# 20. THE SOUTHERN LABRADOR SEA – A KEY TO THE MESOZOIC AND EARLY TERTIARY EVOLUTION OF THE NORTH ATLANTIC.

A. S. Laughton, National Institute of Oceanography, United Kingdom

Prior to the separation of Rockall Plateau from Greenland in the early Tertiary, the Labrador Sea was the northern part of the Atlantic Ocean. An understanding of the tectonic development of the Labrador Sea tells, therefore, of the early history of the North Atlantic following the break away of northwestern Europe from the North American continent. In particular, the southern Labrador Sea between Greenland and Newfoundland provides the key to the change from a two plate situation to a three plate situation after the split between Rockall Plateau and Greenland 60 million years ago.

During the last six years, geophysical data about the Labrador Sea have been collected both by airborne and ship surveys, and it is now possible to describe in some detail the major features of the bathymetry, the magnetic anomaly field, the sediment distribution and the crustal structure. Theories of the evolution of the Labrador Sea have been developed from these data and can now be further elaborated. The results of drilling at the three sites (111, 112 and 113) in the Labrador Sea, and the additional geophysical data taken on passage by *Glomar Challenger* have led to a re-interpretation of the area, and hence to a better understanding of the early development of the North Atlantic.

## BATHYMETRY

The continents of Northeastern Canada and Greenland are bordered by continental shelves between 100 to 150 kilometers wide. In the north, Baffin Island and Greenland are joined across the narrow Davis Strait by shoal water not deeper than 1000 meters, although in Baffin Bay to the north, the basin depth exceeds 2000 meters. The Labrador Sea is therefore confined to the southwest, northwest and north by continental margins or shoal areas. The basin is sediment filled and hence, has a smooth bottom; the depth increases gently from 2500 meters in the northwest to 3700 meters in the southeast where it is open to the northwestern Atlantic. The Northwest Atlantic mid-ocean canyon, a Quarternary feature due to depositional-erosional processes, (Heezen, Johnson and Hollister, 1966) runs southeasterly through the entire basin before going south around Flemish Cap.

Seven hundred kilometers southeast of Cape Farewell in Greenland is the mid-Atlantic Ridge trending northeast to the Reykjanes Ridge and to Iceland, and south to the Charlie Gibbs Fracture Zone[1] (Olivet *et al.*, in press), south of which it is offset 370 kilometers to the east (Fleming, Cherkis and Heirtzler, 1970). An extinct branch of the mid-Atlantic Ridge is believed to underlie the Labrador Sea (Drake, Campbell, Sander and Nafe, 1963; Manchester, 1964; Godby, Baker, Bower and Hood, 1966; Mayhew, 1969; Johnson, Closuit and Pew, 1969; Le Pichon, Hyndman and Pautot, 1971). Apart from a short section south of Cape Farewell, the ridge is totally buried beneath the sediments and has been located only by seismic reflection and magnetic surveys.

A bathymetric survey by the U.S.N.O.O. (Johnson, Vogt and Schneider (1971) of the central and southern part of the Labrador Sea was made with 15-kilometer spaced lines and delineated part of the northwestern Atlantic mid-ocean canyon and various seamounts and ridges lying to the east of it. These data have been combined with additional soundings from *Glomar Challenger* and other research vessels (notably *Vema*), and the *GEBCO* collected sounding sheets, and have been recontoured (Figure 1) in the light of seismic reflection profiles and magnetic data. The topography has been moulded by basement ridges of which only the tops are seen, and by various modes of sedimentation, influenced by bottom current activity. South of Cape Farewell, the Eirik Ridge trends southwesterly (Johnson and Schneider, 1969) toward Site 113. Further south, and inside a semicircle of basement ridges and seamounts, a sediment body is topped by sinuous ridges which can be traced with some confidence over 300 kilometers in length. The largest of these is over 100 fathoms (200 meters) high and can be traced from 56°N 44°W to 54.5°N, 48°W. It is sharp crested (Figures 2 and 5a), curving and sometimes dividing, sometimes the result of converging ridges. The axes of the major ridges resulting from present or past current systems are shown in Figure 1. The topography of the Charlie Gibbs Fracture Zone is shown here diagramatically and is taken from Olivet, Sichler, Thonon, Le Pichon, Martinais and Pautot (1970) following the *Charcot*-04 cruise. Between the Charlie Gibbs Fracture Zone and the basement ridges to the north, the soundings, although prolific on the *GEBCO* sounding sheets, do not allow a meaningful contour chart to be drawn owing to the poor quality of the data. The sharp bends in the mid-ocean canyon near 52°N, 46°W are well controlled by *Glomar Challenger* and *Vema* tracks and probably reflect changes in the regional depth associated with the buried western extension of the Charlie Gibbs Fracture Zone.

## THE BASEMENT STRUCTURE

Seismic reflection profiles have been obtained by various cruises of the Lamont-Doherty Geological Observatory (*Vema*-17, 23 and 27), by the C.N.E.X.O. laboratory in France (*Charcot*-05), by U.S.N.O.O. (*Mariposa*) and by

[1] Since the names of Charlie and Gibbs for this feature have both become established in the literature and hence give rise to some confusion, it is suggested that they be coalesced in honor of a fictitious geomorphologist and that the feature be referred to as the Charlie Gibbs Fracture Zone.

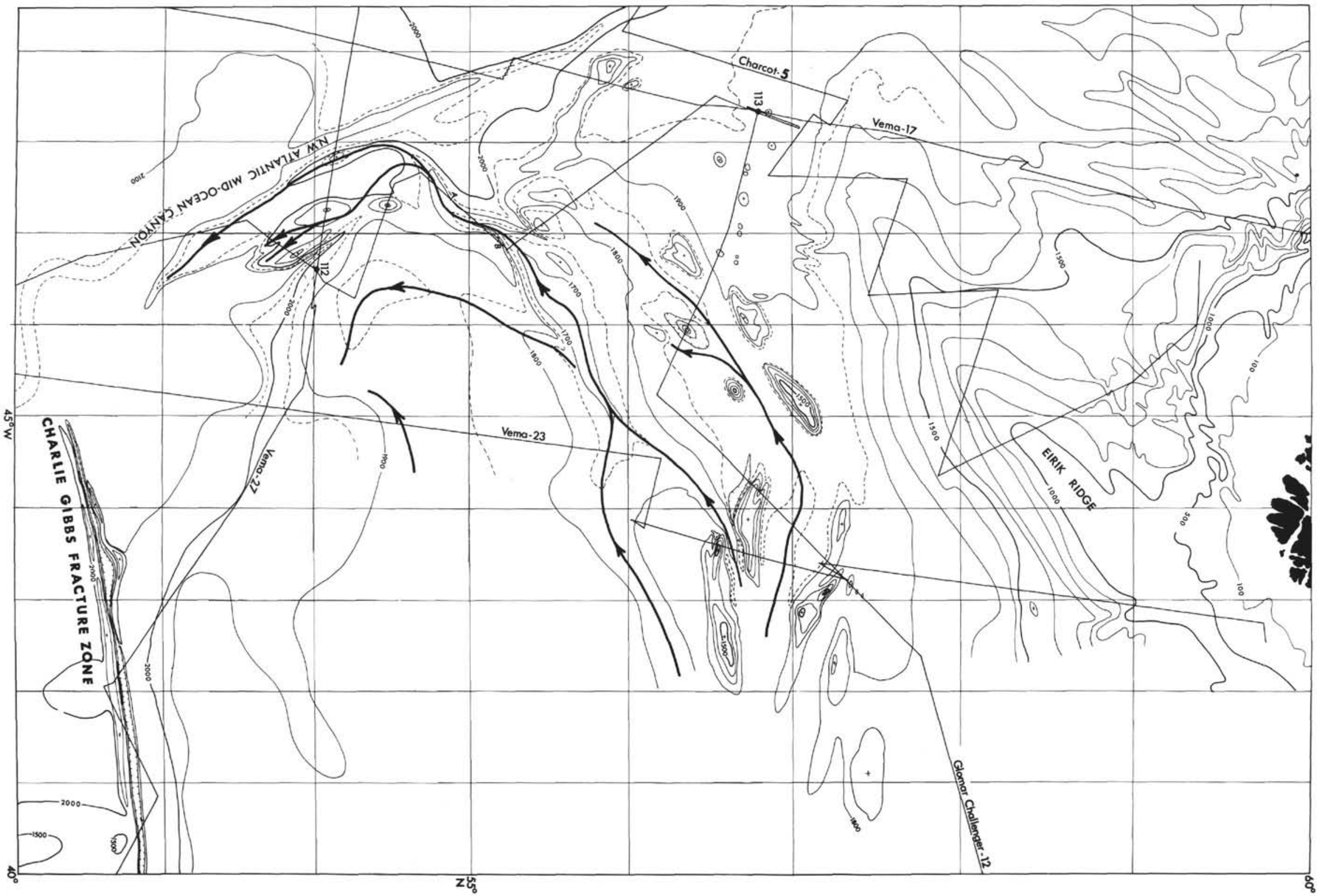



Figure 1. *Bathymetric chart of the southern Labrador Sea, based partly on Johnson, Vogt and Schneider (1971) and on new data. Contours in uncorrected fathoms (at 800 fm/sec) at 100 and 50 fathom intervals. Tracks with seismic reflection profiles are shown. Heavy lines with arrows denote axes of current controlled sediment ridges.*

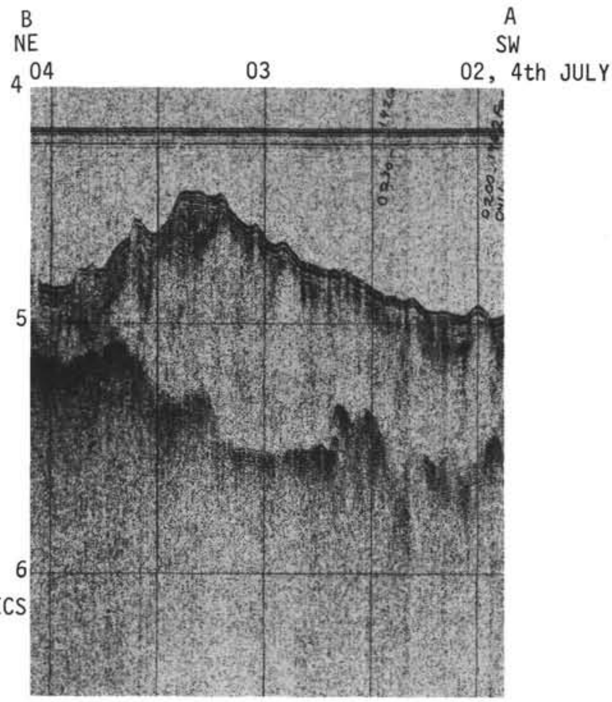



Figure 2. *Section across sediment ridge (by GC-12). Position of AB is shown on Figure 1.*

*Glomar Challenger*-12. Sediments 1000 to 2000 meters thick cover the basement over most of the Labrador Sea (Johnson, Closuit and Pew, 1969; Le Pichon, Hyndman and Pautot, 1971), except in the southeast where some basement ridges have not yet been covered. From these profiles and from the exposed basement ridges, it is possible to reconstruct the pattern of the basement topography for the southern Labrador Sea (Figure 3), and to recognize some of the typical features of sea floor spreading, that is, mid-ocean ridges, median valleys and transform faults. At 57°N, 48°W, Le Pichon *et al.* identified the buried median valley by the absence of reflectors (Eocene/Oligocene and Paleocene) found north and south of it, and by the disturbance of sediments in the rift. This position and orientation is consistent with the magnetic data in the area. Further east at 57°N, 43°W, two lines of basement ridges are separated by a sediment-filled valley, striking WNW-ESE (Figure 4). The magnetic survey data of Vogt, Avery, Schneider, Anderson and Bracey (1969) supports the interpretation that this is a median valley paralleled by magnetic anomalies. On this meridian, it is the only place between the Charlie Gibbs Fracture Zone and Cape Farewell where the basement topography suggests a spreading center (Figure 5a). Furthermore, the basement ridges to the north and south both appear to have been uplifted and tilted away from the axis, preserving a cover of about 0.2 second of sediment on their outer flanks.

Between the two sections of median valley mentioned above, which are not co-linear, lies a broad ridge complex striking NE-SW of which only the peaks can be seen above the sediment. The reflection profiles (Figure 6), however, show that the base of the ridge is some 70 kilometers wide, and that the correlation between the two *Glomar Challenger* profiles is reasonable. The ridge can best be interpreted as a fracture zone or transform fault offsetting the axis of the median valley. The strike of the transform fault is in general agreement with the pole of rotation of 62°N, 92°W for the last phase of opening of the Labrador Sea (Le Pichon *et al.*, 1971).

Under the Eirik Ridge, Le Pichon *et al.* located basement ridges which they interpreted as a transform fault (the Farewell Transform Fault), and have associated this with the first phase of opening of the Labrador Sea. Further south, they also associate the buried part of the Charlie Gibbs Fracture Zone between 45° and 47°W with this phase, and from these two features they compute the pole for the first phase of opening at 80°N, 90°W.

The remaining structural trend which has not been discussed so far is that west of Site 112. This lies approximately normal to the west end of the Charlie Gibbs Fracture Zone and is perhaps truncated by it. It is likely, therefore, that the ridges on this trend (Figures 5b and 7) are the remains of structures parallel to the spreading axis during the first phase of opening of the Labrador Sea. The magnetic analysis discussed later suggests that the ridges may in fact be the extinct spreading axis. Further NW, the ridge at 55.7°N, 48.5°W is parallel to the median valley to the north of it and probably belongs to the second phase of opening.

In summary, all the basement trends (except the more exposed part of the Charlie Gibbs Fracture Zone) mapped from the seismic profiles can be correlated with either the spreading axes or transform faults associated with the two phases of opening of the Labrador Sea. The Charlie Gibbs Fracture Zone east of 43°W is associated with spreading about the axis of the mid-Atlantic Ridge further east. The basement ridges form a semicircle open to the east and have in the past provided a barrier to deep-water circulation and associated sediment transport, as seen in the following section.

## THE SEDIMENTS

Seismic profiles have revealed two quite distinct sedimentation regimes in the area of the Southern Labrador Sea which are described and discussed in greater detail in Chapter 11 of this report.

### Deep Current Controlled Sediment Body

Within the semicircle of the basement ridges discussed above, there is a body of sediment believed to have been deposited under the influence of deep and near bottom currents. North-south and east-west crossings of the body are shown in Figure 5(a and b) from Lamont seismic profiles, and the borders were further investigated by *Glomar Challenger* crossings illustrated in Figures 4, 6 and 7. The sediment body contains a characteristic reflector which was shown by drilling at Site 112 to be Middle to Early Oligocene. The extent of the reflector is the shaded area in Figure 3 and is essentially confined by the basement ridges. The upper part of the sediment body covers the ridges and is identifiable out to the terrigenous sediments (stippled) which pinch out over it. It is not possible to follow it far beneath these sediments.

The sediment ridges found in this body of sediment are attributed to deposition from the margins of near-bottom

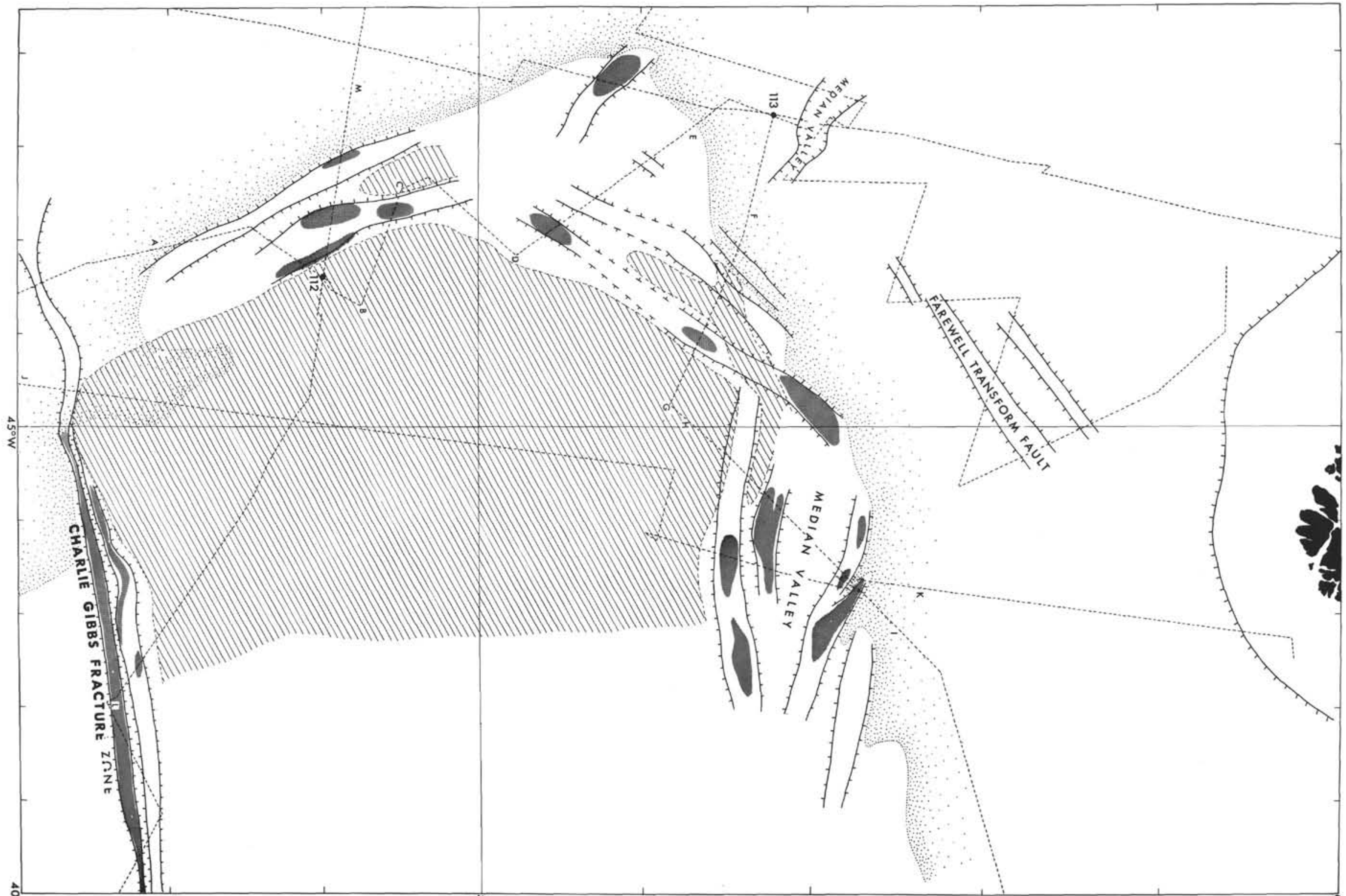



Figure 3. *Basement structure and sediment cover of the southern Labrador Sea derived from seismic reflection profiles and from bathymetry.*

| | | |
|---|---|---|
| *Ticked lines* | - | *basement scarps.* |
| *Dense hachure* | - | *basement exposures on sea floor.* |
| *Stippled boundary* | - | *contact between terrigenous sediments and bottom current controlled sediment body.* |
| *Light hachure* | - | *area of Oligocene mid-sediment reflector.* |

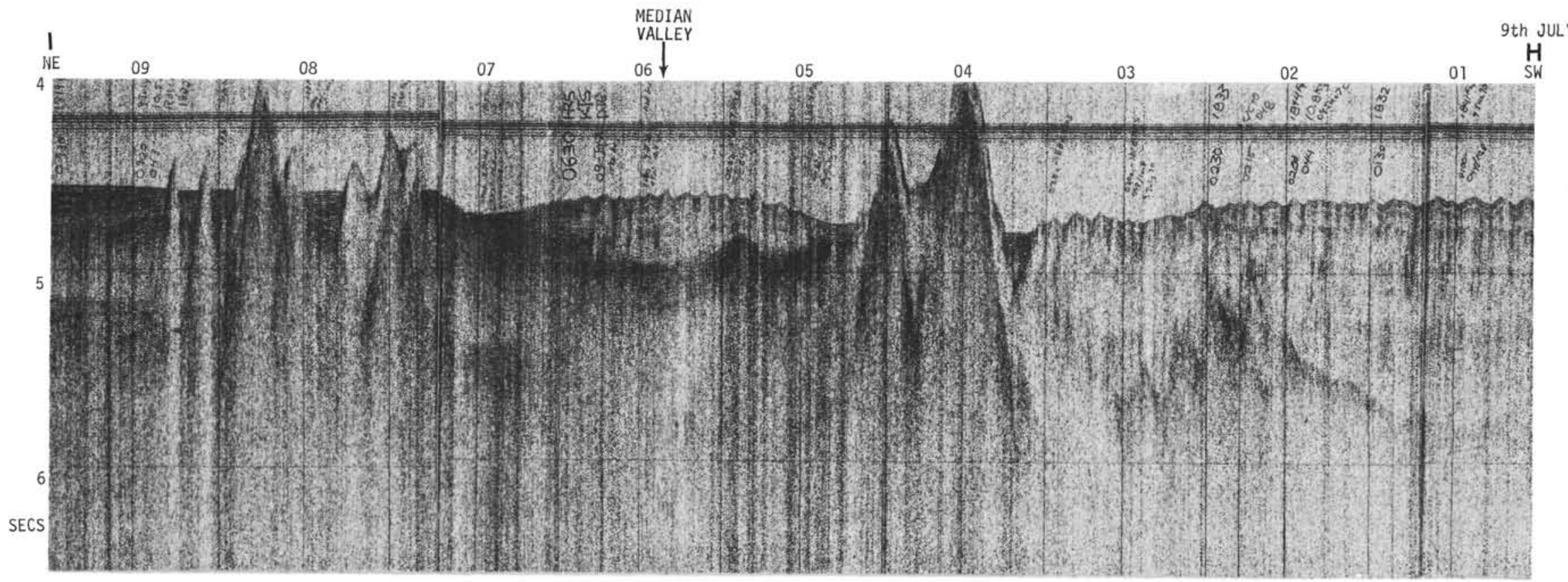



Figure 4. *Seismic profile HI (GC-12) across extinct mid-ocean ridge and median valley.*

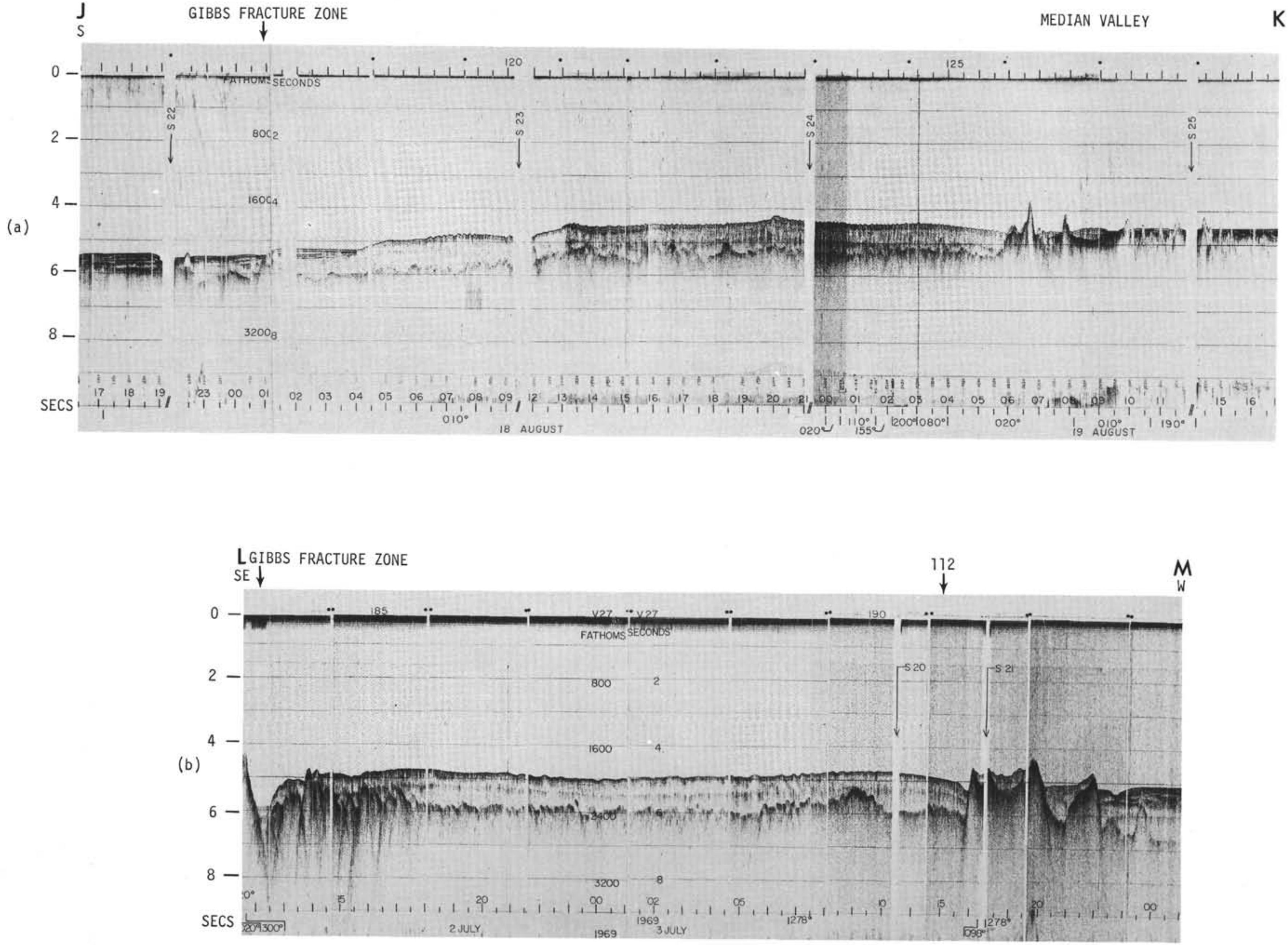
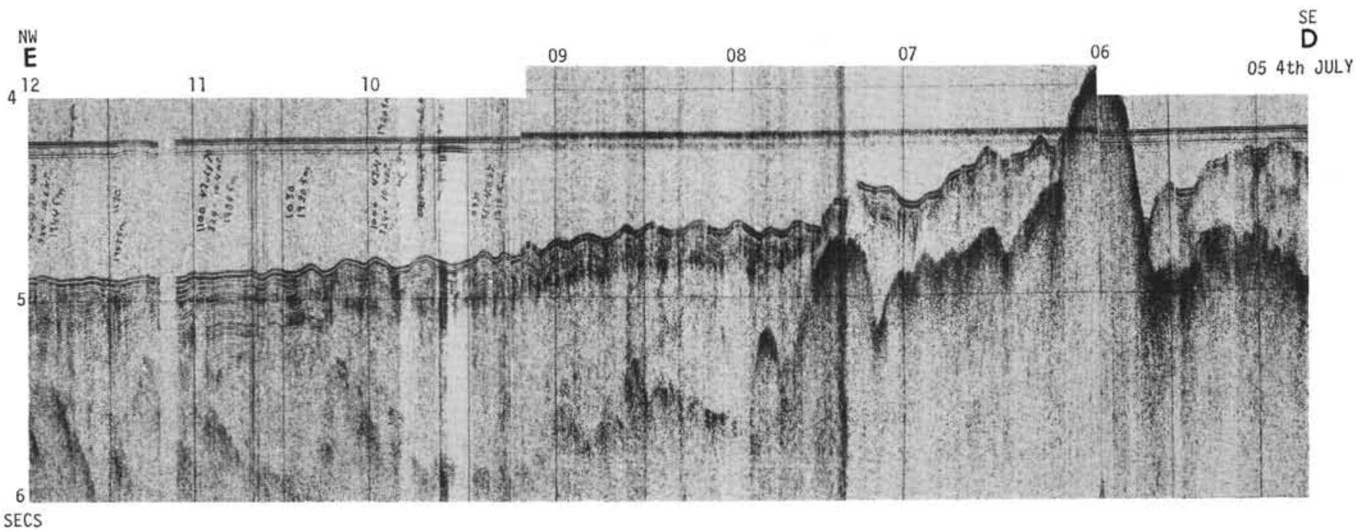



Figure 5. *(a) North-South seismic profile JK (*Vema-*23) across southern Labrador Sea, (b) East-West seismic profile LM (*Vema-*27) across southern Labrador Sea through Site 112 (by courtesy of Lamont-Doherty Geological Observatory).*



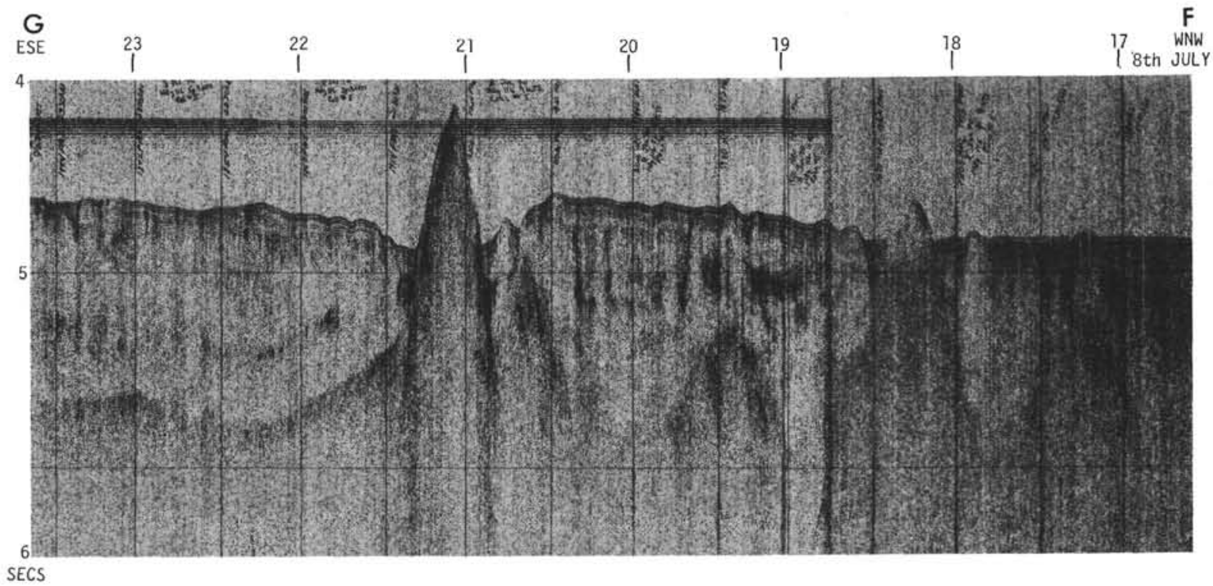




Figure 6. *(a) Seismic profile DE (GC-12) across fracture zone, (b) Seismic profile FG (GC-12) across fracture zone.*

currents. The evidence for this is presented in Chapter 11, and is based on the existence of marginal channels, moats and the wavy surface of the sediment. Sediment-laden Norwegian Sea overflow water travels southwest down the Iceland Basin and westwards through the Charlie Gibbs Fracture Zone (Johnson and Schneider, 1969; Jones *et al.*, 1970; Worthington and Volkmann, 1965; Garner, in press), and part of it appears to form an anticlockwise gyre some 500 kilometers in diameter circulating about a point at about 55°N, 43°W.

The lower part of the sediment sequence was laid down in conditions when the basement ridges were much more effective barriers to the deep circulation than they are at present. The oldest sediments inferred from the results of Hole 112 are Early Paleocene (65 million years), so that from then until the Early Oligocene at least, the sediments were accumulating in the area and were confined to the north, west and south.

From the magnetic data discussed in the next section it will be seen that the age of the sea floor underlying the sediment body increases westward from 50 million years at 43°W to about 60 million years, 70 kilometers west of Site 112, a spreading rate of about 1.3 cm/year. *Vema*-27 section through Site 112 does not however show a significant increase in sediment thickness towards the west (Figure 5b). This suggests that the sediment has not been accumulating at a uniform rate since the formation of the basement, but has been deposited mainly during the period

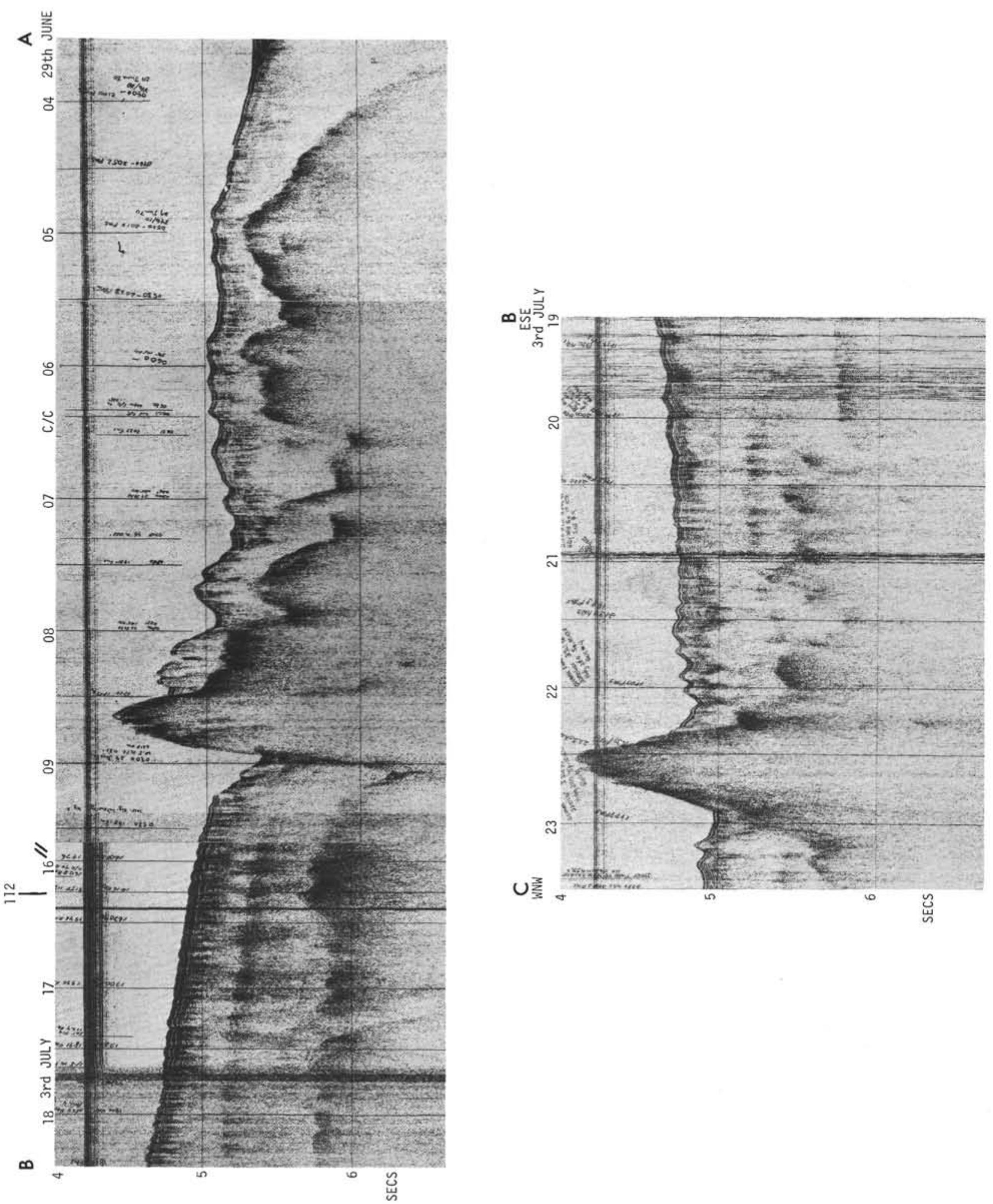



Figure 7. *(a) Seismic profile AB (GC-12) across late Cretaceous midocean ridge(?) through Site 112, (b) Seismic profile BC (GC-12) across part of late Cretaceous midocean ridge(?).*

after 50 million years. The north-south section of *Vema-23* (Figure 5a) is essentially along the 60 million year isochron. It is significant that the thickness of sediment beneath the Oligocene reflector is greater at the southern end (0.5 second) than at the northern end (0.2 second) indicating a higher sedimentation rate in the south in early Tertiary, due perhaps to the circulation pattern.

Some estimate of the age of the sea floor near the median valley can be made from the 0.5-second thickness of sediment underlying the Oligocene reflector just south of the bordering ridges, seen on *Glomar Challenger*-12 record at 0330/9th July (Figure 4). A 0.5-second sediment is equivalent to 450 meters (at 1.8 km/sec); at a sedimentation rate of 2.5 cm/1000 years this represents 18 million years, making an age of basement of 53 million years, the age suggested by the magnetic Anomaly 21 believed to run through the same place. The sedimentation rate assumed is about twice that found at the base of Hole 112, but this may be a consequence of sediments deposited from currents banked up against the median valley ridges.

In a later section of this chapter, paleogeographic reconstructions of the North Atlantic are made based on the isochrons determined from magnetic anomalies. It is instructive to consider the palogeography (Figure 8) during the middle Oligocene when the mid-sediment reflector was deposited (that is, 35 million years or Anomaly 12). Banked up against the eastern flank of the Reykjanes Ridge is the contour current deposited Gardar Ridge (Johnson and Schneider, 1969). The western boundary of this coincides approximately with Anomaly 12 and an associated steep scarp in the subbottom topography. Two profiles by *Vema*-27 across the Gardar Ridge and two just north of the Charlie Gibbs Fracture Zone at 27° and 30°W show a sediment body with a mid-sediment reflector similar in character to that in the Southern Labrador Sea (Figure 9). This similarity and the proximity, on an Oligocene reconstruction of the North Atlantic, of the areas where it has been seen, suggests that it is also mid-Oligocene and that up to this time the sediments in the Southern Labrador Sea were connected to the southern end of the Gardar Ridge. It is possible that prior to the mid-Oligocene the Reykjanes Ridge was a much less pronounced feature (Iceland is believed to be not more than 20 million years old), and that the early Gardar Ridge may have spilled over into the eastern side. At this time there were many E-W fracture zones crossing the ridge (Vogt *et al.*, 1969) providing easy routes.

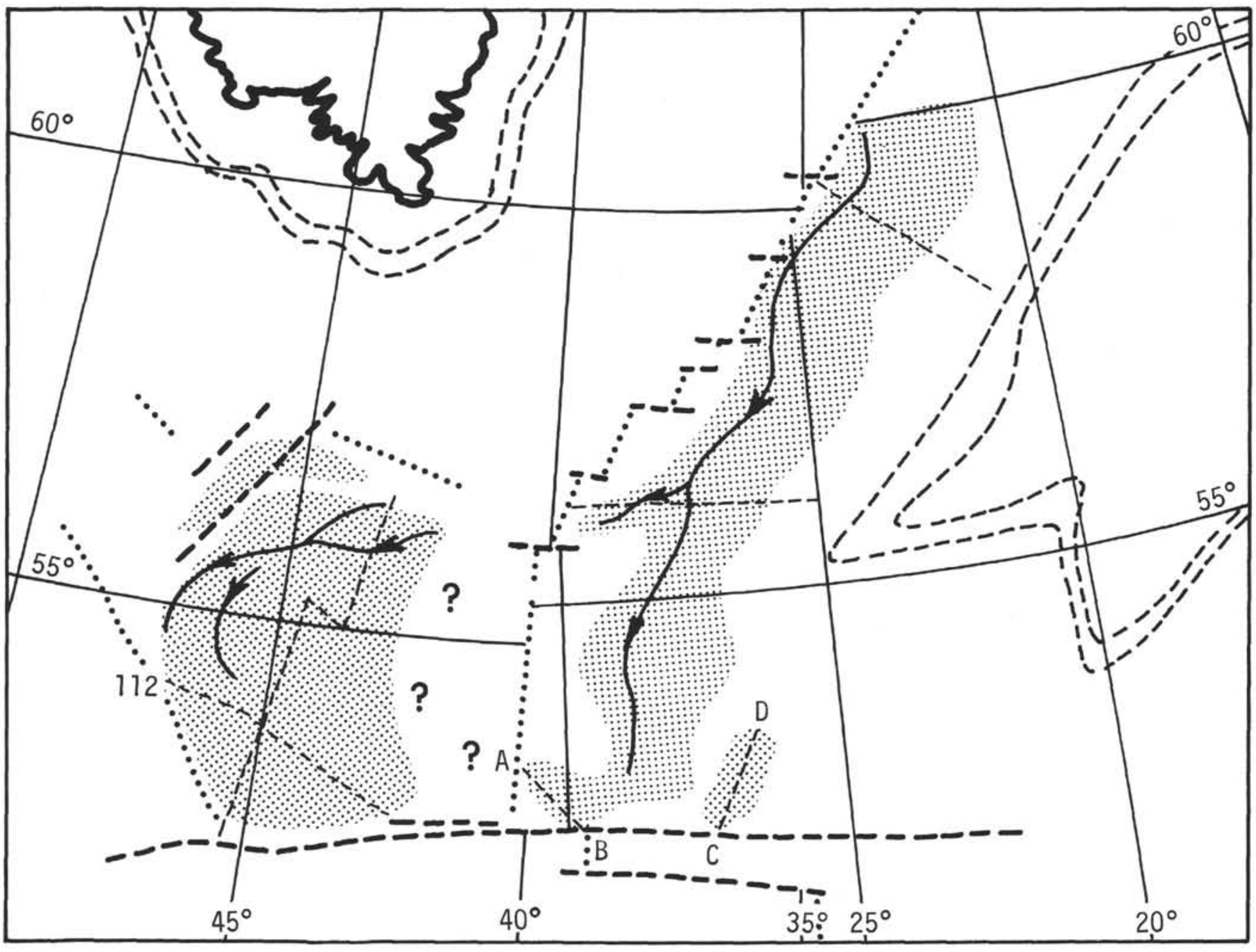



Figure 8. *Paleogeographic reconstruction of the North Atlantic at Anomaly 12 (35 my-Oligocene) showing proximity between southern end of Gardar Ridge (east of the spreading axis) and the sediment body in the Southern Labrador Sea. Areas believed to have Oligocene mid-sediment reflector shown stippled.*

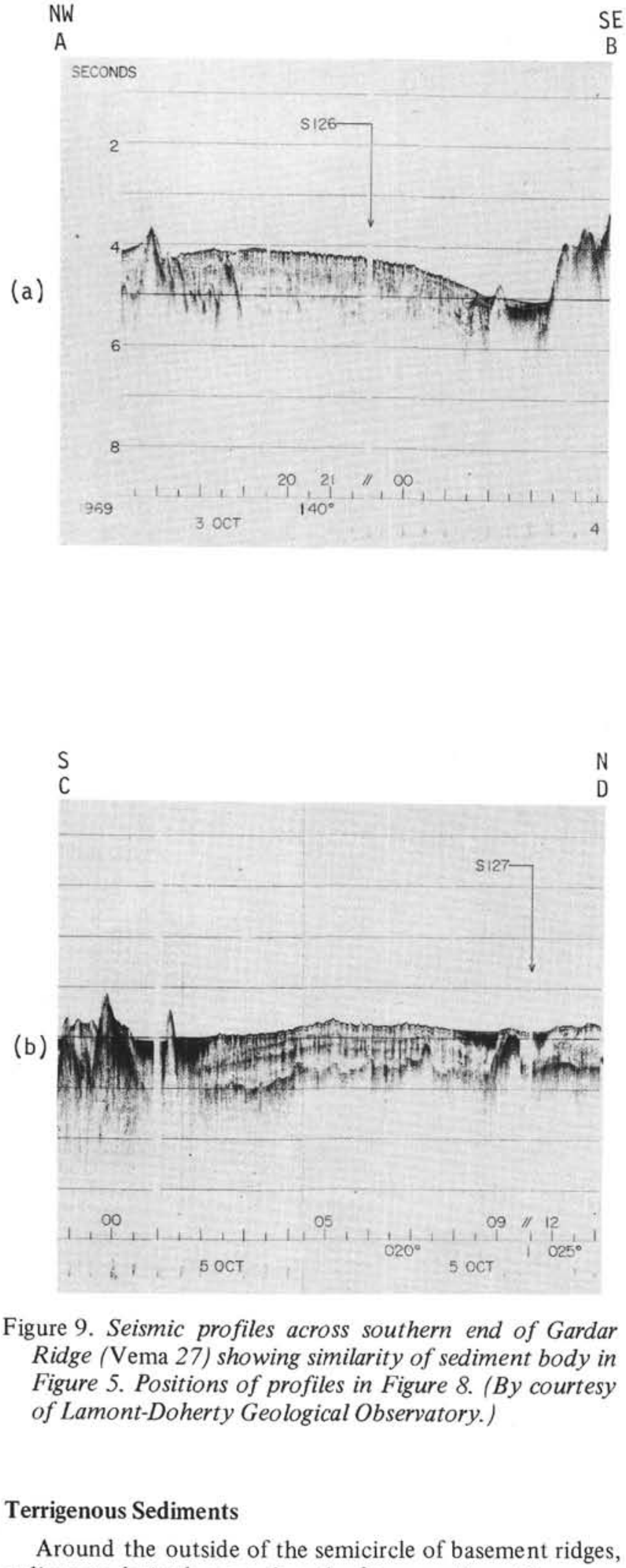



Figure 9. *Seismic profiles across southern end of Gardar Ridge (*Vema *27) showing similarity of sediment body in Figure 5. Positions of profiles in Figure 8. (By courtesy of Lamont-Doherty Geological Observatory.)*

### Terrigenous Sediments

Around the outside of the semicircle of basement ridges, sediments derived more directly from continental sources and transported by turbidity currents have been deposited lapping onto and over the sediment body discussed above.

The boundary between these terrigenous sediments and the bottom current deposited sediments can be easily seen on seismic profiles and echo-sounding records, and is plotted in Figure 3 as a stippled boundary.

These sediments were sampled at Site 113 which showed extremely high sedimentation rates (10-20 cm/1000 yrs), and the hole penetrated only to the Miocene at 923 meters. However, some reworked Oligocene and Eocene pelagic sediments were found in a matrix of Pliocene clay and were interpreted as having come from nearby hills thought to have been uplifted in Oligocene times (Chapter 5). Such tectonic activity may be related to the absence in the central region of the Labrador Sea of an otherwise widespread reflector R (Eocene/Oligocene) discussed by Le Pichon *et al.* (1971).

## MAGNETIC ANOMALY FIELD

Magnetic data in the Labrador Sea have been obtained by air (Godby, Baker, Bower and Hood, 1966), by miscellaneous ships on irregular tracks (Manchester, 1964; Mayhew, 1969; Mayhew, Drake and Nafe, 1970; Le Pichon *et al.*, 1971) and by sea survey (Johnson, Closuit and Pew, 1969; Avery, Vogt and Higgs, 1969; Vogt, Avery, Schneider, Anderson and Bracey, 1969). The data reveals the existence of a symmetrical pattern of anomalies trending NW-SE in the central Labrador Sea, and trending E-W south of Cape Farewell (Figure 10). The pattern is offset by two fracture zones trending NE-SW. The axis of symmetry is magnetically smooth but two groups of high amplitude anomalies (500 gamma peak-to-peak) lie halfway between the axis and the continental slope. To the south of Cape Farewell the southerly group of these anomalies bends sharply southwards parallel to the axis of the mid-Atlantic Ridge. At 52.5°N they are offset eastwards by the Charlie Gibbs Fracture Zone.

An analysis of the magnetic anomaly pattern of the whole North Atlantic by Vogt *et al.* (1969), taken together with other available geological and geophysical evidence, suggests that the ridge axes have occupied three positions north of 53°N, corresponding to three stages of spreading:

(1) Rockall Trough, separating Rockall Plateau from NW Europe.

(2) Labrador Sea, separating Greenland from NE Canada.

(3) Reykjanes Ridge, separating Greenland from Rockall Plateau.

Stages (1) and (2) may have been contemporaneous but stage (3) is well documented to have occurred later during the last 60 million years. Between 40° and 53°N, Europe and the continental shelf off Newfoundland were at one time contiguous (Bullard, Everett and Smith, 1965) and started to separate probably at the same time as stages (1) and (2). The almost complete absence of earthquake activity in the Labrador Sea (Barazangi and Dorman, 1969) implies that it has virtually ceased spreading. (A few earthquakes, however, reported by Godby *et al.*, (1966) show some residual activity on the axis of the median valley.)

The interpretation of the tectonic history of the Labrador Sea depends critically on the correct age identification of the linear magnetic anomalies found, and of the age of the axis. The period of spreading has been variously estimated as 77 to 65 million years ago (Mayhew, 1969) to 165 to 20 million years (Johnson, Vogt and Schneider, 1971),

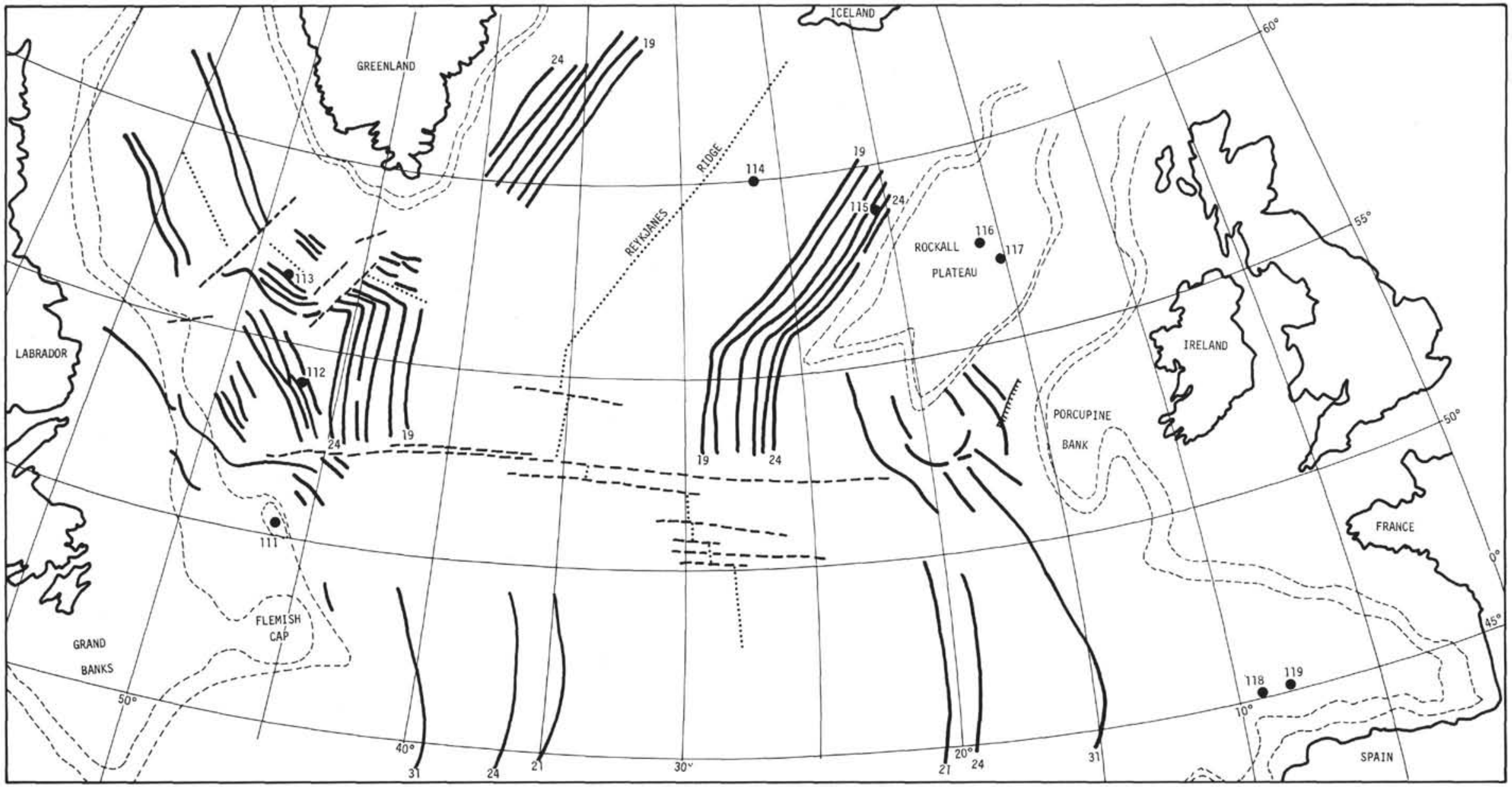



Figure 10. *Magnetic anomaly trends in the North Atlantic. Top and bottom of continental slope shown by dashed lines. Positive magnetic anomalies from number 19 and older shown by solid lines. Heavy dashed lines are fracture zones. Dotted line shows present and extinct spreading axes.*

depending on anomaly identification and on the dating of tectonic activity on the neighboring continental margins. Johnson *et al.* identify the high amplitude anomalies as numbers 20 to 24 (49 to 60 million years). They suggest that between the Jurassic (when dikes in Greenland are associated with initial rifting) and Anomaly 24 (60 million years), two-thirds of the Labrador Sea opened without any separation of Rockall Plateau and Greenland. However in a later paper (Johnson and Vogt, in press), these authors state that although initial rifting was as old as the Jurassic, very little of the sea floor was created prior to 60 million years ago. Between Anomaly 24 and 18 (60 to 45 million years), spreading in the Labrador Sea continued but with an additional break between Greenland and Rockall giving rise to a triple junction southeast of Cape Farewell. After Anomaly 18 (45 million years), spreading in the Labrador Sea nearly stopped and the major axis of the mid-Atlantic Ridge continued northward to the Reykjanes Ridge. Slow spreading continued in the Labrador Sea until Anomaly 6 (20 million years).

Le Pichon *et al.* (1971) arrive at a similar sequence of events, although they propose that the opening was initiated in the late Cretaceous and not the Jurassic. They list the following events in the development of the North Atlantic and Labrador Sea:

(1) Before Anomaly 32 (76 my) there was an opening between Rockall and Europe.

(2) Between Anomalies 32 and 24 (76 to 60 my), the first two-thirds of the Labrador Sea was created.

(3) Between Anomalies 24 and 20 (60 to 49 my), there was a triple point junction in the North Atlantic with spreading in the Labrador Sea, in the newly formed Reykjanes Ridge and along the extinct ridge in the Norwegian Sea.

(4) After Anomaly 20 (49 my), the Labrador Sea opening nearly stopped, and Mohn's Ridge in the Norwegian Sea started.

For phase (2), the spreading rate in the southern Labrador Sea between Greenland and Labrador is 0.8 cm/year (8.9° about a pole at 80°N, 90°W) and for phase (3) 0.5 cm/year (9.2° about a pole at 61°N, 92°W). Small circles about these two poles correspond to the Farewell Transform Fault and the western end of the Gibbs Fracture Zone on the one hand, and the transform fault at 56.5°N, 46°W on the other.

The magnetic anomaly pattern in the Southern Labrador Sea (Figure 11) reflects these two phases of opening. North of the line from 55°N, 49°W to 56°N, 42°W (dot-dash in Figure 11) the contours are those of Vogt *et al.* (1969), modified by the additional tracks shown. South of this line the area is newly contoured based on the tracks indicated. Between 42° and 45°W, north-south anomalies can be correlated with fair certainty and can be matched with a simulated anomaly pattern for Anomalies 18 to 24 (Heirtzler, Dickson, Herron, Pitman and Le Pichon, 1968) with a spreading rate of 1.3 cm/yr parallel to the Charlie Gibbs Fracture Zone (Figure 12). Some dislocation of this pattern may however be present along the heavy dashed line in Figure 11, which is a westward continuation (parallel to the Charlie Gibbs Fracture Zone) of the fracture zone crossing the mid-Atlantic Ridge at 53.5°N (Johnson, 1967).

West of 45°W, the magnetic anomaly pattern trends NW-SE parallel to the basement ridges near Site 112. The correlations in this area are less certain than the N-S ones, but the trend is clear, and continues to the northwest into the area of better mapped anomalies in the Labrador Sea. In the immediate vicinity of Site 112, the lack of continuity may be the result of the possible fracture zone there. The same NW-SE trend is repeated toward the southwest as far as the continental margin. Further evidence for a change of pattern west of Anomaly 24 comes from the absence on the projected profiles in Figure 12, of Anomalies 25 and 26.

A triangular area centered on 55°N, 46°W, in which there is no data, is enclosed by the three prominent trends. In order to interpret the changes of trend and to relate the magnetic anomalies with the age of basement deduced from Hole 112, it is necessary to reconstruct the North Atlantic into the configuration appropriate for the Lower Tertiary and Upper Mesozoic.

## PALEOGEOGRAPHY OF THE NORTH ATLANTIC

A stage by stage closing up of the northern part of the North Atlantic (Laughton, 1971) can now be made with some certainty following the areas of well-mapped magnetic anomaly pattern and the fracture zones (Figure 10). The magnetic anomalies of the outer parts of the Reykjanes Ridge were mapped by Godby, Hood and Bower (1968), and identifications with respect to the Heirtzler time scale can be made by relating these with the more closely mapped anomalies near Rockall Plateau (Avery, Vogt and Higgs, 1969). South of Rockall Plateau, anomaly trends have been mapped by Avery *et al.*, and by Williams and McKenzie (1971). Anomaly identifications south of 50°N are by Pitman and Talwani, (in press) and Williams and McKenzie (1971), and for the purposes of this paper are guidelines to the opening south of the group of fracture zones between 50° and 53°N. The source of magnetic data for the Labrador Sea has already been discussed, except for the anomalies near the western end of the Charlie Gibbs Fracture Zone which have been derived from Fenwick, Keen, Keen and Lambert (1968), supplemented by additional data kindly supplied by the U.S.N.O.O. Magnetic data younger than Anomaly 19 has not been presented here.

The principal fracture zone controlling the North Atlantic opening is the Charlie Gibbs Fracture Zone. In the central region, this has been well mapped by Fleming, Cherkis and Heirtzler (1970), at the western end by Olivet *et al.* (1970, in press), and at the eastern end by the National Institute of Oceanography (Roberts, personal communication) and the U.S.N.O.O. South of this are numerous fracture zones offsetting the ridge axis to 28°W, indicated by earthquake epicenters and contoured by N.I.O. For the purposes of closing up the Atlantic these have been lumped together as one extra fracture zone at 50°N. The fracture zones in the Labrador Sea have already been discussed above.

Figure 10 shows the symmetry of magnetic Anomalies 19 through 24 about the mid-Atlantic Ridge between 53 and 56°N, confirming the identification of the N-S anomalies south of Greenland. On the assumption that the Greenland and Labrador plates have not moved appreciably

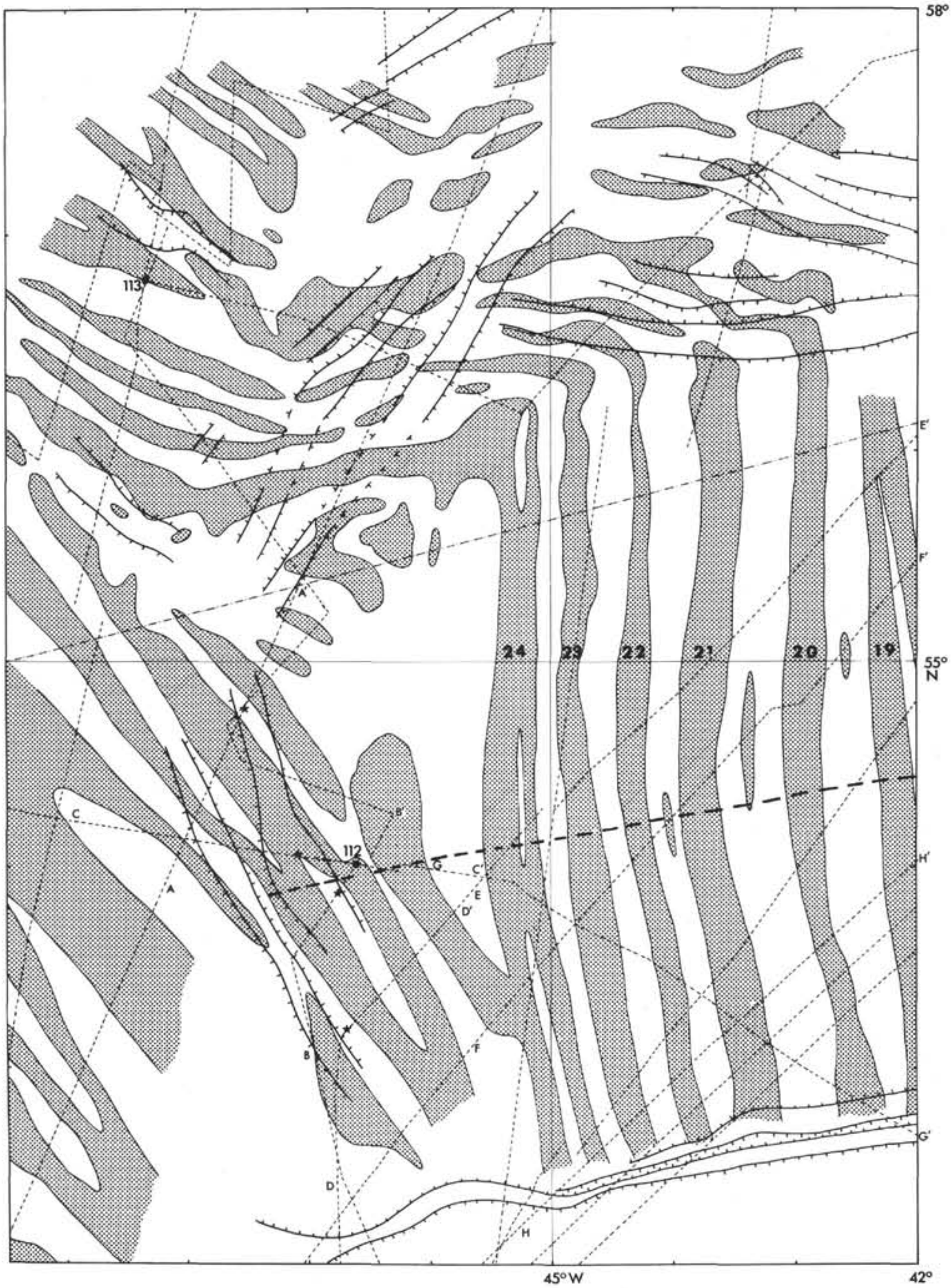



Figure 11. *Magnetic anomaly chart of Southern Labrador Sea. North of dot-dash line, data modified from Vogt* et al. *(1969). South of this, control by tracks shown. Shaded area is positive.*

relative to one another since Anomaly 19 (47 million years), the European plate can be closed into the Labrador-Greenland plate using the Charlie Gibbs Fracture Zone as a control guide to give the 47 million year (Middle Eocene) paleogeography (Figure 13). A good fit of Anomaly 19 is obtained. A consequence of the immobility of Labrador-Greenland plate boundary after 47 million years is that the median valley south of Cape Farewell should not extend further east than 41.5°W, a result that can be tested by further survey.

Prior to 47 million years, it is necessary to close Greenland and Labrador along the lines indicated by the fracture zones offsetting the mid-Labrador Sea Ridge axis. The Anomaly 24 or 60 million year (Paleocene) paleogeography is shown in Figure 14, which differs slightly from that presented by Vogt *et al.* (1969) in the greater counter-clockwise rotation of the European plate. It is interesting to note that Rockall Plateau is not close up against the continental slope of Greenland at this time although Anomaly 24 is very close to Rockall Plateau. The original Greenland

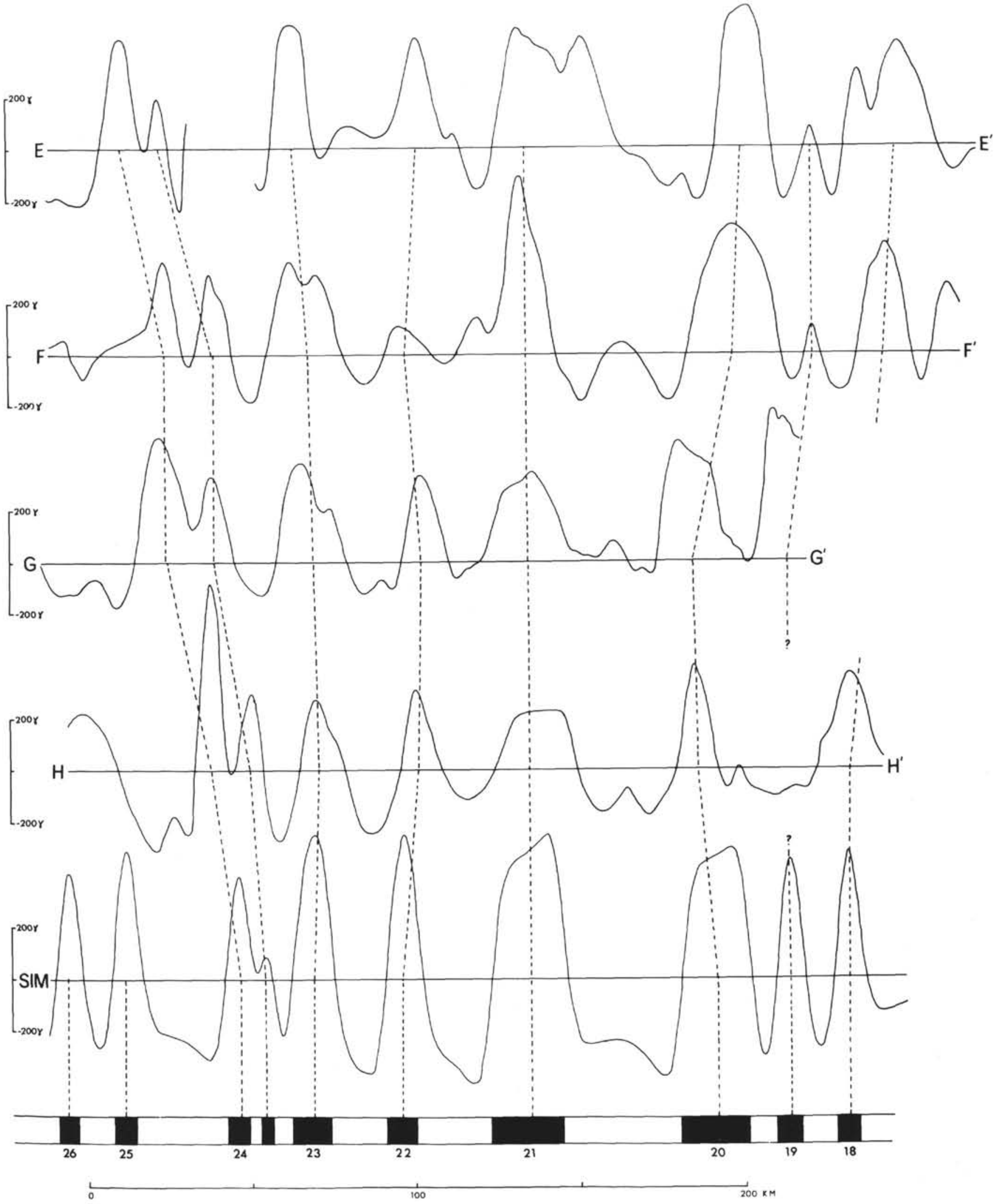



Figure 12. *Magnetic anomalies along tracks EE′, FF′, GG′ and HH′ (cf. Figure 11) projected perpendicular to anomaly trend 170°, compared with simulated anomaly using Heirtzler* et al. *(1968) time scale for Anomalies 18 to 26. (Magnetized layer 4.5 to 6.5 kilometers below sea level; effective susceptibility ±0.01 cgs units; black blocks normally magnetized. Spreading rate of 1.26 cm/yr.).*


Figure 13. *Paleogeographic reconstruction at Anomaly 19 (47 my - Middle Eocene).*


Figure 14. *Paleogeographic reconstruction at Anomaly 24 (60 my- Paleocene). Thin dashed lines show possible small circles of transform faults, and dotted line shows spreading axes prior to 60 my.*

continental margin may, perhaps, have been downwarped, following the break away of Rockall Plateau, or else an Upper Cretaceous geosynclinal sedimentary basin may have existed. Alternatively, the position of the spreading axis may have moved from the center to the eastern side of the Paleocene Iceland Basin at this or an earlier time. In the central Labrador Sea, the two prominent magnetic anomalies are apparently older than 60 million years.

At 60 million years, the entire anomaly pattern changed as a result of the separation of the European plate from Greenland. Prior to this time, the opening followed two plate geometry. All magnetic anomalies older than 60 million years have a trend more NW-SE than those of 60 million years and younger. These trends were directed parallel to the Labrador continental margin and approximately parallel to that of the Greenland-European plate margin. Most prominent amongst these trends are those in the vicinity of Site 112 which are now median to the Paleocene ocean, and offset from the Central Labrador Sea anomalies by the Farewell Transform Fault and its counterpart on the Labrador margin (Le Pichon *et al.*, 1971). This transform fault may be part of the line of weakness continuing northeast into the region between Rockall Plateau and Greenland which subsequently split to give the Reykjanes Ridge. A parallel fault may be responsible for the E-W scarp of the southwest end of Rockall Plateau. It is suggested that the anomalies near Site 112 and the associated basement ridges are in fact part of the fossil ridge axis resulting from the final phases of the pre-Paleocene spreading before a shift of stress pattern beneath the plates. The initiation of spreading between Rockall Plateau and Greenland profoundly modified the geometry by the introduction of a triple junction and switched the spreading axis near Site 112 from NW-SE to N-S.

If such a theory is correct, the age of the sea floor near Site 112 should increase towards the northeast, up to the angle of Anomaly 24, and the magnetic anomaly pattern across the ridge should be symmetrical. Some profiles, projected at right angles to the ridge are presented in Figure 15. Some crude symmetry can be seen about an axis between two positive peaks. Only profile AA′ by *Hudson* 24-65 is long enough without course alterations to test the symmetry in detail beyond the positive peaks. The symmetry axes are indicated in Figure 11 by stars, and it will be seen that these do not lie in a straight line along the ridge. Either the detailed contouring of the ridge (both by basement topography and by anomaly) is wrong or there are undetected fracture zones offsetting the old axis. The track spacing is inadequate to resolve these possibilities.

The basement age at Site 112 is believed from the drilling results to be about 65 million years, that is, about Anomaly 26. However, the profiles are not long enough to compare model with the observed profiles to test this age. The absence of large anomalies to the northeast of 112 agrees with the suggestion that the positive peak near the site is Anomaly 26, in which case, the central negative anomaly would be at 64 million years. But the basement age of Site 112 is based on an extrapolation back in time from 50 to 55 million years, the age of the oldest sampled sediments, using a constant sedimentation rate of 1.5 cm/1000 yrs (Chapter 4). The basement is however unlikely to be younger than 60 million years (Anomaly 24) but could be as old as 70 million years based on a sedimentation rate of 0.8 cm/100 yrs. But it is most likely that the switch of spreading axis took place during the period 64 to 60 million years.

If the western end of the Charlie Gibbs Fracture Zone is another transform fault, as suggested by Le Pichon *et al.* (1971), the pre-Paleocene spreading center south of it will be further east. The eastward end of this transform fault might be found in the southeastern margin of Rockall Plateau and the anomalies perpendicular to this may be parallel to this spreading center. A second, and parallel, fracture zone may be linked to the south end of the Jean Charcot Fault (Le Pichon, Cressard, Mascle, Pautot and Sichler, 1969) in Rockall Trough. The suggestion that the south end of Rockall Trough has resulted from NE-SW transform faults bounding NW-SE magnetic anomalies is contrary to previous ideas that a spreading axis lay parallel to the Rockall Trough, and the absence of anomalies further northeast may be related to an earlier quiet zone (for example, Vogt, Anderson, Bracey and Schneider, 1970). However, if the trough is floored by oceanic crust, the central and northern parts must have spread about an axis parallel to the trough in the manner discussed later.

Using (a) the two suggested transform faults, and (b) the position of spreading centers (i) in the central Labrador Sea in the same position as after 60 million years, (ii) in the southern Labrador Sea on the ridge near Site 112 and (iii) in the Atlantic on a median line between Anomalies 31 on either side, a tentative reconstruction (Figure 16) can be made for Anomaly 31 (72 million years, or Late Senonian; see Cretaceous geochronology in Chapter 2). The continuity of Anomaly 31 south of Rockall Plateau (Williams and McKenzie, 1971) suggests that the transform faults between 50° and 53°N did not exist at this time, and that the spreading axis was therefore inclined to the 60 million year spreading axis. The change from a continuous spreading axis to one interrupted by transform faults probably took place during the development of the triple junction 60 million years ago, and is reflected in the change of orientation of the magnetic anomalies immediately south of the eastern end of the Charlie Gibbs Fracture Zone.

Prior to 72 million years ago, there are inadequate mapped magnetic anomalies to use this method of reconstruction. Williams and McKenzie (1971) have plotted the negative anomaly between 31 and 32, and have shown it to be continuous in the eastern Atlantic from 53°N to 40°N. From their profiles the position of Anomaly 32 can be inferred to lie at the foot of the continental slope southwest of Porcupine Bank. A prominent anomaly northwest of Flemish Cap may also be Anomaly 32. Assuming these identifications to be correct and assuming the same pole of rotation that obtained for Anomalies 31 to 24, a reconstruction for Anomaly 32 (78 million years – Early Senonian) can be drawn (Figure 17). The Labrador Sea is virtually closed up, (although there is little control on the amount of closure during this period), Rockall Plateau and Porcupine Bank lie against the Labrador continental margin and Flemish Cap, respectively. According to Le Pichon *et al.* (1971), the Bay of Biscay had already opened by the Late Cretaceous, so at this stage Spain was already remote from the Grand Banks off Newfoundland.

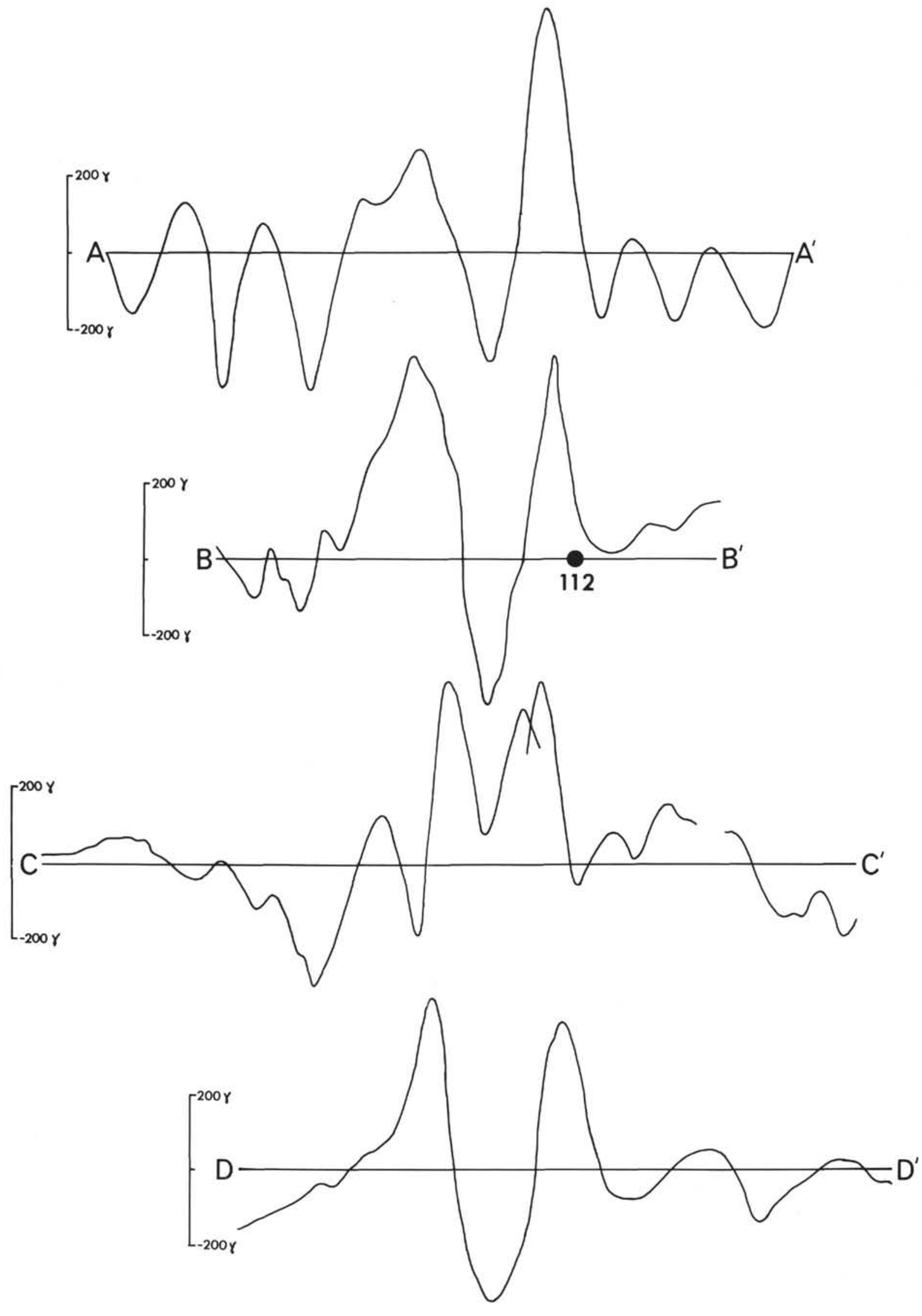



Figure 15. *Magnetic anomaly profiles AA′, BB′, CC′ and DD′ (cf. Figure 11) across ridge near Site 112 projected perpendicular to trend 330°.*

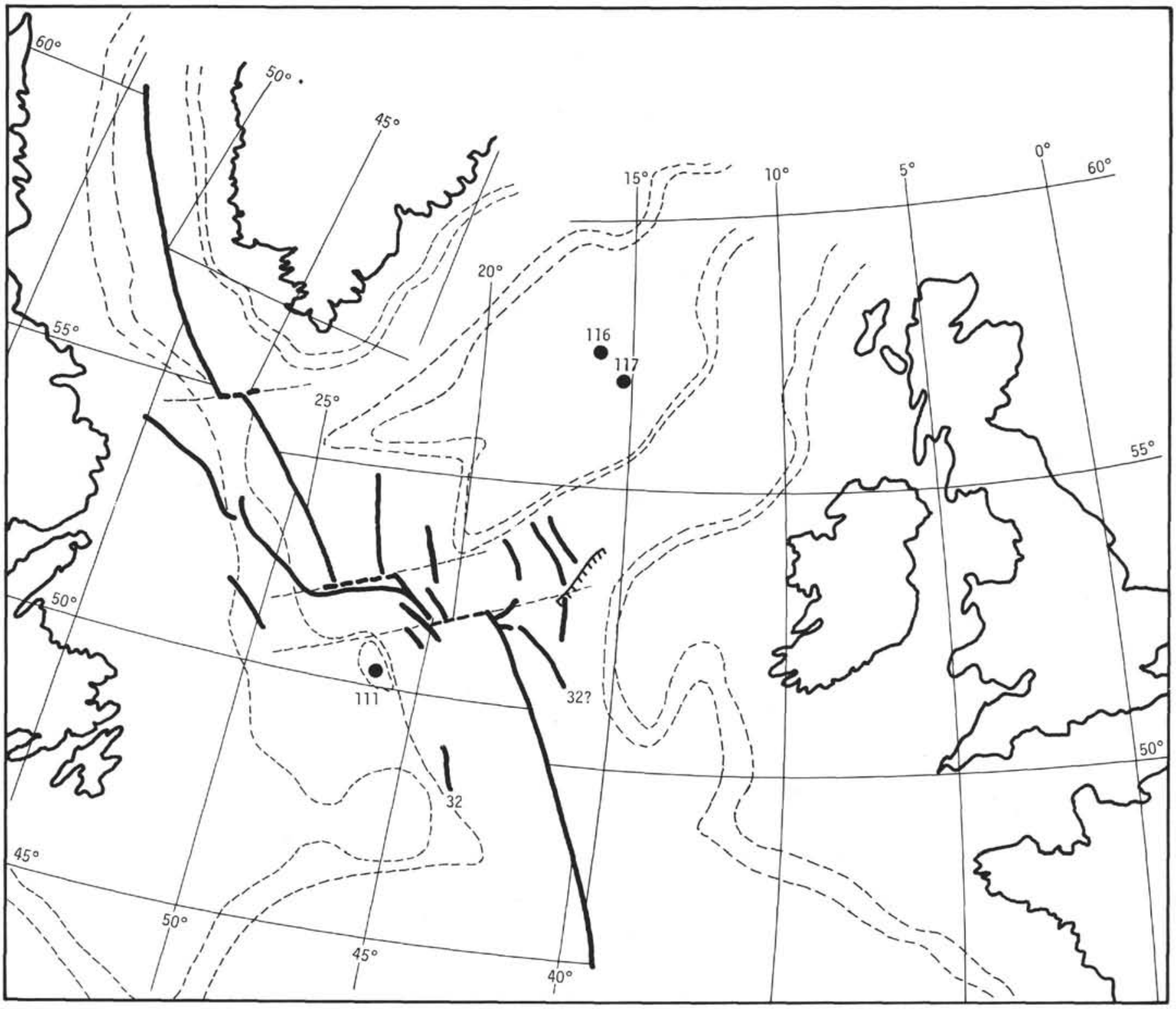



Figure 16. *Paleogeographic reconstruction at Anomaly 31 (72 my - Late Senonian). Ticked line is Jean Charcot Fault (Le Pichon* et al., *1969).*

Le Pichon *et al.* (1971) believe that the rotation of Spain away from the continental margin southwest of Great Britain was about a rotation pole near Paris, in contrast with earlier ideas that the pole was in the Aquitaine area. Reversing this rotation places Spain 350 kilometers further northwest than was suggested by Bullard *et al.* (1965), in the position shown in Figure 18. They suggest that the opening movement was initiated at the end of the Jurassic (150 million years ago), that is, some 30 million years after the initial separation of Africa and North America, and lasted until the Late Cretaceous (80 million years).

Holes 118 and 119 (Chapter 10) in the Bay of Biscay did not reach sediments older than Paleocene, but a considerable thickness of sediments lay below this horizon and the lowest of these are probably at least as old as Early Cretaceous (Sibuet, Pautot and Le Pichon, 1971). In the surrounding areas, a post-Triassic and pre-Cretaceous distension has been recognized on land and has been related to the initial stages of the opening of Biscay. A later compressive phase lasting from the Upper Cretaceous to the Present has moved Spain northwards and caused the Biscay sea floor to be overridden, the north Spanish trough to be formed and the Pyrenees to be uplifted. A major episode of this compression was recognized in Holes 118 and 119 in the Late Eocene uplift. A volume containing papers about the history of the Bay of Biscay resulted from a meeting on the subject in Paris in 1970 (Debyser *et al.*, 1971).

The closure of the Bay of Biscay gives the relative positions of the Iberian and European plates in the Late Jurassic (150 million years), but in Figure 18 the relative positions of the European and North American plates has been left unchanged from the Late Cretaceous (78 million years) position of Figure 17. It can be seen that the primitive Iceland Basin, Rockall Trough and some ocean floor between Spain and the Grand Banks remains. There is little evidence to say whether the primitive Iceland Basin and Rockall Trough are in fact floored by oceanic rocks and, if

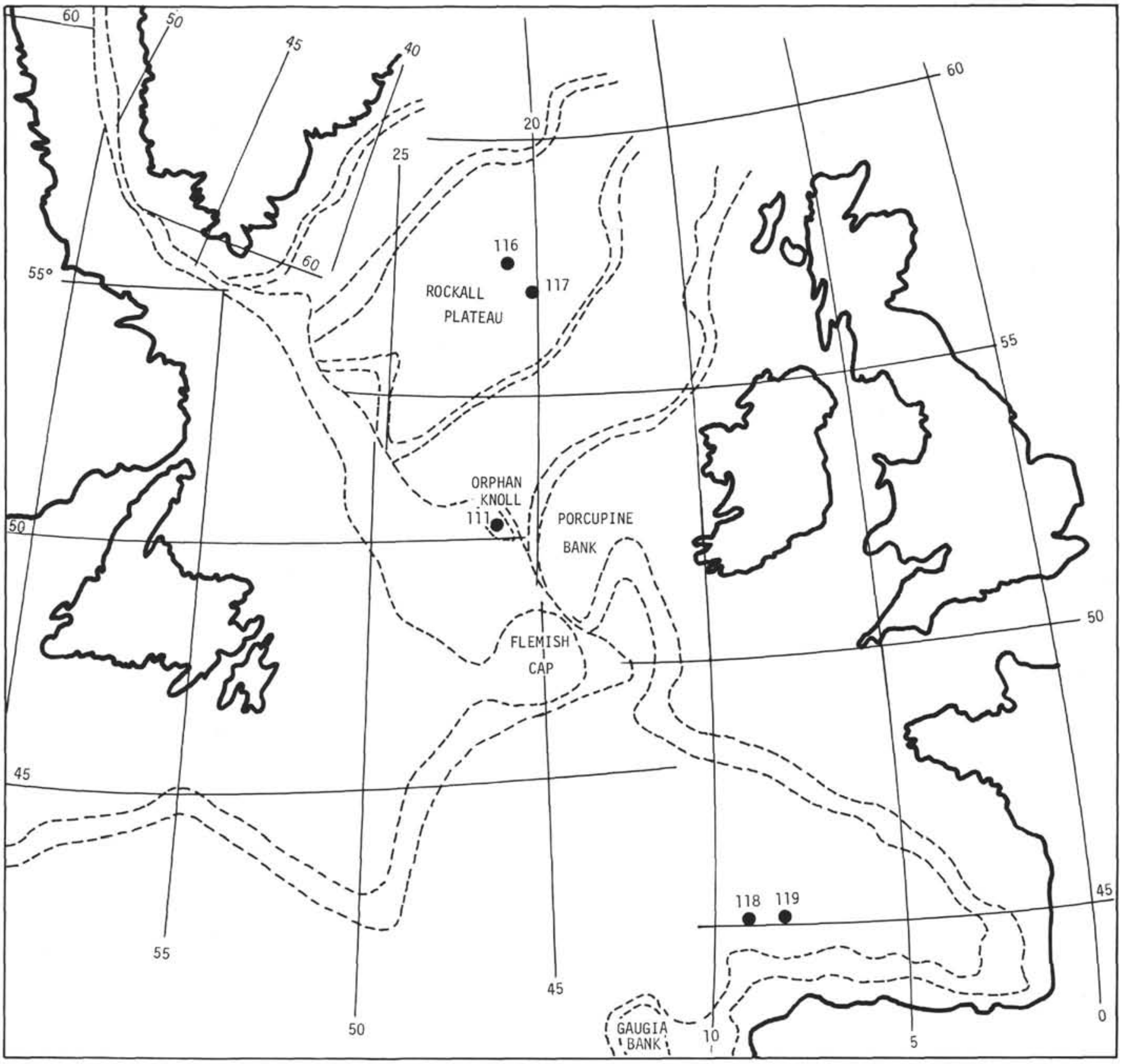



Figure 17. *Paleogeographic reconstruction at Anomaly 32 (78 my - Late Senonian).*

so, of what age. However it is probable that the sea floor lying between Portugal and the Grand Banks is oceanic, and that the closure of the European and American plates necessary to bring Portugal against the Grand Banks would also close Greenland, Rockall and northwestern Britain. The movements would be linked by a transform fault running between South Greenland and northwestern Spain. This reconstruction (Figure 19) requires that Rockall Plateau, Porcupine Bank, Orphan Knoll, Flemish Cap and Galicia Bank are all continental fragments that have been displaced from their original positions in relation to their large neighboring plates and have been derived from a region between Ireland and Newfoundland. It is not possible to determine whether this initial period of break up of the North Atlantic continents was prior to the opening of Biscay (as is drawn in Figures 18 and 19) or whether it took place during the same period of 150 to 80 million years ago. The orientation of the axes of spreading and of the Greenland-Spain transform fault are very different from those obtaining subsequent to the Late Cretaceous so that it is possible that a considerable hiatus in spreading activity occurred.

The assemblage of continents in Figure 19 differs in two major respects from that of Bullard *et al.* (1965). Rockall Plateau has been retained as a coherent plate, whereas, Bullard *et al.* condensed the two banks forming the east and west boundaries of the plateau. Evidence for the continental nature of the Hatton-Rockall Basin has been presented by Scrutton and Roberts (1971) and by the results of Holes 116 and 117 (Chapter 8). Secondly, the position of Spain against Europe is different due to the different closure of Biscay.

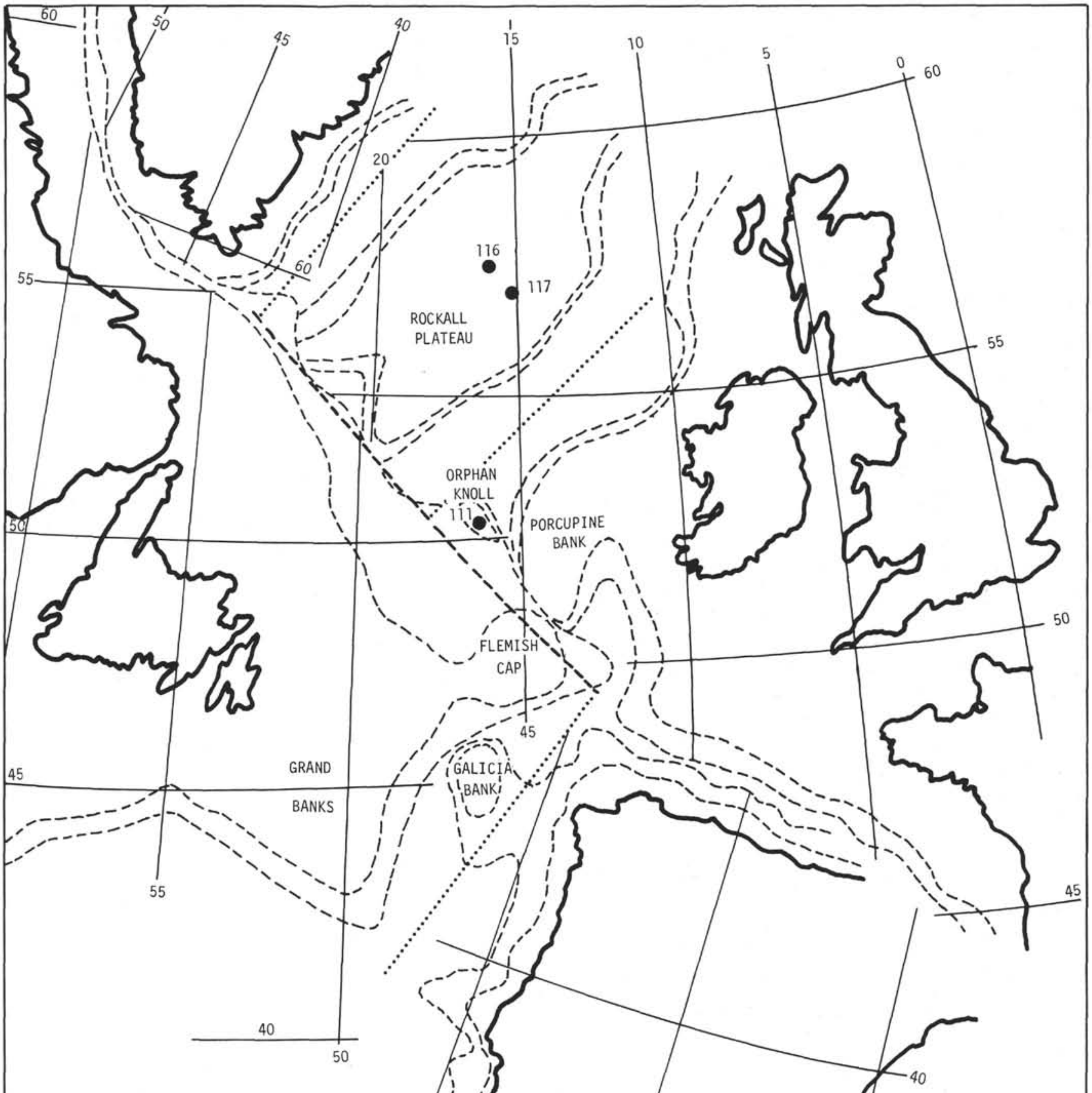



Figure 18. *Paleogeographic reconstruction in Late Jurassic (150 my) assuming primitive Iceland Basin and Rockall Trough had opened before this time.*

Evidence of tectonic activity and subsidence of the smaller fragments of continent might give some indication of the age of initial break up. The tectonic history of Rockall Plateau, as revealed by Holes 116 and 117, shows that there was major subsidence in the Paleocene but no rocks older than that have been sampled. However, there

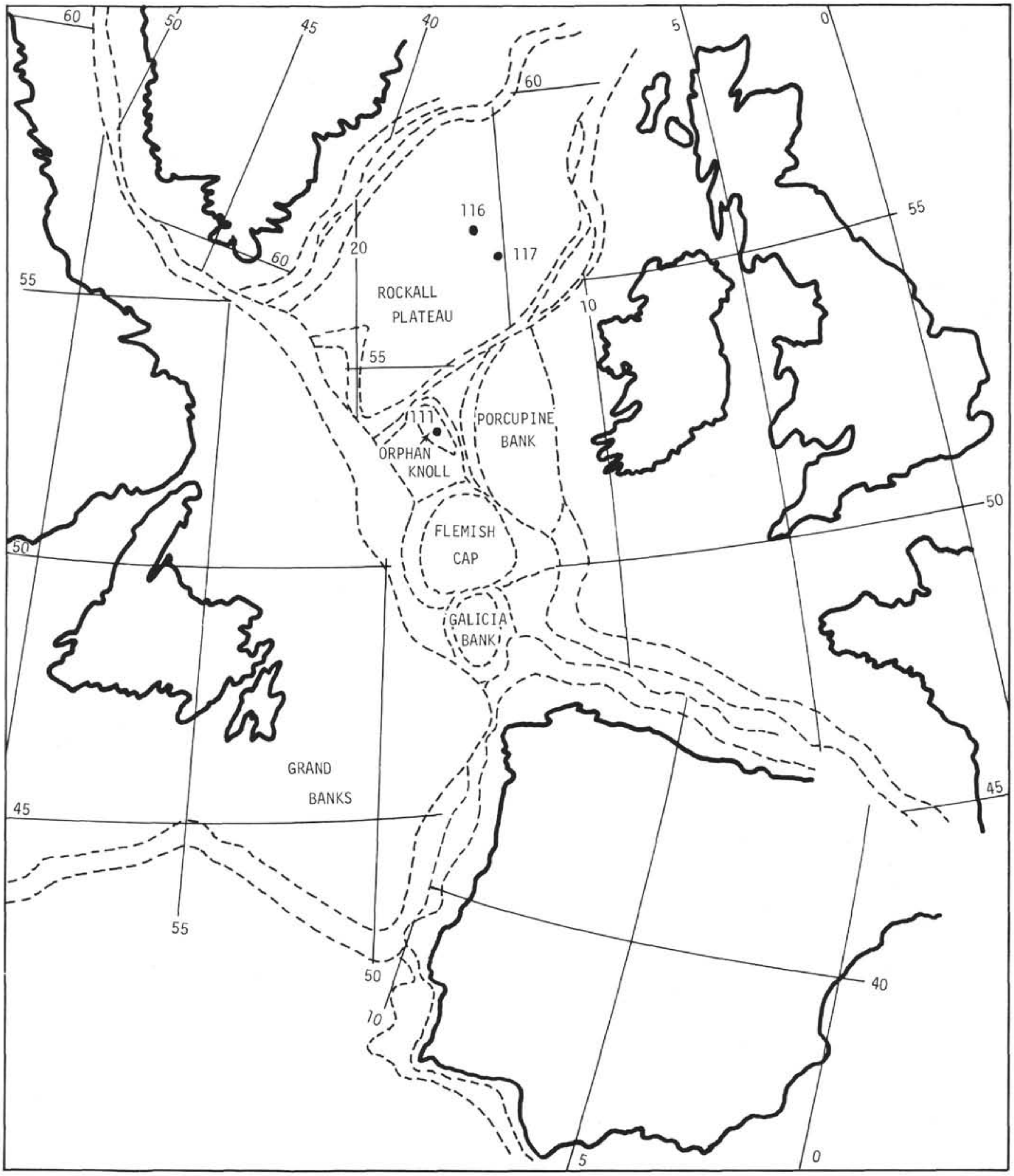



Figure 19. *Paleogeographic reconstruction prior to initiation of spreading, with continental fragments packed into available space in approximately correct N-S order. If primitive Iceland Basin and Rockall Trough opened at the same time as the Bay of Biscay, this reconstruction represents the Late Jurassic (150 my).*

are deeper sediments as yet unsampled. Porcupine Bank is underlain by a ridge of "basement" rocks, the northern part of which is believed to consist of Caledonian rocks similar to those north of Galway Bay (Clarke, Bailey and Taylor-Smith, 1971). The ridge is separated from the continental shelf southwest of Ireland by the Seabight Trough, which may have resulted from the westwards translation of Porcupine Ridge. There is no data on the possible age of such movement. Hole 111 drilled on Orphan Knoll showed that the major subsidence occurred in the Paleocene, although earlier orogeny, erosion and subsidence took place during the Jurassic and Early Cretaceous (Chapter 3). A review of work done on Flemish Cap also appears in Chapter 3. Granite, quartzite and Lower Cretaceous carbonate rocks have been obtained, but no tectonic interpretation has yet been made. It does appear to be separated from the continental shelf by a sediment filled trough. Galicia Bank and some associated seamounts have been shown to be continental (Black *et al.*, 1964), and Cretaceous and younger limestones similar to Mediterranean and Iberian facies have been dredged. The bank is fault bounded and is separated from Spain by a deep col.

These continental fragments have all been studied in isolation and, in the light of their proximity prior to the formation of the North Atlantic, comparative studies might be very profitable. Details of their pre-Cenozoic geology in relation to that of the neighboring continental margins might enable them to be placed more accurately in their original position. Neither Rockall Plateau nor Orphan Knoll started their major subsidence until many tens of millions of years after the initial break up. This may reflect a fundamental process of fractured continental margins, or it might be the result of subsequent tectonic activity in the Paleocene associated perhaps with the development of the triple junction.

The geology of the continents surrounding the North Atlantic has been compiled by Kay (1969) in order to test continental reconstructions. More recently Hallam (1971) has examined the Mesozoic geology to find evidence for the age of the initiation of the dispersion of the continents. North of a line joining Newfoundland and Spain, he accepts the Bullard fit and shows the consistency of pre-middle Jurassic paleogeography. However the analysis does not include the small continental fragments or data from the shelves, and is therefore unable to resolve the differences between the Bullard fit and that suggested here. On the basis of the development of the Jurassic transgression, Hallam concludes that the African plate separated from the North American plate in the Lower-Middle Jurassic, and that in the Upper Jurassic the spreading extended northward between the European and North American plates.

There are clearly many geological checks that can be made on the proposed assembly of continents (Figure 19) and it is not possible to examine these here. The main purpose is to provide a possible framework in order to guide further studies and to stimulate more research into the problem.

## SUMMARY

Geophysical and geological data from Leg 12 has been combined with other existing data to provide a history of the Mesozoic and Tertiary evolution of the northern North Atlantic. The following sequence of events is closely related to that proposed by Le Pichon in various publications (*q.v.*).

(1) 180 million years: African plate started to separate from North American plate accompanied by shearing between Africa and Europe.

(2) Between 180 and 80 million years: Separation of European and North American plates along Greenland-Spain fracture zone gave rise to primitive Iceland Basin and Rockall Trough, and separated Spain from the Grand Banks. Orphan Knoll, Porcupine Bank, Flemish Cap and Galicia Bank were detached and displaced.

(3) 150 to 80 million years: Spain rotated anticlockwise about rotation pole in Paris to open Bay of Biscay.

(4) 80 to 60 million years: There was spreading between North American plate and plate comprising Greenland, Rockall Plateau and Northwestern Europe, to give Labrador Sea and North Atlantic.

(5) 60 million years: Rockall Plateau separated from Greenland along new spreading axis on east side of primitive Iceland Basin. Triple junction developed, and spreading axes and fracture zones shifted to accommodate new geometry.

(6) 60 to 47 million years: Simultaneous opening of Labrador Sea, Reykjanes Ridge and North Atlantic.

(7) 47 million years: Greenland virtually stopped moving relative to North America, and Labrador Sea growth finished.

(8) 47 million years to present: Reykjanes Ridge and North Atlantic grew as European plate separated from North America-Greenland plate. Details of spreading regime during this time are discussed by Vogt *et al.* (1969).

The changing shape of the North Atlantic has had a significant effect on the sedimentation. The oldest sediments at Site 112 (65 million years) were laid down during the last phases of the spreading about the NW-SE axis. During the period 60 to 47 million years, sediments from the northeast were brought in by near-bottom currents developing as the circulation became modified by the changing geometry, and Norwegian Sea water arrived through the widening Iceland Basin. These sediments were trapped in the semicircular barrier of basement ridges in the South Labrador Sea. The young Reykjanes Ridge does not appear to have been an appreciable barrier to these sediments.

After the Middle Eocene (47 million years), spreading virtually ceased in the Labrador Sea and the topography became progressively covered by rapid sedimentation from the continental margins, although the sediments were confined to the outside of the basement barriers. Bottom currents from the northeast continued to build the sediment body near Site 112. In the Oligocene (35 million years) some tectonic activity in the central Labrador Sea may have thrown up the small seamounts found near Site 113, and hence destroyed the continuity of the Eocene/Oligocene reflector there; and, at the same time, some change in the environmental conditions produced the Oligocene mid-sediment reflector in the sediment body near Site 112. At this time, the sediment body was still connected to the southern end of the lower part of the Gardar Ridge.

Later spreading appears to have given rise to a higher relief for the Reykjanes Ridge, virtually isolating the east and west sides from bottom transport of sediments except through the Charlie Gibbs Fracture Zone. By early Miocene (20 million years), Iceland had developed at the north end of the Reykjanes Ridge separating the flow of water from the Norwegian Sea into two parts. That flowing through the Denmark Strait west of Iceland carried its own sediment load down the east coast of Greenland building up the Eirik Ridge and contributing to the high rate of sedimentation in the central Labrador Sea. The other part east of Iceland traveled down the east side of the Reykjanes Ridge, continuing to build the Gardar Ridge, the ridge at Site 114, and others, and some of it crossed the mid-Atlantic Ridge through the Charlie Gibbs Fracture Zone to feed the sediment body there. The present day circulation can explain the major features of recent current controlled sedimentation that have been observed.

## ACKNOWLEDGMENTS

A broad analysis of an oceanic area involves data from a very wide variety of sources. In order to plan Leg 12 of the Deep Sea Drilling Project and to make the best interpretation of the data obtained, many organizations and scientists provided data, unpublished manuscripts and ideas. I would like to thank particularly X. Le Pichon of the Centre National de l'Exploitation des Oceans, France, L. Montaderf of the Institut Francais du Pétrole, France, M. Ewing of the Lamont-Doherty Geological Observatory, U.S.A., P. R. Vogt, G. L. Johnson and R. H. Higgs of the U.S. Naval Oceanographic Office, U.S.A., K. S. Manchester and A. C. Grant of Bedford Institute, Canada, R. A. Scrutton of the Department of Geodesy and Geophysics, Cambridge, England and D. G. Roberts of the National Institute of Oceanography, England. The inspiration, and many of the ideas, for this study have come from my colleagues on Leg 12 and I thank them for their valuable help.

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