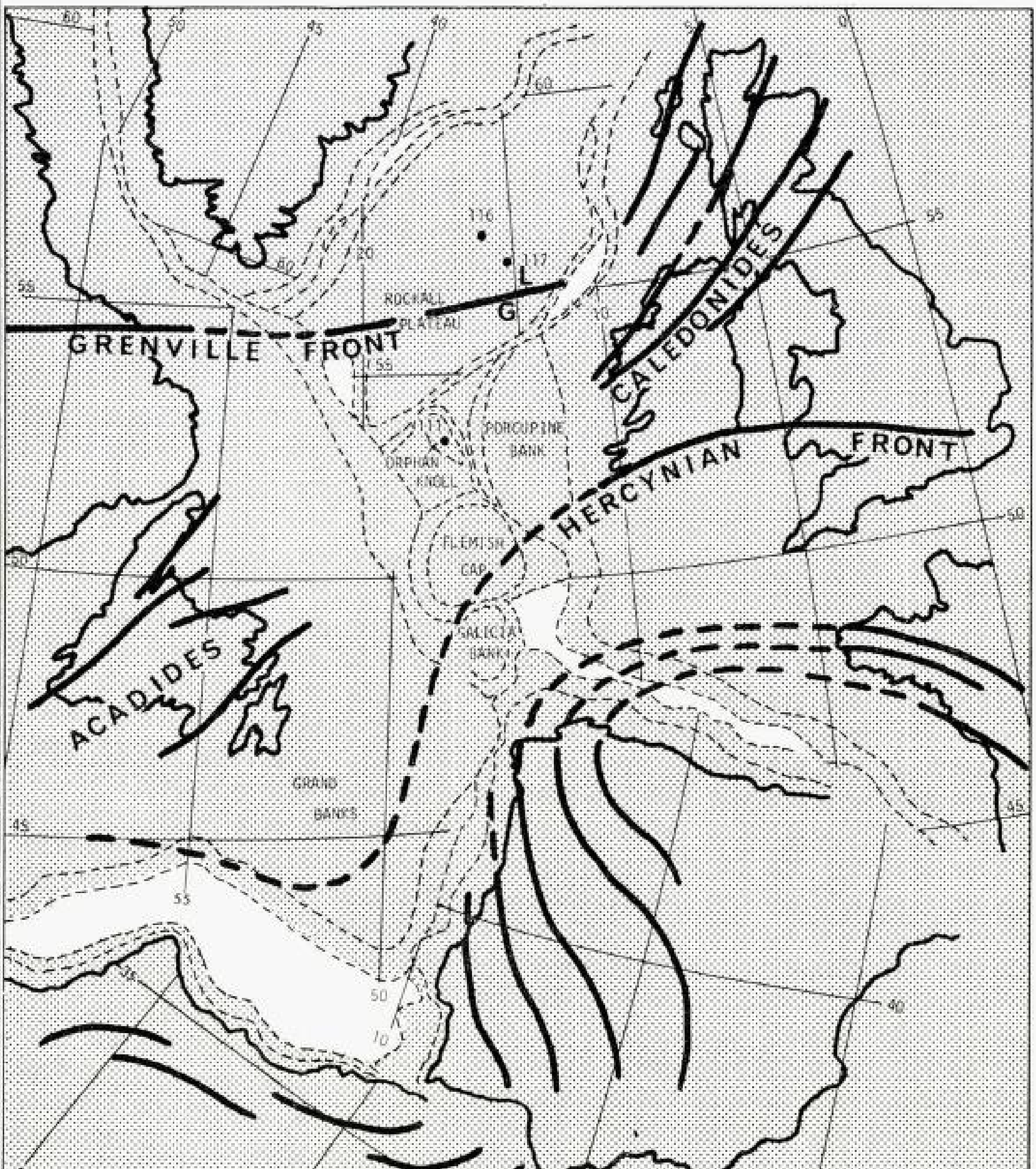

Fig. 2. Palaegeographic reconstruction prior to initial split showing correlation of major orogenic belts (N.B. Orphan Knoll, Flemish Cap and Galicia Bank have been moved arbitrarily to fill the gap between Porcupine Bank and the Labrador Shelf). L and G show positions of Laxfordian and Grenvillian rocks sampled on Rockall Bank.

very shallow coastal environment were sampled which contained detrital anthracite similar to South Wales anthracite (Hole 111, Laughton et al. 1972). This suggests that Orphan Knoll lay south of the Hercynian Front and thus south of the position shown in Fig. 2.

The initial split of Africa away from N. America took place at the beginning of the Early Jurassic at about 180 my based on magnetic anomaly interpretations (Pitman & Talwani 1972) and on the age of Jurassic sediments sampled at hole 105 near the continental margin of N. America (Hollister et al. 1972). During the Early Jurassic, Africa moved SE relative to the America–Eurasia plate along a transform fault running from south of Newfoundland to the south of Iberia. Dewey et al. (1973) suggest that during this movement smaller plates broke off NW Africa, but that north of the transform fault, the America–Eurasia plate remained intact until the middle of the Early Cretaceous.

Early Cretaceous

The sequence of events associated with the first propagation of the Atlantic split northwards is difficult to establish with certainty. The split between Iberia and the Grand Banks could have been continued north of Spain and into the Pyrenees as a transform fault, carving off the Iberian plate, as has been suggested by Dewey et al (1973). In this case the date of the initial split can be related to geological data in Iberia and northwest Europe and has been argued by Dewey et al. to be Hauterivian (120 my). Choukrane et al. (1973) proposed, from similar evidence and from data on the Bay of Biscay, that the Iberian plate started to rotate in the Cretaceous following a subsidence of the margins of Biscay at the beginning of the Early Cretaceous.

However, it is possible that the split also extended northwest in the direction of the Labrador Sea. Grant (1972) speculated that there had been an 'intracratonic' depression in the proto Labrador Sea and running SE to the Grand Banks since the early Palaeozoic, in which Mesozoic sediments accumulated. Seismic profiles clearly delineate the landward side of this depression. This syncline could have been the forerunner of a line of split running from Baffin Bay to the Pyrenees. Mesozoic sediments have been postulated (but not proved) to lie deep in Rockall Trough over oceanic crust (Stride et al. 1969; Scrutton & Roberts 1971) and possibly in the region off SE Greenland. Thus the opening between Iberia and the Grand Banks in Early Cretaceous may have continued northward into Rockall Trough and the proto-Iceland Basin through a transform fault parallel to the shelf edge NE of Newfoundland (Fig. 3). If the pole of rotation implied by such geometry were not too far to the northeast, the amount of opening would be rapidly reduced northwards, where oceanic crust would be hard to recognise or may be absent if a degree of continental crustal thinning took place.

It is possible that both spreading in Rockall Trough and the proto-Iceland Basin, and shear and opening of the Bay of Biscay may have taken place

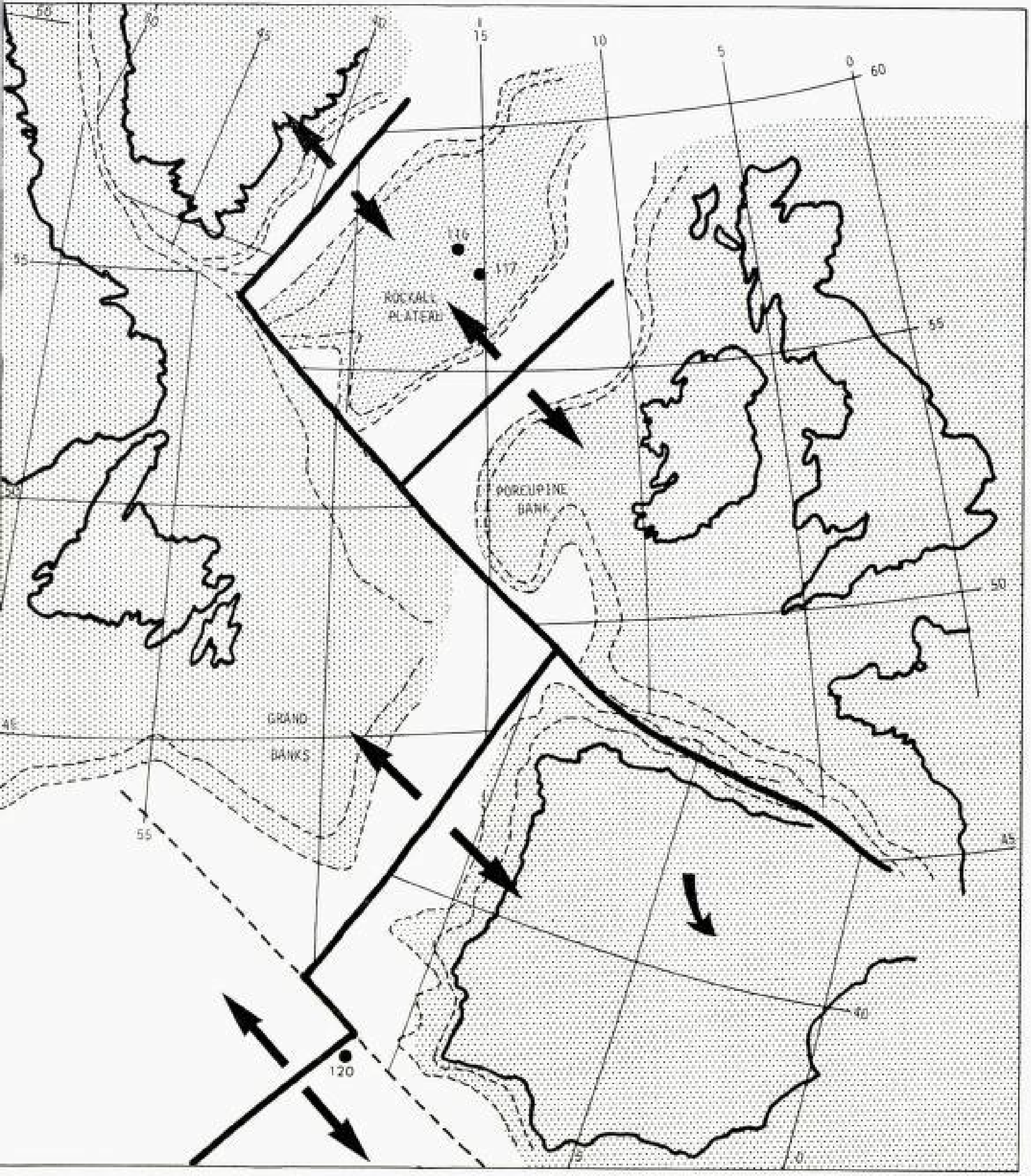

Fig. 3. Palaeogeographic reconstruction in Early Cretaceous (110 + 10 my) showing the end of the evolution of proto-Iceland basin and Rockall Trough and the start of the opening of Biscay. These events may, however, have been simultaneous.

simultaneously in the Early Cretaceous to accommodate the opening between Iberia and the Grand Banks. Between 85 and 110 my, Larson & Pitman (1972) have shown that there were no magnetic reversals and therefore in this period there would be no magnetic anomalies created to be used to date the ocean crust. In hole 120 of DSDP, samples of bathypelagic Barremian (115 my) marl ooze were recovered from the uplifted Gorringe Bank (Ryan et al. 1973), but the position of this hole is somewhat south of the Iberian–Grand Banks split and may in fact belong to ocean crust generated by the separation of Africa and North America.

Two-plate spreading during the Late Cretaceous and Palaeocene (80-60 my)

The Bay of Biscay was fully opened by the Late Senonian (75 my) since anomaly 31–32 can be traced unequivocally more or less parallel to the mid-Atlantic Ridge, cutting across the E–W magnetic lineations of Biscay (Williams & McKenzie 1971). Choukrane et al. (1973) argue that the westward migration of the rotation pole of Iberia in the Late Cretaceous blocked the shear movement along the Pyrenean fault and prevented further rotation of Iberia. However, the opening may alternatively have been stopped as a result of a major change of the stress field between the plates, resulting in an E–W separation of the American and Eurasian plates. The transform fault between the United Kingdom and Labrador became at this time a spreading centre, extending NW between Labrador and Greenland (Fig. 4).

Geophysical data in the Labrador Sea (Le Pichon et al. 1971) followed by deep drilling (Laughton et al. 1972) show that Greenland started to separate from Labrador about 80 my ago, although the separation is relatively small in Baffin Bay (Keen & Barrett 1972). At the same time north of Greenland, the Wegener fault linked the Baffin Bay opening to the Arctic Ocean (Ostenso 1973).

Le Pichon & Fox (1971) attribute the change of stress field at 80 my throughout the North and South Atlantic regions to the fact that the thick continental lithosphere of West Africa ceased to be constrained against the thick continental lithosphere of the northeast part of South America, as they gradually moved apart. This initiated a widespread change of spreading axes and spreading rates. Greenland, Europe and Iberia were now acting as one plate separating from North America. Any earlier spreading in the proto-Iceland Basin and Rockall Trough had ceased and thick sediments accumulated from the nearby continental masses. At this time Rockall Plateau was still above sea level and may have been mountainous along its eastern margin. (See sites 116 and 117 in Laughton et al. 1972.)

Spreading proceeded with this geometry into the Palaeocene (from 80 to 60 my), giving linear magnetic anomalies that are well mapped in the Atlantic as far north as southern Greenland but which are not so easily identified (except for the anomalies 24 and 25) in the Labrador Sea, perhaps on account of the thick sediments, marginal downwarping and slow initial spreading rate. The spreading rate per limb in the Atlantic at about 45°N increased from 1.1 cm/year at 80 my to about 2.5 cm/pear at 60 my (Williams & McKenzie 1971) whereas in the Labrador Sea, the mean rate was only 0.8 cm/year

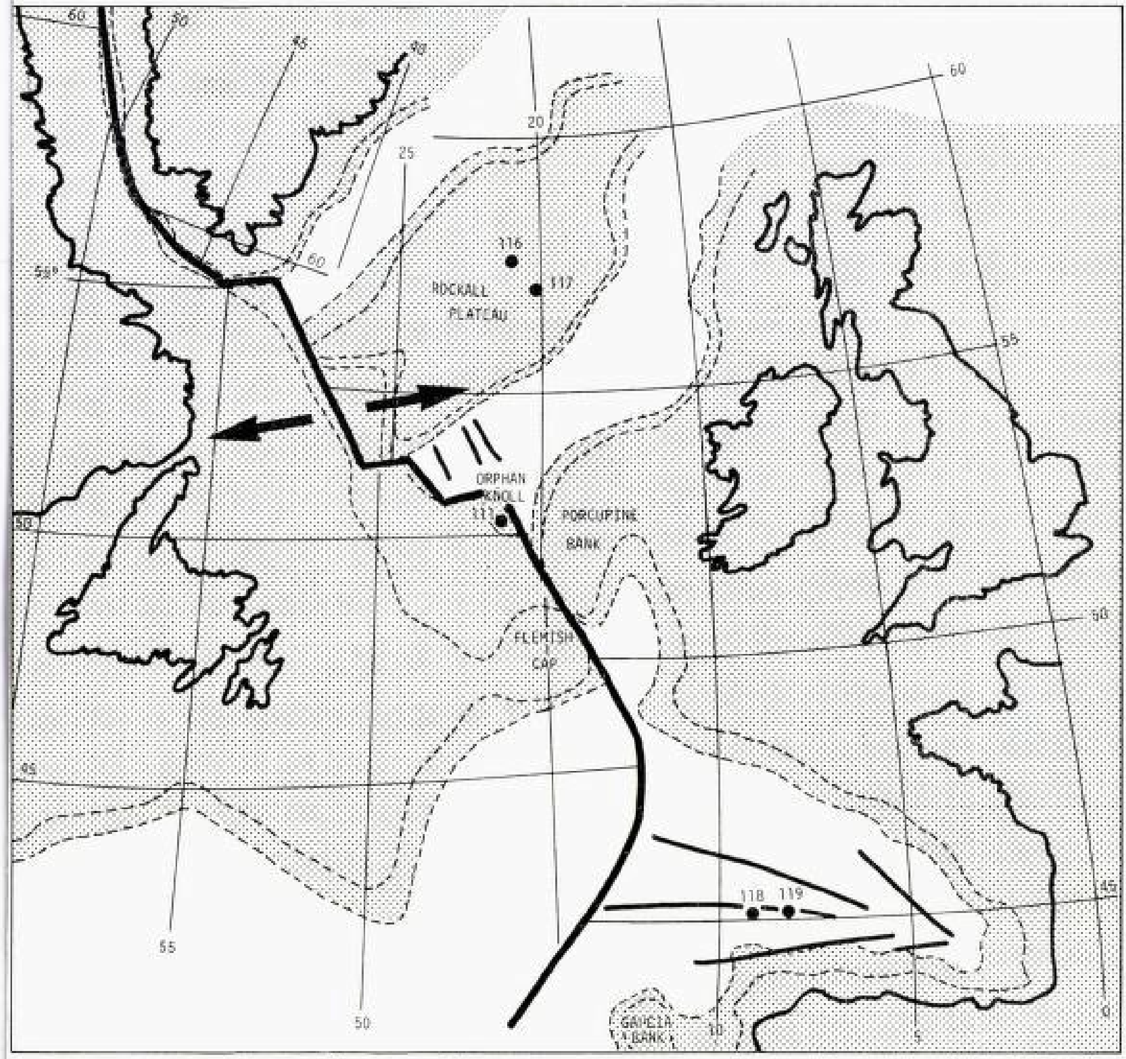

Fig. 4. Palaeogeographic reconstruction at anomaly 32 (78 my–Santonian). Black lines show mapped magnetic anomalies.

(Le Pichon et al. 1971). If both America and Eurasian plates were rigid during this period, then in the Labrador Sea a similar acceleration of spreading occurred which would have been from 0.5 to 1.1 cm/year in order to give the correct mean rate. The initial spreading rate may therefore have been too slow to give identifiable magnetic anomalies.

Fracture zones south of Greenland and between Newfoundland and Rockall Plateau reflect offsets (Fig. 4) in the initial line of opening, which may in turn have been determined by Grenvillian and Acadian fault trends (Grant 1972; Olivet et al. 1974). Spreading continued through the Campanian (Fig. 5) and Maestrichtian until the Palaeocene. The dotted line in Fig. 6 shows the last position of the spreading axis prior to the major change at

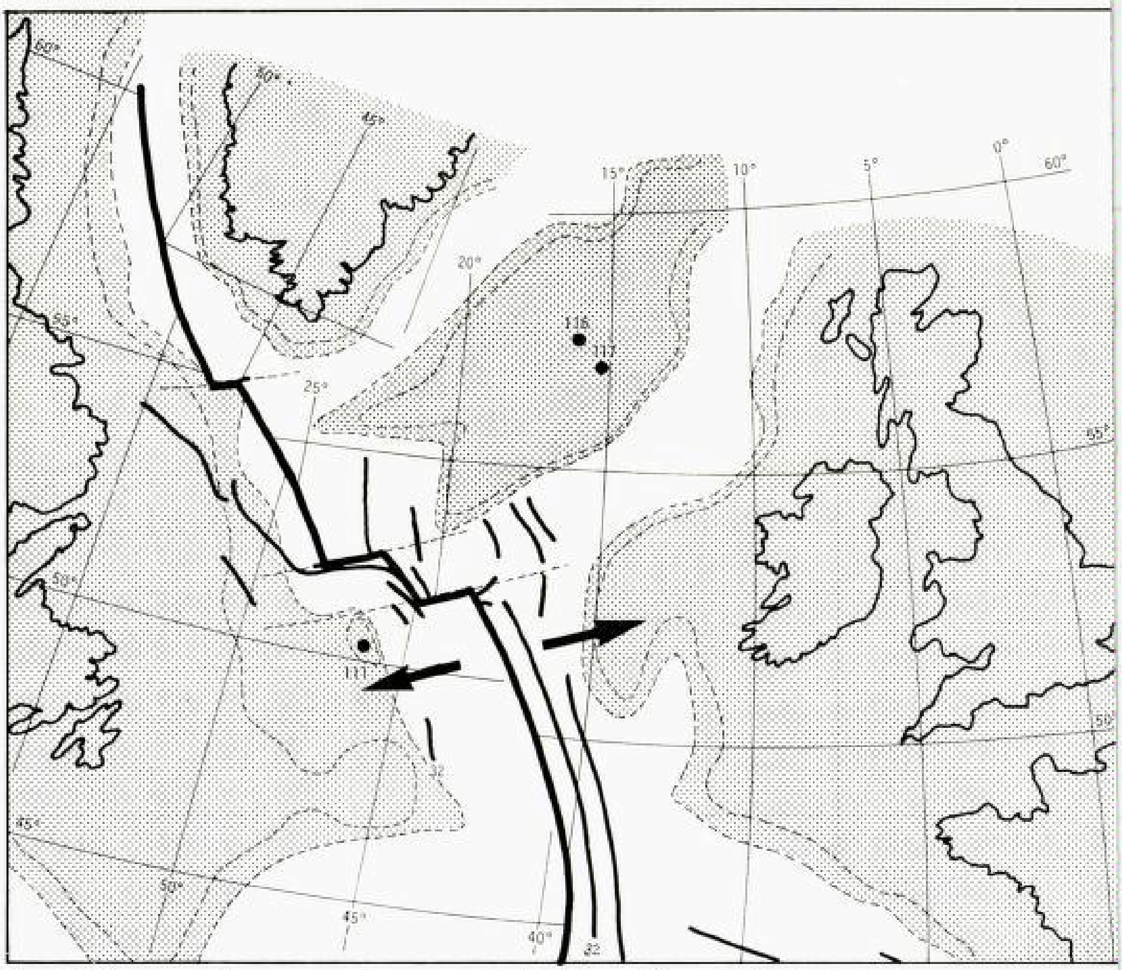

Fig. 5. Palaeogeographic reconstruction at anomaly 31 (72 my–Campanian). The dashed lines show small circles of transform faults.

60 my. Hole 112 sampled basement, just east of this axis, the age of which was estimated at 65 my (Laughton et al. 1972).

Three-plate spreading during Palaeocene and Eocene (60-47 my)

In the Palaeocene at about the time of anomaly 24 (60 my), another major readjustment of spreading geometry occurred caused by a further change in the pattern of forces driving the plates (Fig. 6). The Greenland plate became detached from the Eurasia plate and the spreading centre propagated northeastwards between Greenland to the west, and Rockall Plateau, Faeroe

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Fig. 6. Palaeogeographic reconstruction at anomaly 24 (60 my–Palaeocene). The dotted lines show spreading axes prior to 60 my. Arrows denote relative spreading direction between plate pairs.


IRELAND
116
117
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119
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112
31
32

Islands, Vøring Plateau, the northwest Norwegian continental shelf and the Barents shelf to the east. Northeast of Greenland, Spitsbergen split away along a transform fault coupling the Norwegian Sea spreading axis to the Arctic spreading axis. The date of initiation of this split is well determined from the mapped anomaly 24 which lies close to the west margin of Rockall Plateau (Vogt & Avery 1974; Ruddiman 1973), and which can be identified near the margins of the Norwegian Sea (Avery et al. 1968; Phillips 1973). The evolutionary story of the Norwegian Sea has been developed through the last five years by many workers using the data both from the sea floor and from the geology of the neighbouring continents (Johnson & Heezen 1967; Avery et al. 1968; Vogt et al. 1970; Johnson et al. 1971, 1972; Bott 1973), and their data and arguments will not be repeated here. Only their main results will be used in this chronological account of the north Atlantic evolution.

Between Rockall Plateau and Greenland, the new split lay to the east of the axis of the proto-Iceland Basin, against the foot of Hatton Bank. The Reykjanes Ridge began to develop leaving the older sea floor attached to Greenland. At about the latitude of the Iceland–Faeroes Ridge the axis was offset to the east creating the Norwegian Seamount chain (also called the Aegir Ridge). The spreading centre continued northward along the flanks of the Mohns Ridge which was linked to the Nansen Ridge in the Arctic by the Spitsbergen Fracture Zone (de Geer shear zone).

The effect of the new split east of Greenland was to change the geometry from two to three plates, since the Labrador Sea continued to open (Laughton 1971, 1972). The stresses on the three plates, and hence their relative motions, changed, resulting in an alteration of spreading axes. South of Greenland a triple junction appeared in relatively old ocean crust 150 miles from the previous spreading axis (Fig. 6). In the southern Labrador Sea new fracture zones appeared at a different orientation, but further north the axis stayed constant (Le Pichon et al. 1971). South of the triple junction the spreading axes became N–S not NW–SE, and E–W fracture zones developed starting in the position of the older ones (Olivet et al. 1970). Oblique spreading gave way to orthogonal spreading and the spreading rate was substantially reduced from 2.5 to 1.0 cm/year (Williams & McKenzie 1971; Pitman & Talwani 1972).

Johnson & Vogt (1973) associate a topographic ridge in the eastern N. Atlantic with the 60 my isochron and suggest that this was caused by increased mantle plume activity related to the change of stress pattern. They also recognise a change in spreading style from oblique to a series of en échelon orthogonal spreading axes. Considerable volcanic activity occurred at this time in NW Scotland (50–60 my), on Rockall (60 my), in the Faeroe Islands (50 my) and in East Greenland (50–60 my) (Bott 1973) and apparently continued to the present day from the position of Iceland, throughout the period of separation of Europe and Greenland to create the Iceland–Faeroes Ridge (Bott et al. 1971).

After splitting from Greenland, Rockall Plateau began to subside. Evidence

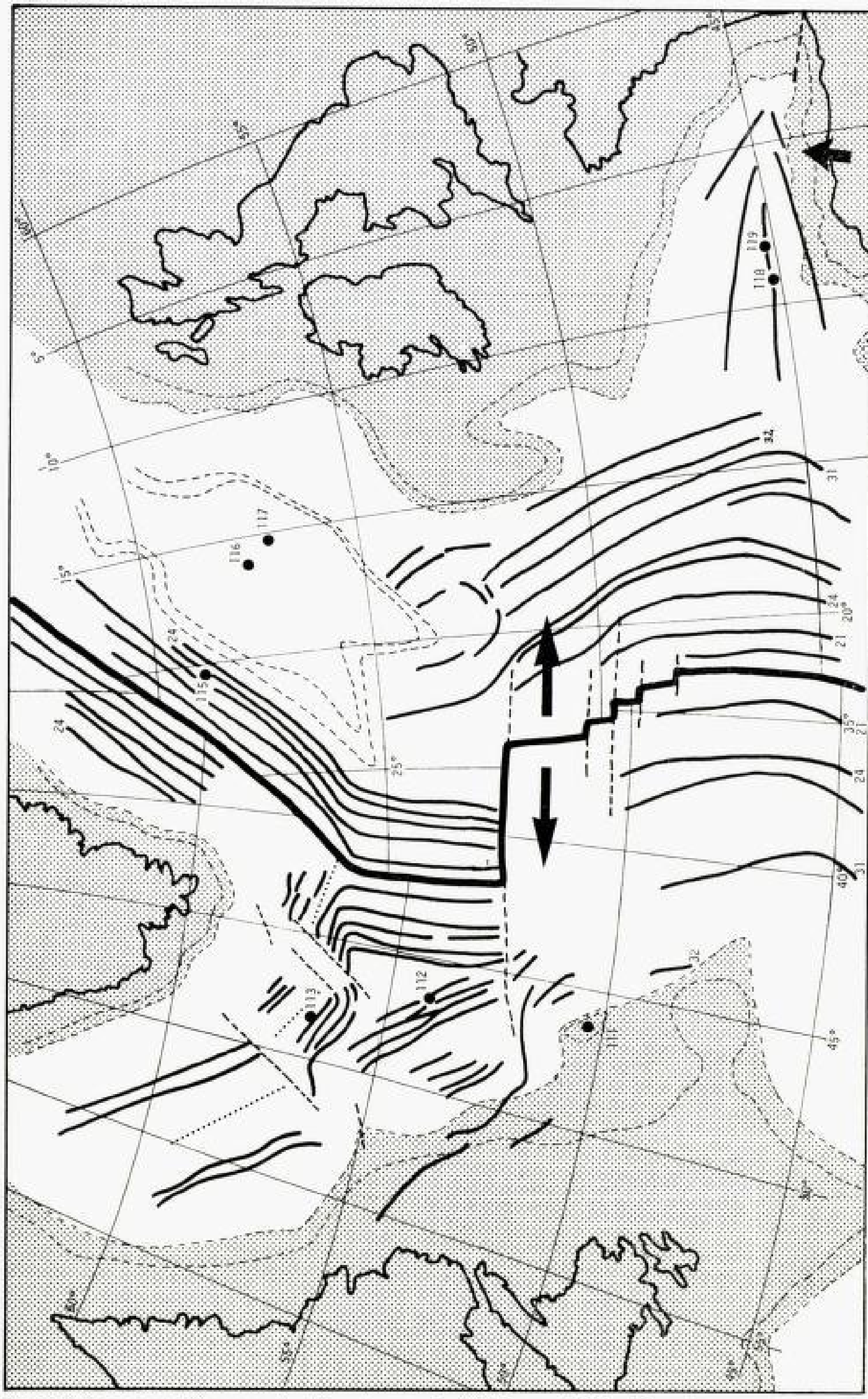

Fig. 7. Palaeogeographic reconstruction at anomaly 19 (47 my–Middle Eocene).

of the palaeoenvironment of sedimentary deposition in samples from drill holes 116 and 117 has provided a subsidence curve showing that between 55 and 50 my, Rockall Bank sank 1200 metres (Laughton et al. 1972). At the same time, Orphan Knoll subsided by 1800 m (Hole 111) even though it was not close to the new split. Evidence of subsidence of the continental sediment basin on the Vøring Plateau and of the region between the Faeroes and the Shetland Islands after the start of the formation of the Norwegian Sea, has been presented by Talwani & Eldholm (1972). These subsidences may be associated with the downwarping and block faulting along continental margins subsequent to split as discussed by Bott (1973) and Sleep (1973).

Two-plate spreading from Eocene to Early Miocene (47-20 my)

The youngest anomalies in the centre of the Labrador Sea are about 47 my, indicating that spreading virtually ceased at that time (Le Pichon et al. 1971; Laughton 1972). Sedimentation from the neighbouring continents and from sediment laden ocean currents from the east and northeast have covered the basement relief associated with the spreading centre (cf. Hole 113 in Laughton et al. 1972). The triple junction ceased to exist and subsequent spreading was between the two plates of America–Greenland and Eurasia (Fig. 7). The spreading rate progressively slowed until it was at a minimum value of about 0.7 cm/year per limb on the Reykjanes Ridge at 30 my (Johnson & Vogt 1973). The Charlie Gibbs Fracture Zone, with an offset of the N. Atlantic spreading axes of 350 km at 60 my, continued to indicate the direction of spreading between the two plates (Olivet et al. 1970).

However, a change occurred in the style of spreading at about this time. On the Reykjanes Ridge, oblique spreading, which had produced strikingly linear anomalies between 60 and 45 my (Fig. 7), gave way to nearly orthogonal spreading in a series of en échelon sections separated by fracture zones, the change being attributed to a small change in the spreading direction (Vogt et al. 1969; Ruddiman 1972). This tendency for oblique spreading axes to change to orthogonal axes was noted by Menard & Atwater (1968) in the Pacific.

Further south the northward movement of Africa (Dewey et al. 1973) during the Eocene resulted in compression along the northern edge of the Iberian plate and along the Pyrenees. This caused a limited subduction of the Biscay oceanic lithosphere beneath the Spanish continental lithosphere (Choukrane et al. 1973) and uplift of a central ridge in the Biscay sea floor (Holes 118 and 119 in Laughton et al. 1972). Le Pichon & Sibuet (1971) associate this Eocene compression phase with the evolution of King's Trough, a 370 km long tectonic feature cutting diagonally across the eastern flanks of the mid-Atlantic Ridge (Matthews et al. 1969). However, the age of crust cut by the western end of King's Trough is Oligocene (29 my) and this would imply that the compression lasted well beyond the Eocene. Certainly some western continuity of the subduction zone is necessary on geometrical grounds but this could be acommodated by a shear zone parallel of the western edge of the Iberian plate.

North of Iceland, the spreading axis jumped westwards from the Aegir Ridge to the Greenland continental margin possibly cutting off a piece of the outer shelf which may be preserved today as the northern part of the Jan Mayen Ridge (Johnson & Heezen 1967), although there are some doubts about the continental nature of all this Ridge (Hinz, this volume). Johnson et al. (1971) suggested an alternative model where the Ridge is part of the early product of the relocated spreading centre. The age of the jump in spreading axis has been variously estimated as 42 my (Vogt et al. 1970), before 30 my (Johnson et al. 1971), 30 my (Johnson et al. 1972) and 18.6 my (Eldholm & Talwani 1973). The new spreading axis is thought to have lain somewhat east of the present axis of the Iceland–Jan Mayen Ridge (also called the Kolbeinsey Ridge).

North of the Jan Mayen Fracture Zone the spreading axis has apparently remained along Mohns Ridge. The older aeromagnetic data in the southern Norwegian Sea of Avery et al. (1968) have now been extended northwards from Jan Mayen Island to the north of Greenland (Phillips 1973). The data reveal that the Mohns Ridge, which in its flank regions comprises linear anomalies arising from oblique spreading, consists on its crest of a series of en échelon sections with right lateral offsets.

Further north still, the fracture zone splitting Spitsbergen from Greenland, changed at about the time of anomaly 20 (49 my) into a spreading axis as the result of a change in the position of the pole of rotation between the Norwegian and Greenland plates (Phillips 1973) and gave rise to the Atka Ridge.

Early Miocene to Present (20-0 my)

From the Early Miocene to the Present (Fig. 8) the plate boundaries did not move much, although the style of spreading changed. South of the Charlie Gibbs Fracture Zone, the en échelon sections of orthogonal spreading that had formed since 60 my now changed gradually into sections of orthogonal spreading linked by oblique spreading, transform faults being nearly absent in crust younger than 10–20 my (Johnson & Vogt 1973). On the Reykjanes Ridge, after 18 my the transform faults disappeared and spreading once more became oblique and parallel to the present axis of the Ridge (Vogt et al. 1970; Ruddiman 1972). At about the same time Iceland began to emerge as an island. The oldest rocks sampled in Iceland are 16 my (Piper 1973) although erosion may have cut back some of the older margins. Ward (1971) has interpreted the geology of Iceland in terms of plate tectonics and identifies two rather diffuse fracture zones on the northern and southern limits of the island which displace the present active spreading centre (the neo-volcanic zone) about 70 miles east of the line joining the Reykjanes Ridge to the Kolbeinsey Ridge. An older spreading centre active about 10 my ago lies in

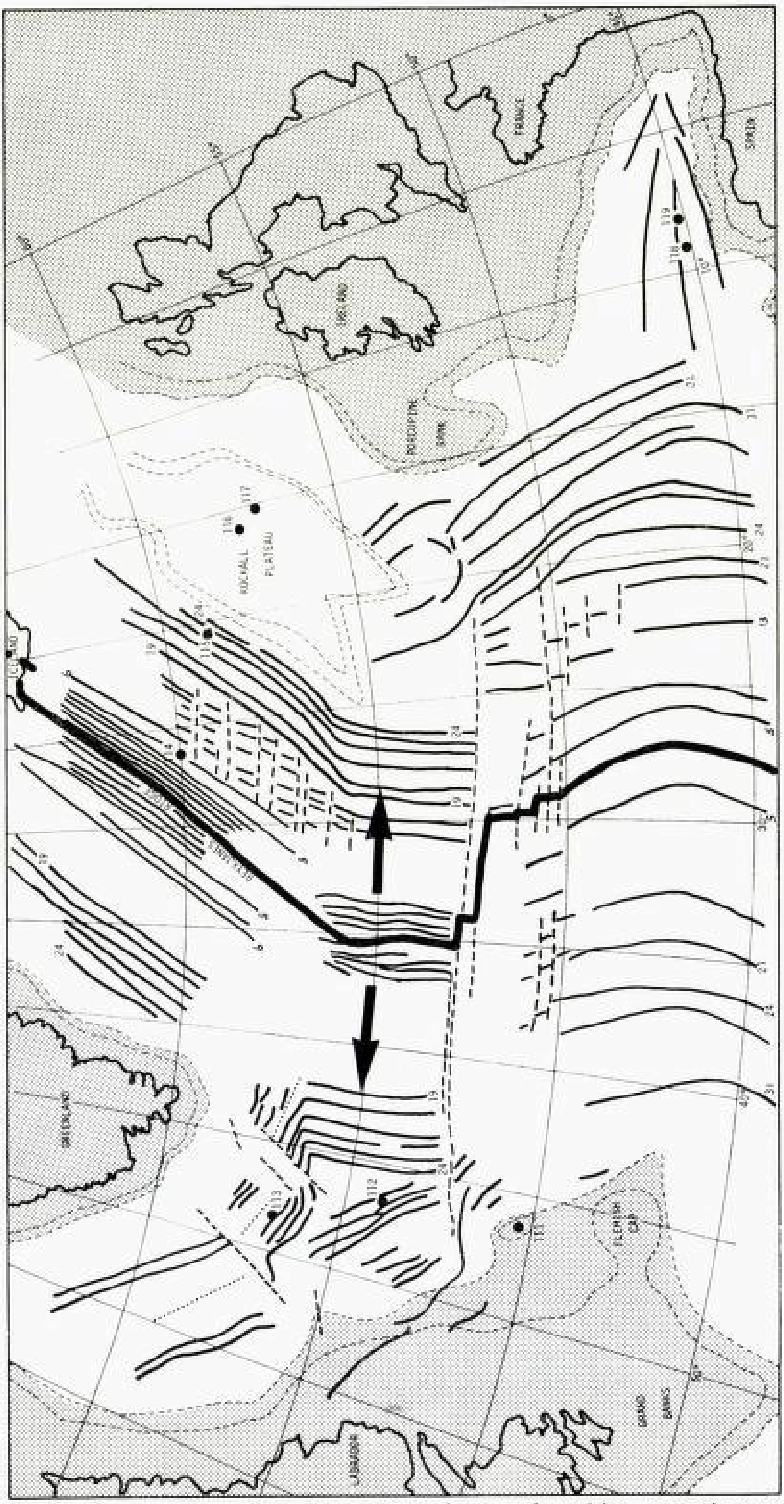

Fig. 8. Present. Heavy lines show principal mapped positive magnetic anomalies with identifications. Heavy dashed lines are fracture zones. Dotted lines are extinct spreading axes. Thin dashed lines are top and bottom of continental slope. Black dots are drill sites.

the western part of the island. Piper (1973) believes that the western zone ultimately became extinct about 5 my ago. Iceland is clearly the site of excessive lava production from the asthenosphere, several times that of the mid-Atlantic Ridge, and may be the surface expression of a mantle plume or hot spot, that has given rise also to the anomalous Iceland–Faeroes Ridge (Bott 1973). The mode of crustal spreading and dyke injection is not, however, the same as that in an oceanic ridge, being spread over a wider area and thus the magnetic anomaly pattern is not so linear (Gibson & Piper 1972).

Between Iceland and Jan Mayen Island, a second jump of the spreading axis to the west may have occurred 10 my ago (Johnson et al. 1972) to bring it to its present position. A detailed survey reported by Meyer et al. (1972) detected that 3 my ago a minor perturbation in the spreading axis created the Spar Fracture Zone.

Throughout the Neogene, the spreading rates have generally increased. At 50°N, the rate increased from 0.7 to 1.4 cm/year (Johnson & Vogt 1973). Similar increases of rate are found on the Reykjanes Ridge (Vogt et al. 1970) and in the Norwegian Sea (Phillips 1973).

Seismic activity continues today along the axis of the mid-ocean ridge system and along the transform faults. The mechanisms of emplacement of the new oceanic lithosphere and of the tectonic forces which in places uplift the ridge either side of the injection axis leaving a median valley and in other places building only a ridge (e.g. Reykjanes Ridge) are not yet fully understood. Nor are the forces understood which are driving the plates and which periodically change to give rise to a different pattern of spreading. However, the existence of sea floor spreading and the related kinematics are now established beyond doubt and must be the basis for understanding oceanic evolution.

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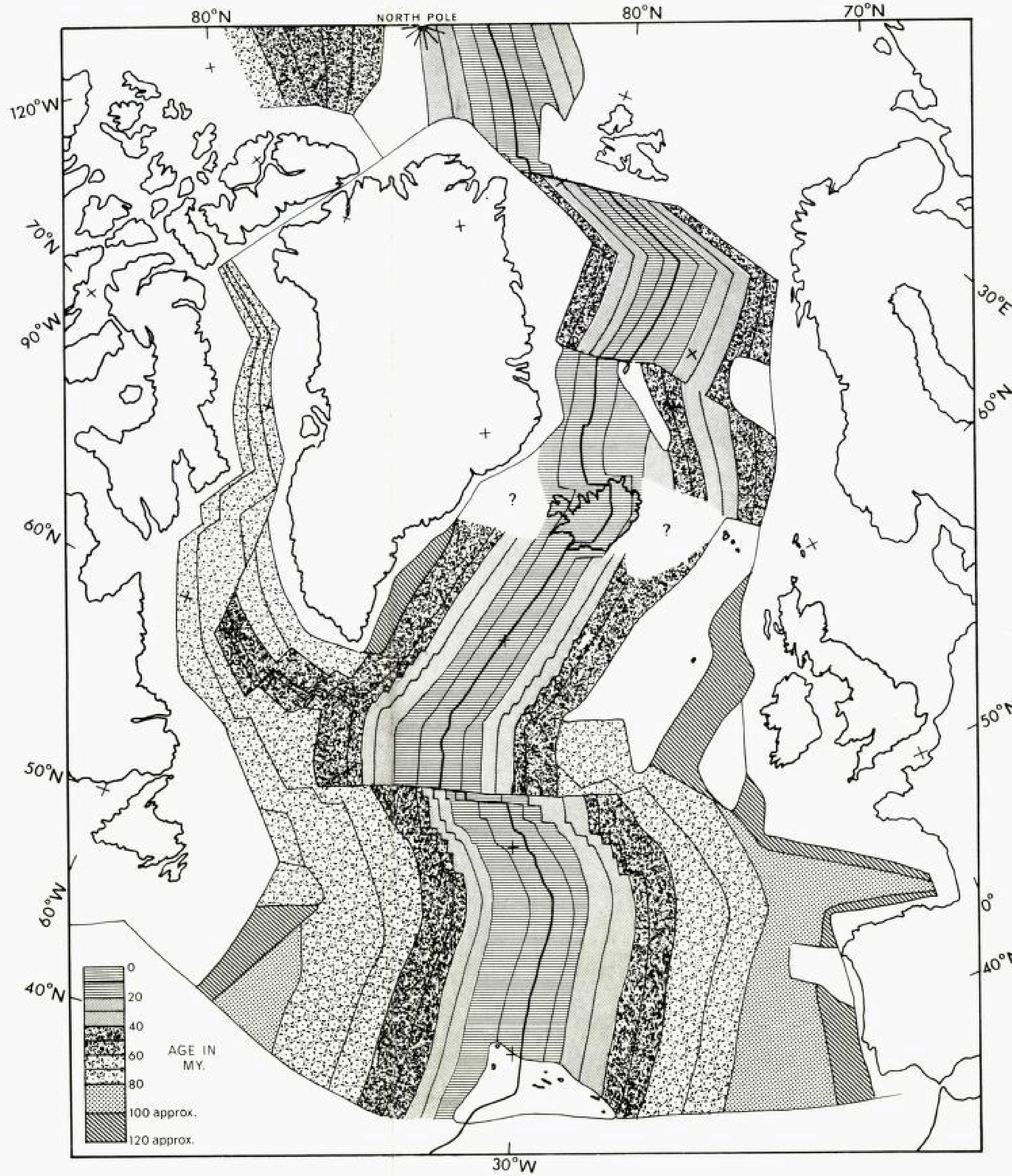

Plate 2. Isochrons of the age of oceanic lithosphere derived from magnetic anomaly surveys, and plate tectonic reconstructions.

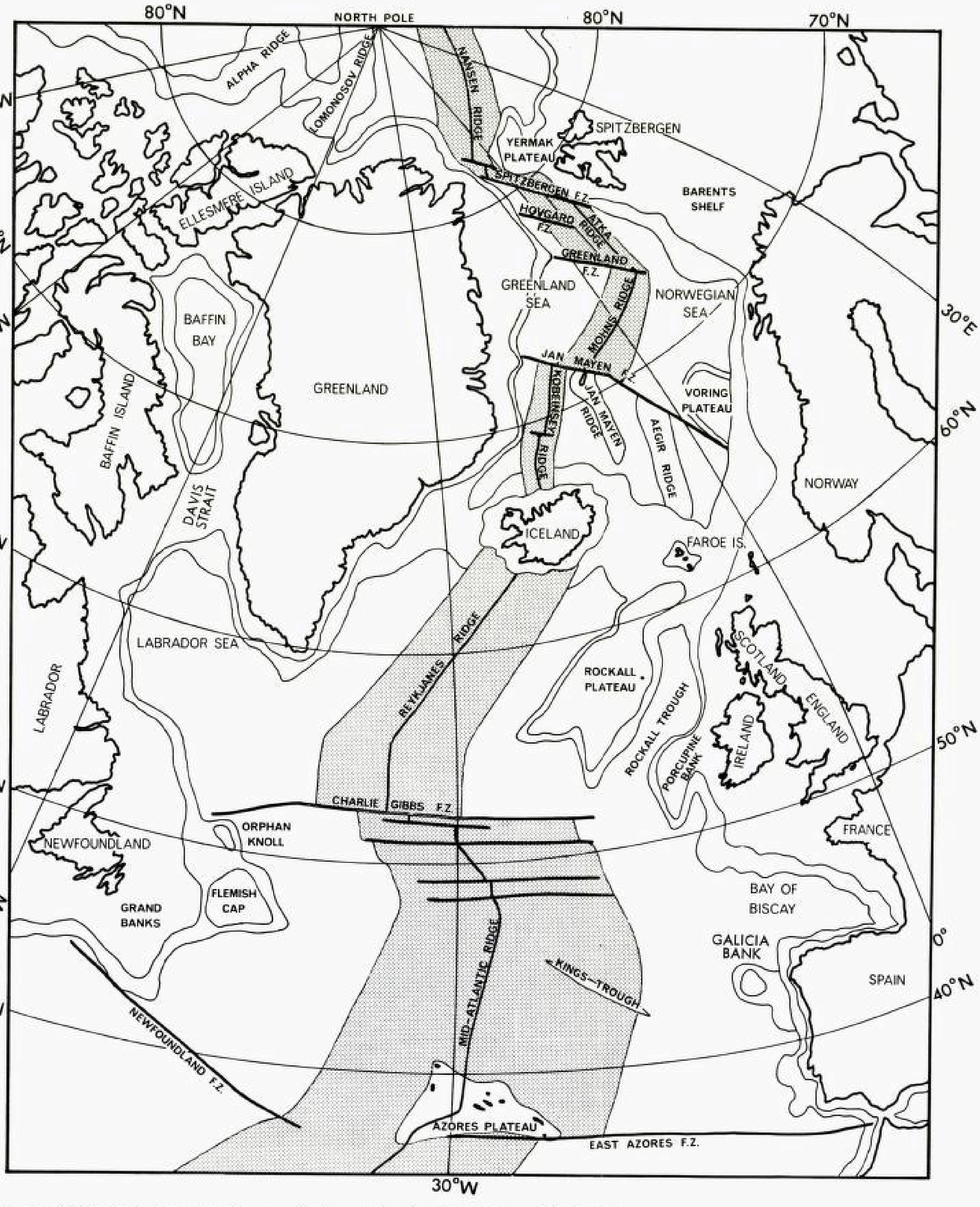

Plate 1. Principle physiographic features of the sea floor in the northeast Atlantic. The two lines bordering the continents represent the top and bottom of the continental slope. The mid-ocean ridge system is shaded. (The projection, which is approximately equal area, has been taken from Dietrich & Ulrich 1968).

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