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Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic

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Summary. Geophysical data collected from 1972 to 1975 during a systematic mapping program of the Labrador Sea have been analysed to investigate its geological history and evolution. The data have been used to establish the location of the ridge axis, the age of the ocean floor, and the direction of movement of Greenland relative to North America. Different poles of rotation for the Eurasian and Greenland plate relative to the North American plate in the Late Cretaceous have been derived in order to fit together satisfactorily the plate boundaries defined by the magnetic anomalies in the Labrador Sea and the North Atlantic. The analysis shows that active seafloor spreading commenced in the southern Labrador Sea during the Campanian (anomaly 32) and in the northern Labrador Sea during the Maastrichtian (anomaly 28), with little or no spreading in the Baffin Bay region during this period. With the commencement of active seafloor spreading in the Norwegian Sea during the lower Paleocene (anomaly 24), the direction of seafloor spreading changed in the Labrador Sea and spreading commenced in Baffin Bay. The spreading ceased in the Labrador Sea and Baffin Bay during the lower Oligocene (pre-anomaly 13) when Greenland started to move with the North American plate.

Paleogeographic reconstruction of the three plates shows that Greenland moved north relative to North America during the first phase of opening of the Labrador Sea (75–60 Myr), giving rise to compressive forces between northern Greenland and the Canadian Arctic Islands. During the second phase of opening of the Labrador Sea (60–40 Myr) Greenland moved past Ellesmere Island in the left lateral sense along Nares Strait. Some compression is also inferred from these constructions between the margins of northeast Greenland and Svalbard. The poles of rotation obtained for the three plates show a different set of events which may have been responsible for the separation of Rockall Plateau from the British Isles during the early evolution of the North Atlantic.

1 Introduction

The idea that the Labrador Sea was formed by a seafloor spreading process originated when Drake *et al.* (1963) showed, from their seismic reflection measurements in the centre of the Labrador Sea, the presence of a buried basement high. This they identified as the mid-Labrador Sea Ridge. Later the aeromagnetic data collected by Godby *et al.* (1966) across the Labrador Sea showed that parallel bands of magnetic anomalies, similar to those observed across regions formed by seafloor spreading, were present on either side of an axial quiet zone in the central region. Since then much more aeromagnetic (Hood & Bower 1973) and sea magnetic data (Mayhew, Drake & Nafe 1970; Le Pichon, Hyndman & Pautot 1971; Laughton 1971, 1972; Vogt & Avery 1974; Srivastava 1975a; Kristoffersen & Talwani 1977) have been collected and they all confirm the presence of similar anomalies in the Labrador Sea.

Vogt *et al.* (1969a) were the first to show direct evidence of a period of simultaneous seafloor spreading in the Labrador and Norwegian Seas and the North Atlantic Ocean from their magnetic measurements near the triple junction south of Greenland. It has now been well established, from the identification of a group of magnetic anomalies (20 to 24) in the southern Labrador Sea, the Reykjanes Basin and in the North Atlantic (Laughton 1971; Vogt & Avery 1974; Kristoffersen & Talwani 1977), that there was simultaneous spreading in these regions from Paleocene to Eocene. It has further been established that spreading in the Labrador Sea ceased in the lower Oligocene (40 Myr ago) when Greenland started to move as part of the North American plate (Kristoffersen & Talwani 1977).

The early part of the history of evolution of the Labrador Sea remained very uncertain because neither the magnetic anomalies nor the direction of the fracture zones belonging to this period could be identified throughout the Labrador Sea. The fracture zones are buried under thick sediments and the magnetic anomalies show variability in their signatures which has made it difficult to correlate them between widely spaced tracks. Several authors, however, have described its evolution (Laughton 1972; Le Pichon *et al.* 1971; Mayhew 1969; Hood & Bower 1973; Hyndman 1973; Johnson *et al.* 1969, 1973; Vogt & Avery 1974; van der Linden 1975a) and their estimates for the commencement of seafloor spreading in the Labrador Sea vary from the Jurassic to Upper Cretaceous.

It could be argued that prior to separation of Greenland from Europe the seafloor spreading in the Labrador Sea must have been linked directly to the seafloor spreading in the North Atlantic; thus, knowing the history of evolution of the North Atlantic (Pitman & Talwani 1972) and of the Norwegian–Greenland Sea (Talwani & Eldholm 1977) it should be possible to deduce the history of evolution of the Labrador Sea. Serious discrepancies, however, may arise in taking this indirect approach because neither the early opening history of the North Atlantic is known accurately enough nor the time when Greenland separated from Europe. Besides, the recent findings of Kristoffersen & Talwani (1977) on the nonrigid behaviour of the North American, Greenland and Eurasian plates during the simultaneous opening in the North Atlantic Ocean, Labrador and Norwegian Seas may complicate the situation further. Thus to find a definite answer to the evolution of the Labrador Sea and to relate it to the early opening of the North Atlantic when the British Isles including the Rockall Plateau separated from Newfoundland, several systematic surveys were carried out by the Bedford Institute of Oceanography in the Labrador Sea. The present paper is a compilation of all the data collected on these cruises together with those collected on earlier reconnaissance cruises as well as the published material. The data have been used to establish the location and extent of the extinct Labrador Sea Ridge, the age of the ocean floor, and direction of movement of Greenland relative to Labrador. The implications of the seafloor spreading in the Labrador Sea to the formation of Baffin Bay and the movement in the Canadian Arctic are examined.

The findings as reported here are based on a large amount of data which cannot be presented here in detail and thus only representative sections of data are presented for illustrative purposes. A detailed account of all the data will be published elsewhere.

2 Presentation of data

The majority of the data presented in this paper comes from the systematic geophysical surveys carried out by the Bedford Institute of Oceanography in the Labrador Sea since 1972. Additional data included in the compilation of the various geophysical parameters presented here include those collected by the Bedford Institute of Oceanography from ships on passage through this region since 1965, deep seismic reflection data bought from geophysical prospecting companies on a participation basis, and the published and unpublished data made available to us by other research institutions.

Primary positioning during the systematic geophysical surveys was accomplished through a combination of satellite and Loran-C receivers, which gave an overall accuracy of 100–200 m. On other cruises the positioning was less accurate because of the use of satellite or Loran-C receivers alone. On some of the older cruises whose data have been used here the only aid available was dead reckoning and data from such cruises were used with due caution in the overall compilation presented.

During all the Bedford Institute of Oceanography cruises continuous measurements of bathymetry, gravity and magnetics were made along all tracks while seismic measurements were made on preselected tracks.

2.1 MAGNETIC FIELD

Almost all of the data used here in identifying magnetic lineations in the Labrador Sea and the Northwest Atlantic were obtained using ship-towed magnetometers though the published aeromagnetic data of Hood & Bower (1973) were also used in regions of sparse shipboard coverage. The identification of the anomalies in the Labrador Sea and in the Northwest Atlantic north of the Charlie Fracture Zone is largely based on the data collected along the tracks shown in Fig. 1. About 20 to 25 north–south tracks exist in the Labrador Sea along which magnetic data have been collected by the Bedford Institute of Oceanography. These and some of the tracks spaced 5 km apart in the southern end of the map (*Martin Karlsen – 75*) are not shown for the sake of simplicity. South of the Charlie Fracture Zone (Fig. 6) a large amount of published and unpublished data was used to identify anomalies and their sources are listed in Table 1.

Magnetic anomalies were calculated with reference to the International Geomagnetic Reference Field (IAGA 1969) and plotted along tracks, Figs 2 and 6. The resulting profiles were then visually correlated. The identification of the anomalies is based on a comparison of observed to calculated anomalies for various spreading rates. Fig. 3 shows the correlation between the calculated profile and a group of representative profiles in the Labrador Sea whose positions are shown in Fig. 4. Similar correlations for the Northwest Atlantic are shown in Fig. 5 for the region north of the Charlie Fracture Zone and in Fig. 6 for the region south of the Charlie Fracture Zone. The calculated profiles use normally and reversely magnetized blocks representing the modified geomagnetic reversal timescale of Heirtzler *et al.* (1968) as given by Le Pichon, Francheteau & Bonnin (1973). The blocks were assumed to be 2 km thick at a depth of 4.5 km and had an intensity of magnetization of 0.0025

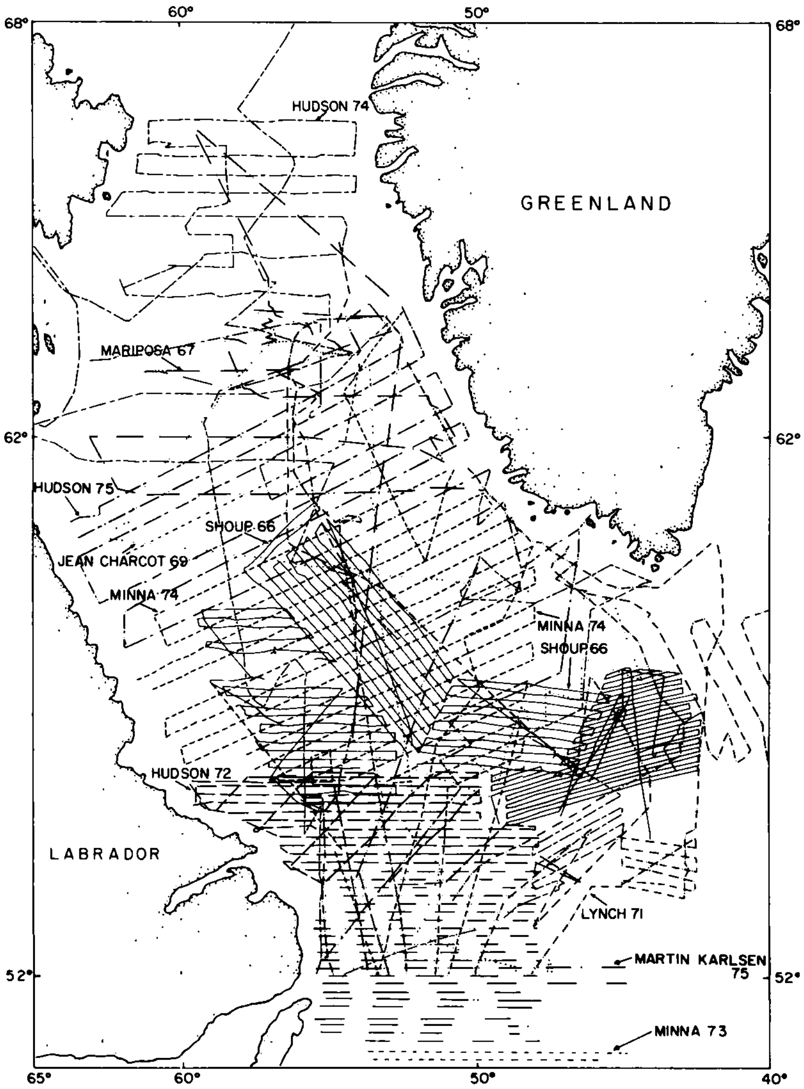

Figure 1. Map showing ship's tracks from different cruises in the Labrador Sea. Magnetic data collected along all of these tracks were used in identifying and correlating magnetic anomalies.

Table 1. Source of magnetic data used in Fig. 6.

Profile No.	Cruise	Organization
1–6	*Hudson 65 to 68* and *Theta 68*	Bedford Institute of Oceanography
7	*Snellius-Mike*	Navado Project
8	*Chain-61*	Woods Hole Oceanographic Institution
9	Alpine (from Pitman & Talwani 1972)	Alpine Geophysical for Naval Oceanographic
10	*Snellius – November*	Navado Project
11 and 12	*Lynch-71*	US Naval Oceanographic Office
13–20	*Aeromagnetic* (from Hood and Bower 1973)	Geological Survey of Canada
21	*Kaine-01A*	US Naval Oceanographic Office
22	*Snellius-Lima*	Navado Project
23	*Snellius-Kilo*	Navado Project

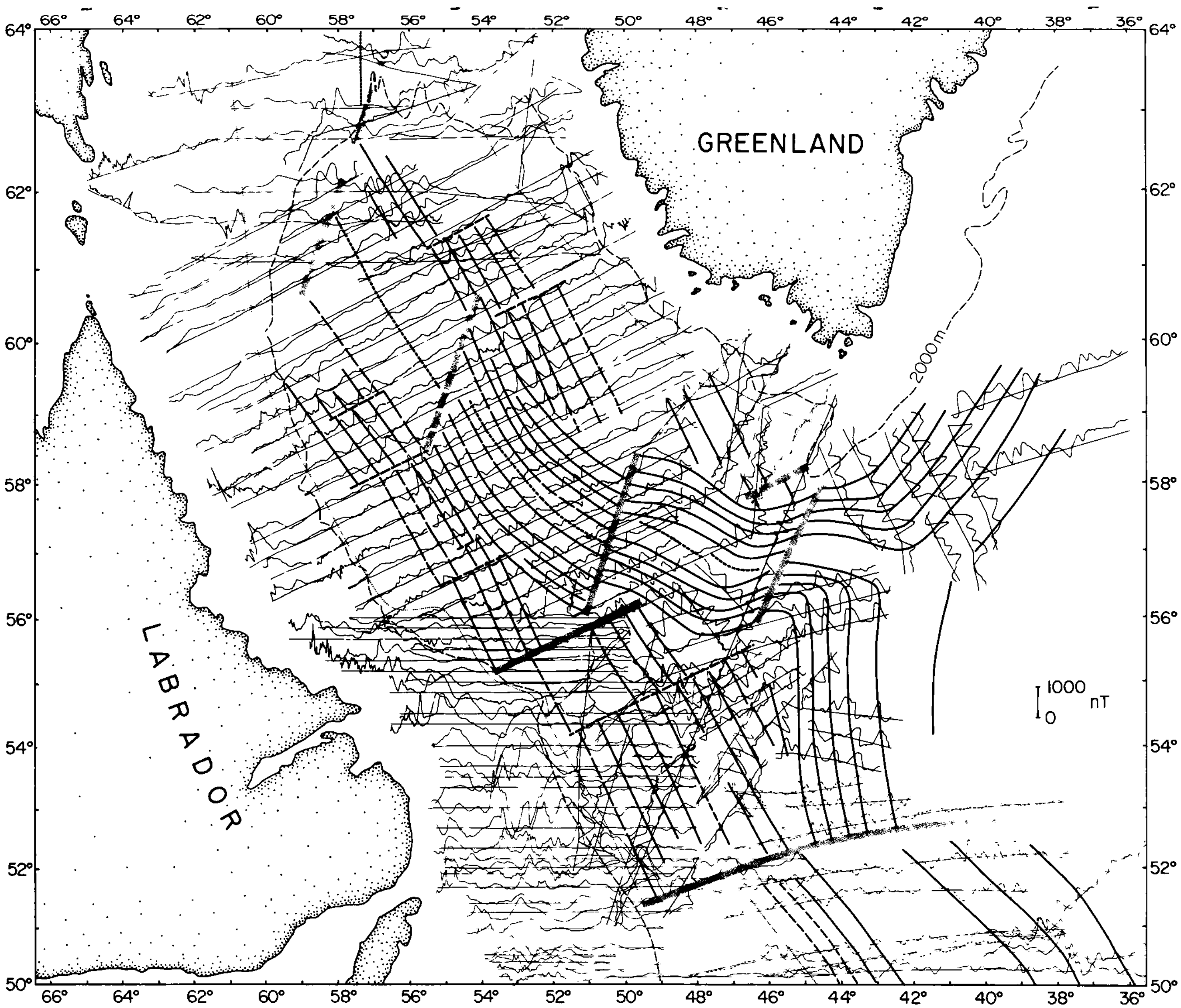

Figure 2. Map showing correlation of magnetic anomalies plotted along selected tracks. The aeromagnetic data of Hood & Bower (1973) plotted along flight paths are shown by dotted lines. The wide stippled lines indicate fracture zones. Also shown are dislocation in magnetic lineations by dashed lines; the ocean–continent boundary by dotted line; the 2000-m water depth contour by long dashed line; and the axis of

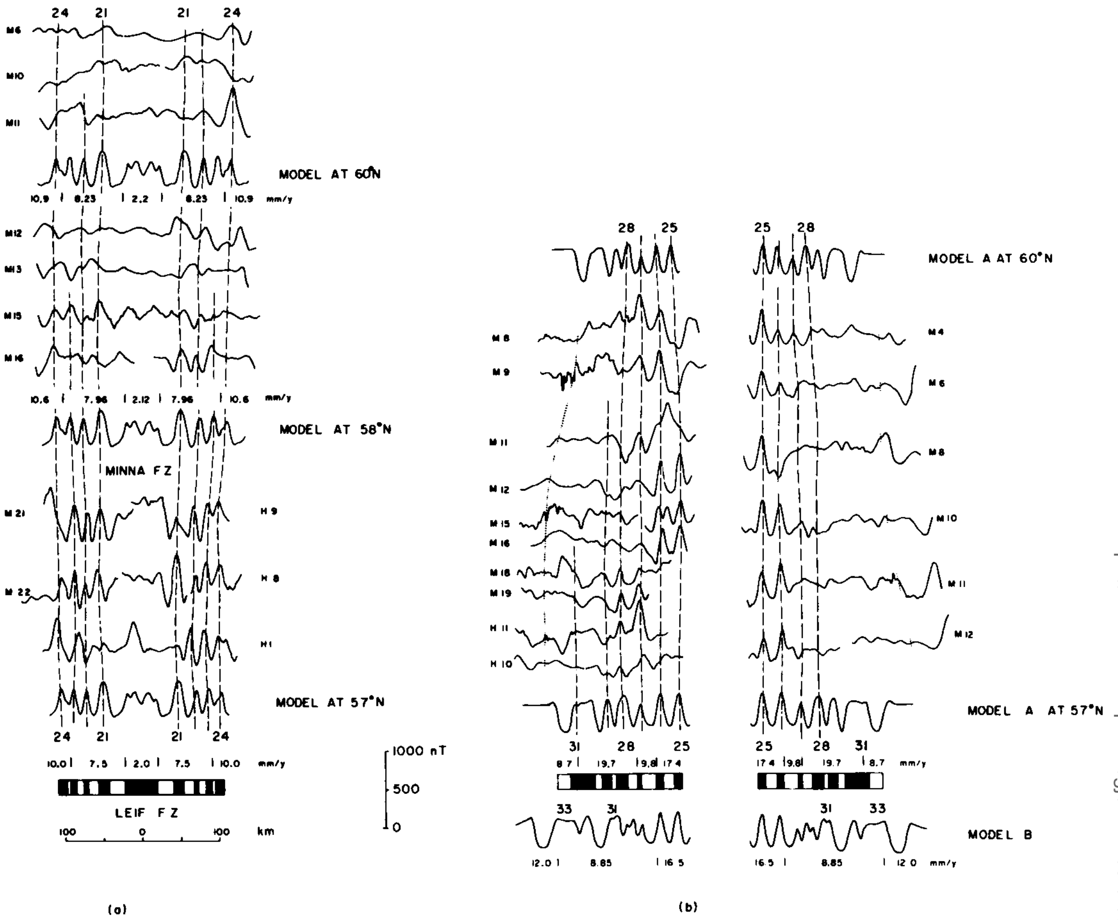

Figure 3. Correlation between the observed and the computed magnetic anomalies in the Labrador Sea. The observed anomalies were projected along a direction of 25° for anomalies between 20 and 24 shown in (a) and along a direction of 65° for anomalies between 25 and 31 shown in (b). The models were calculated at different latitudes and their respective rates of spreading are shown. In (b) Model B was calculated on the expected rates of spreading at 57° N based on the rates of spreading used in Model B, Fig. 6. Model A refers to the rates of spreading proposed here. The location of the tracks are shown in Fig. 4. Positively magnetized blocks for Model A and anomaly numbers are shown. The tracks are identified by their cruises, H–*Hudson*, M–*Minna* and the ocean–continent boundary by dotted lines.

emu/cm^{-3}. Because consideration of the geomagnetic pole during the Tertiary and Upper Cretaceous (Irving & Pullaiah 1976) made little difference (3–4 degrees) to the inclination of the present geomagnetic field in the regions considered here, the magnetization was assumed to be in the direction of the present Earth's magnetic field. The theoretical profiles shown in Fig. 3(a) and (b) were computed along azimuths of 25° and 65° respectively. These azimuths were obtained from the mean direction of the fracture zones in the Labrador Sea for two distinctly different episodes of seafloor spreading. The observed profiles shown in Fig. 3 were projected along these directions. For the Northwest Atlantic the theoretical profiles shown in Figs 5 and 6 were computed along azimuths of 72° and 81° respectively for the two regions.

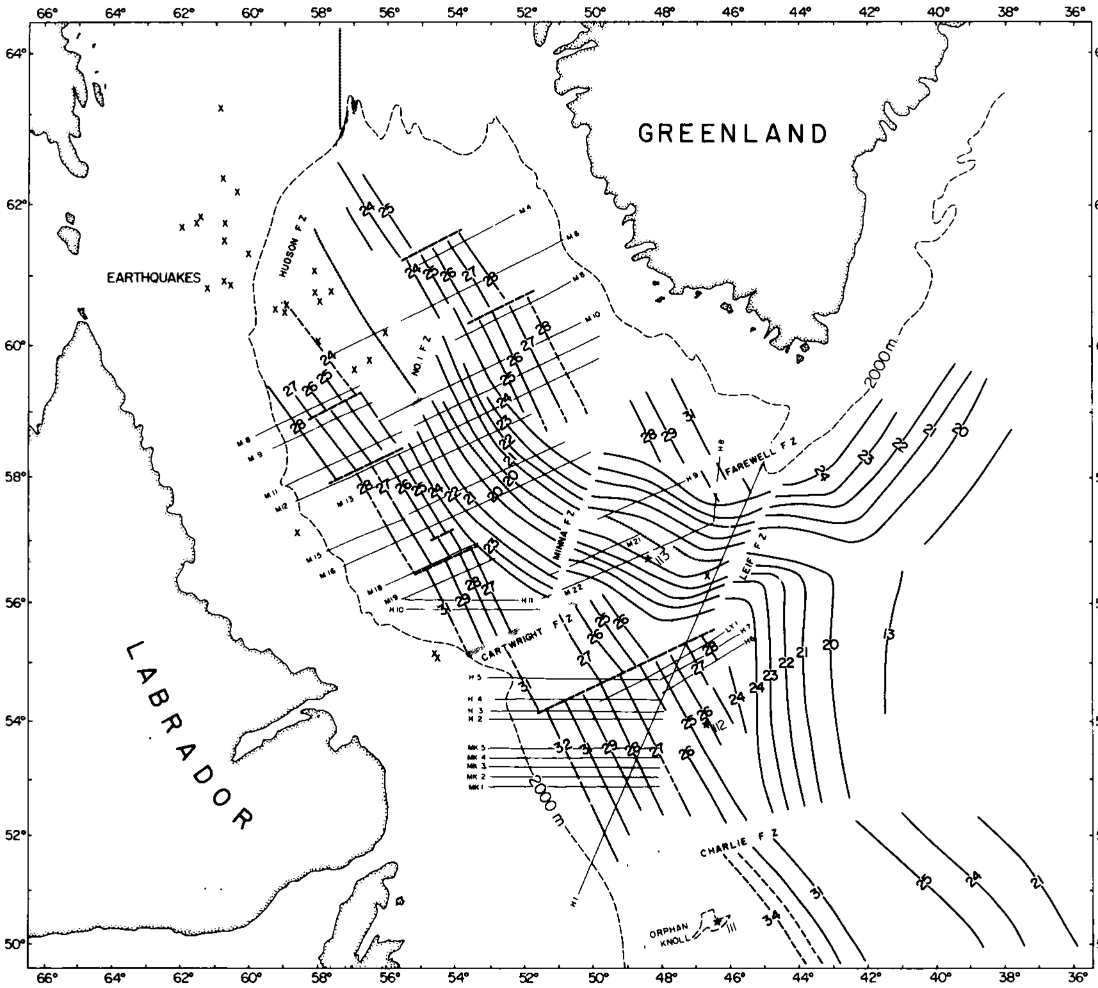

Figure 4. Identified magnetic lineation together with fracture zones in the Labrador Sea. Magnetic data along ship's track shown by thin dashed lines are shown in Figs 3 and 5. Dislocation in the magnetic lineations are shown by thick dashed lines. Earthquake epicentres recorded since 1962 are shown by crosses. Numbers 111, 112 and 113 refer to DSDP holes. 2000-m water depth contour is shown by thin dashed lines.

2.1.1 Labrador Sea

Two factors make it relatively difficult to delineate the magnetic anomalies throughout the Labrador Sea. Firstly, the magnetic anomalies are not well developed everywhere. In the south and near the ridge axis (Fig. 2) the anomalies are well developed and can be correlated with the Heirtzler *et al.* (1968) timescale (Fig. 3(a)). In the north the anomalies are very small in amplitude and their correlation with the anomalies in the south is difficult (Fig. 3(a)). Secondly, a complex pattern of fracture zones exists in the Labrador Sea making it difficult to correlate anomalies even between closely spaced tracks. Thus the resulting identification and correlation of anomalies between tracks was guided by: (a) the fit between the model and projected profiles in Fig. 3(a) and (b); (b) the dense coverage of the

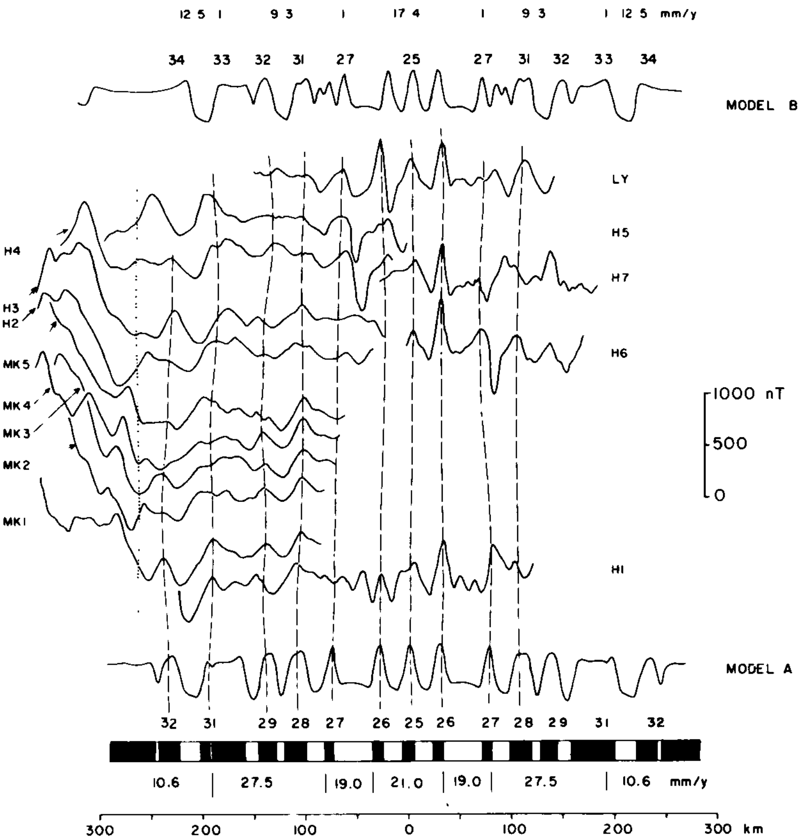

Figure 5. Correlation between the observed and the computed magnetic anomalies in the South Labrador Sea and Northwest Atlantic, north of the Charlie Fracture Zone. The observed anomalies were projected perpendicular to the lineations along a direction of 72°. Computed anomalies for two rates of spreading are shown. Model A corresponds to the rate of spreading as proposed here and Model B corresponds to the rate of spreading as proposed by Kristoffersen *et al.* (1976). The anomalies were computed using the Heirtzler *et al.* (1968) timescale. The anomaly numbers and the positively magnetized blocks are shown. The location of the tracks are shown in Fig. 4. The tracks are identified by their cruises: H–*Hudson,* MK–*Martin Karlsen,* LY–*Lynch.* The ocean–continent boundary is shown by dotted line.

magnetic data throughout the Labrador Sea (Fig. 1) including the aeromagnetic data of Hood & Bower (1973); (c) the observation that magnetic anomalies are usually symmetrical with respect to the ridge axis; and (d) the fact that as a first approximation the location and trend of every anomaly between two lithospheric plates should be consistent with the overall pattern of the anomalies and of the fracture zones.

The resulting anomaly lineations in the Labrador Sea (Fig. 4) show that the anomalies can be divided into two groups: one forming the central portion of the Labrador Sea (anomalies 20–24) and the other lying on either side of this central zone (anomalies 25–31). The central zone of anomalies were identified by Kristoffersen & Talwani (1977) and Laughton (1971) near the triple junction (57° N, 44–50° W) and their identifications have been used here in correlating these anomalies in the northern Labrador Sea. The identification of anomalies on either side of the central zone of anomalies is different from those reported by Hood & Bower (1973); Vogt & Avery (1974) and van der Linden (1975a).

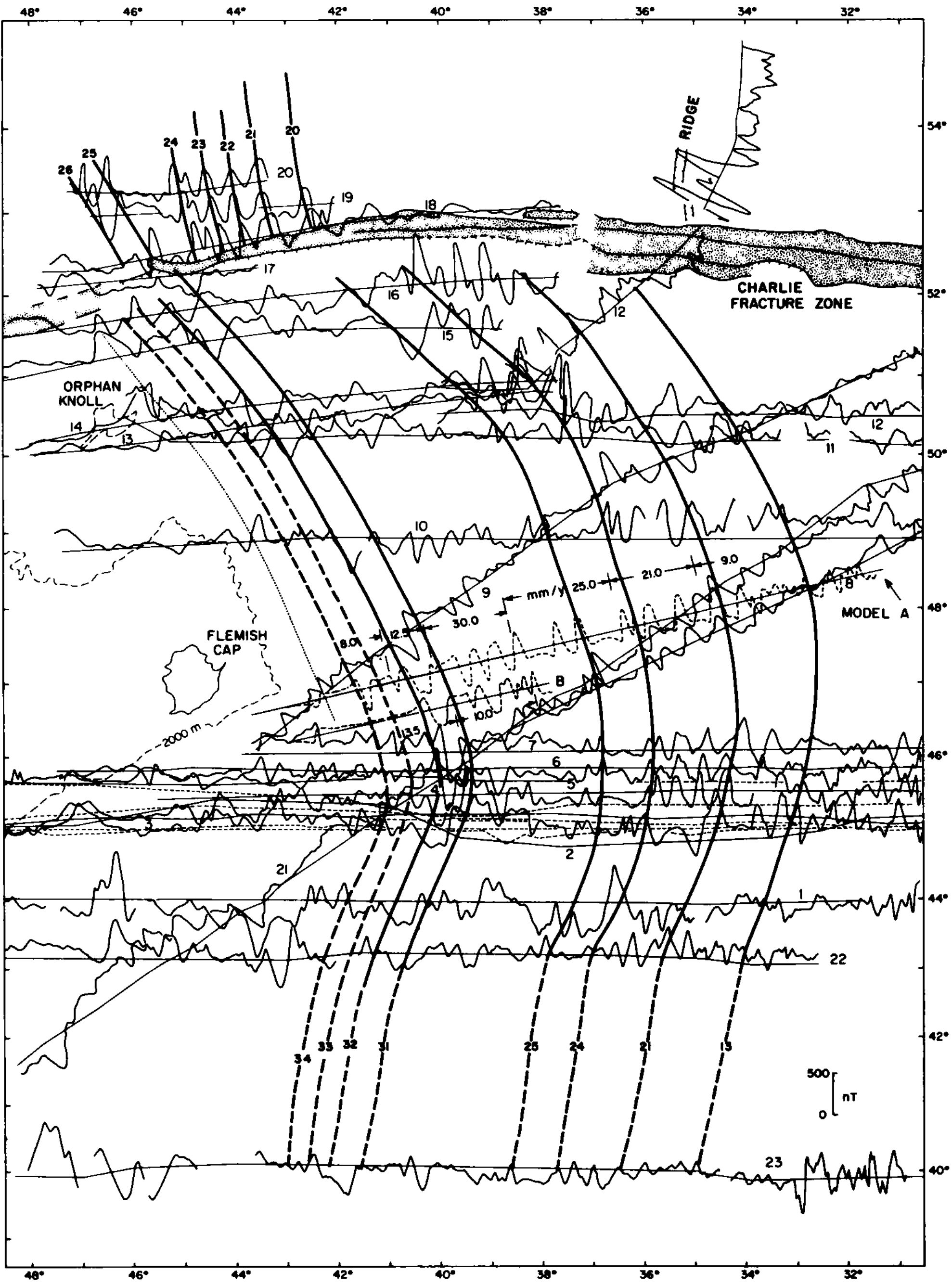

Figure 6. Identification and correlation of magnetic anomalies between tracks in the Northwest Atlantic. Computed anomalies for two different rates of spreading are shown by dotted lines. Model A shows the rates of spreading as proposed here and Model B shows the rates of spreading as proposed by Kristoffersen *et al.* (1976). Number along tracks indicate the source of data as listed in Table 1. The anomaly numbers are shown as thick numbers. Also shown are the ocean–continent boundary by dotted lines off Orphan Knoll and Flemish Cap and 2000-m water depth contour. Trend and position of the Charlie Fracture Zone shown by stippling are obtained from Olivet *et al.* (1974) compilation.

2.1.1(a) Central zone anomalies. In trying to fit the observed with the computed anomalies in the central zone (Fig. 3) it was assumed that anomalies younger than 13 do not exist in the Labrador Sea. Kristoffersen & Talwani (1977) have shown that anomaly 13 is the oldest anomaly on the western flank of the Reykjanes Ridge which continues in the north–south direction north of the Charlie Fracture Zone without bending into the Labrador Sea (Figs 2 and 4). Though a reasonable fit between most of the observed and calculated anomalies exists in Fig. 3(a), the agreement for the quiet zone between the two 21 anomalies is not good. Several other spreading rates were tried and none of them gave a reasonable fit for this region. The computations suggest a gradual decrease in the rate of spreading from anomaly 24 to 20 and a major decrease at anomaly 20.

Anomalies 20–24 are dislocated across four fracture zones: Leif, Minna,* No. 1, and Hudson† (Fig. 4). The location and trend of these fracture zones were found from the combined analysis of magnetic, gravity, and seismic data as presented later. Of these four fracture zones, Minna shows the maximum offset in the anomalies (about 50 km). The Hudson fracture zone in the north has been interpreted to lie in the region where the direction of the ridge axis changes from northwest–southeast to north–south. The magnetic anomalies near it are too subdued in their amplitude to be identified.

The decrease in the amplitude of the anomalies north of No. 1 fracture zone (Figs 2 and 4) is rather surprising. It has been suggested that such a decrease in the amplitude could be caused by : (a) strike slip motion along a northeast–southwest transform fault (Le Pichon *et al.* 1971); (b) the close proximity of this region to the Davis Strait which, it has been argued was the site of a hot spot (Keen & Barrett 1972; Hyndman 1973) or an aseismic ridge (Vogt 1972). The seismic data (Fig. 10) in this region show shallowing of basement to the north (less than 6 s) with steep scarps. The sediments overlying the basement show major unconformities and some disturbances. Furthermore, the anomaly lineations in the central zone are oblique to the fracture zones (Fig. 4). The obliqueness increases to the north. Thus the obliqueness in spreading as well as a strike slip motion in the northern Labrador Sea along the Hudson Fracture Zone may have been responsible for the decrease in amplitude of the anomalies in the northern Labrador Sea.

2.1.1(b) Anomalies 25–31. A different group of anomalies lies either side of the central zone (Fig. 2). The anomalies in this group have been identified on the basis of the fit obtained between the observed and the calculated anomalies (Model A, Fig. 3). Also shown in Fig. 3(b) is Model B based on the calculated rates of spreading for this region obtained from the rate of spreading proposed by Kristoffersen, Cande & Talwani (1976) and more recently by Cande & Kristoffersen (1977) for the North Atlantic. The model of Kristoffersen *et al.* shows a poorer fit to the observed anomalies compared to the one proposed here. Anomalies 25–29 can easily be correlated between tracks, Fig. 3(b), and show good correlation with the computed model.

The trend of anomaly lineations 25–31 varies from north to the south with respect to the trend of the lineations in the central zone (20–24, Fig. 4). North of track M18 (Fig. 4) all the lineations lie parallel to each other while to the south of it lineations 25–31 lie at angles of 30° or more to the central zone lineations. Such a change in their trend is interpreted as resulting from a drastic change in the direction of motion between the Greenland and the North American plates soon after the formation of anomaly 25. Such a drastic change in the direction of motion of the plates can also be seen from the change in the

* The name Minna Fracture Zone is proposed after the motor vessel *Minna* which was used for the survey of the majority of the Labrador Sea. Unfortunately, the ship ran aground near Resolution Island while carrying out the survey in the Labrador Sea and ultimately sank.

† The name Hudson Fracture Zone is proposed as it lies near the mouth of the Hudson Strait.

direction of the fracture zones. A major fracture zone at 56° N, called the Cartwright Fracture Zone,* offsets the older group of anomalies on the Labrador side by 90 km in the left lateral sense (Fig. 4). The location of this fracture zone was first noted by van der Linden & Srivastava (1975) from gravity measurements and later confirmed by deep seismic measurements, which are presented later in this paper. This fracture zone forms the western end of the Farewell Fracture Zone delineated by Le Pichon *et al.* (1971) off Southwest Greenland, and lies at an angle of 50° to the Minna Fracture Zone.

The exact processes which take place at the time of a major change in the direction of spreading are not yet well understood though Menard & Atwater (1969) have suggested that during this time ridges usually attempt to orient themselves normal to a new spreading direction in what is probably a 'minimum work' configuration (Vogt *et al.* 1969b). In the present instance instead of a gradual change in the orientation of the ridge axis near the triple junction the ridge jumped and the spreading started in a completely new direction. This is evident from the configuration of the anomalies south of track M18 (Fig. 4). On the Labrador side, anomalies 27 and 24 are close together in the north and diverge in the south. North of track M18 (Fig. 4) the trend of the anomalies agree with Menard & Atwater's (1969) idea of a gradual re-orientation of the ridge axis and anomaly 24 lies parallel to anomaly 25. However, anomalies 20–24 do not lie normal to the new direction of spreading as Menard & Atwater suggested.

Further evidence of a jump in the ridge axis can also be seen if we consider the anomalies between the Cartwright and Charlie Fracture Zones (Fig. 4). The anomalies in this region have been interpreted to belong to anomaly sequence 25 to 31 (Model A, Fig. 5). Also shown in Fig. 5 is Model B based on the proposed rates of spreading for the North Atlantic by Kristoffersen *et al.* (1976). Though both of the models show equally good fit to the observed anomalies, Model A is favoured here because it shows a better fit to the observed anomalies in the Labrador Sea (Fig. 3(b)). This is discussed further later on. A jump of the ridge axis to the east is implied in Fig. 4 as older anomalies lie between anomalies 25 and 24. North of the Charlie Fracture Zone two 24 anomalies can be recognized (Fig. 2). This region was apparently formed due to the separation of the Eurasian plate from the North American plate as it lies south and west of the triple junction. An examination of the magnetic map south of Rockall Plateau (Vogt & Avery 1974, Fig. 2(b)) shows NNW–SSE trending anomalies east of anomaly 24. Their direction agrees well with the direction of the anomalies observed in the present instance north of the Charlie Fracture Zone. Anomalies south of Rockall Plateau have been identified as anomalies 31 and 32 by Roberts (1974). As will be shown later, this identification agrees well with our identification of anomalies north of the Charlie Fracture Zone in the southern Labrador Sea.

The position of anomaly 25 fits well with the position of an extinct ridge proposed by Laughton (1971). Anomaly 26 lies in the vicinity of DSDP hole 112 (Fig. 4). Recent age determination on the basalt obtained at this site shows it to be 56 ± 6 Myr old (Parrott 1976). Even though the basalt sample obtained at this site was very weathered its age does not differ drastically from the age of anomaly 26 (64 Myr).

2.1.1(c) Anomalies on the Continental Shelf. Large amplitude and low frequency anomalies lie on the continental shelf off the southern Labrador coast except near the coast where they are usually of high frequency and are associated with Precambrian basement. North of 56° N (Fig. 2) these anomalies are smaller in amplitude and do not show any pronounced trends like the ones to the south. A number of positive anomalies can be correlated from

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*The name Cartwright Fracture Zone is proposed as this feature lies in the vicinity of a prominent basement high called the Cartwright Arch by McMillan (1973).

track to track on the continental shelf off the southern Labrador coast (52° N and 53° W, Fig. 2) forming bands which run in a NNE–SSW direction. The source of these anomalies lies in the continental crust as most of them can be traced farther to the south off northeast Newfoundland where the basement rocks are definitely continental (Haworth, Grant & Folinsbee 1976).

Large amplitude and high frequency anomalies also lie on the west Greenland shelf close to the coast and have similar characteristics to those observed over the Precambrian rocks on the Labrador coast.

2.1.2 Northwest Atlantic

Figs 2 and 4 show that the direction of spreading in the early phase of spreading (pre-anomaly 25) in the Labrador Sea was quite different from that in the later phase. To relate the direction of spreading in the Labrador Sea during this period to that in the North Atlantic, magnetic data collected south of the Charlie Fracture Zone were compiled in the form of profiles and correlated (Fig. 6). The identification and correlation of anomalies shown in Fig. 6 agree well with those given by Pitman & Talwani (1972) except for minor modifications in their positions in regions where additional data are now available. A large number of east–west tracks, shown by thin dashed lines, lie in the vicinity of 45° N in Fig. 6. Data plotted along all these tracks together with those shown in Fig. 6 were used in deciphering the overall trend of various anomalies.

In spite of the variability in the signatures of the anomalies from track to track they can be correlated (Fig. 6). The variability becomes pronounced for anomalies younger than anomaly 13. North of 50° N the trends of the anomalies shown in Fig. 6 differ significantly from those given by Pitman & Talwani (1972). This is mainly because Pitman & Talwani had assumed that these anomalies continue due north in this region while in fact the data presented here show these anomalies bend to the west similar to those observed on the eastern side of the Atlantic (Williams 1975). The anomalies have been joined by smooth lines though it is possible that they are offset by a large number of coeval fracture zones similar to the ones observed in the Northeastern Atlantic by Johnson & Vogt (1973). The paucity of the data does not allow the definition of such fracture zones in Fig. 6.

Calculated anomalies based on two different rates of spreading are shown in Fig. 6. Model A uses rates of spreading as determined by Pitman & Talwani (1972) for anomalies up to 26 and a slightly higher rate for older anomalies. Model B is based on the rates of spreading proposed by Kristoffersen *et al.* (1976) and Cande & Kristoffersen (1977) where they identify anomaly 31 of Model A as anomaly 33. Their model uses a very slow rate of spreading (10 mm/yr) between anomalies 27 and 33 making anomalies 27 to 31 indistinguishable from one another and leaving anomalies 31, 32 and 33 as the only recognizable anomalies after anomaly 26. On the other hand a faster rate of spreading for Model A (30 mm/yr) between anomalies 27 and 31 makes these anomalies fairly prominent. The anomalies in the Northwest Atlantic (Fig. 6) do show a rather confused pattern beyond anomaly 26 and anomalies 27–31 can only be recognized in a few places (tracks 2–7 and 9 and 10, Fig. 6). The model proposed by Kristoffersen *et al.* would be right if we did not take into account the presence of anomalies 27–31 in the Labrador Sea. The identification of anomaly 31 as given by Pitman & Talwani (1972) for the Northwest Atlantic and by Williams & McKenzie (1971) for the Northeast Atlantic is favoured here because:

(a) Detailed measurements carried out between the Charlie and the Cartwright Fracture Zones along tracks spaced 5 km apart (Figs 1 and 2) failed to show signatures of anomalies 27–31 similar to those obtained in Model B. Several extra anomalies arising due to the variation in the topography of the basement rocks (van der Linden 1975a, Fig. 5), however, were observed in the vicinity of anomaly 25 and were rejected in correlating anomalies between tracks in this region;

(b) A number of semilineated anomalies lie between the ocean–continent boundary (defined by the large amplitude anomalies) and anomaly 32 (Model A, Fig. 6) in the Northwest Atlantic. These anomalies have been identified as anomalies 33 and 34 in Model A. Similar anomalies can also be recognized in the Northeast Atlantic off Porcupine Bank (Williams & McKenzie 1971). South of Flemish Cap, a large number of semilineated anomalies can be seen west of anomaly 34. These anomalies have not been identified here but detailed studies carried out recently in this region by Hall (1976) suggest that the most western anomalies may belong to the Keathley sequence;

(c) Magnetic anomalies north of the Cartwright Fracture Zone in the Labrador Sea (Figs 2 and 6) show better correlation with Model A than with B, thereby supporting the identification of anomalies 27–31 in the North Atlantic; and

(d) Identification of anomalies 31 and 32 off the southern Labrador coast (Fig. 5) fits well with the earlier identification of these anomalies south of the Rockall Plateau (Fig. 17).

2.2 GRAVITY FIELD

The gravity field measured in the Labrador Sea is shown in Fig. 7 in the form of profiles together with the magnetic lineations obtained from Fig. 4. Several features can be readily seen from this figure:

(a) A pronounced gravity low lies in the middle of the Labrador Sea. Except at 60° N, the position of this low matches well with the axis of symmetry in the magnetic lineations thus marking the position of the axis of the extinct mid-Labrador Sea Ridge. The low is most prominent in regions where magnetic anomalies can easily be identified and continues from the triple junction (Kristoffersen & Talwani 1977) north through the Labrador Sea and possibly into Baffin Bay (Ross 1973; Appleton, Keen & Barrett 1975). In the northern Labrador Sea in the vicinity of the Hudson Fracture Zone (62–64° N, Fig. 7) it is not very distinct, perhaps because of the shallowing of the basement (Fig. 10). Another gravity low (less than – 20 mgal) oriented in the north–south direction lies in the Davis Strait region (Fig. 19). Though it is not certain if this gravity low could be considered as an extension of the Labrador Sea gravity low, its position and orientation fit rather well with the expected magnetic axis of symmetry through this region, as will be shown later.

(b) Prominent gravity highs lie on either side of the gravity low throughout the central Labrador Sea. These highs generally coincide with anomaly 21 (Fig. 8) and with the large relief in the basement rocks seen in seismic profiles (Figs 8, 11, and 12).

(c) The dislocation in the gravity low across the No. 1 and Minna Fracture Zones strengthens the evidence for the presence of these fracture zones.

(d) The gravity field off the Labrador coast is different from that off the Greenland coast. A band of large positive anomalies associated with the shelf edge effect lies across the slope off Labrador. Though a similar band can be seen off the Greenland coast its width and amplitude are much smaller. The overall differences in the gravity field off Labrador and Greenland are a result primarily of the differences in the sediment thickness and the basement topography (Fig. 10) in the two regions.

2.3 THE BASEMENT STRUCTURE

Continuous seismic reflection measurements made by the Bedford Institute of Oceanography across the Labrador Sea together with the published and purchased data (Fig. 9) were used

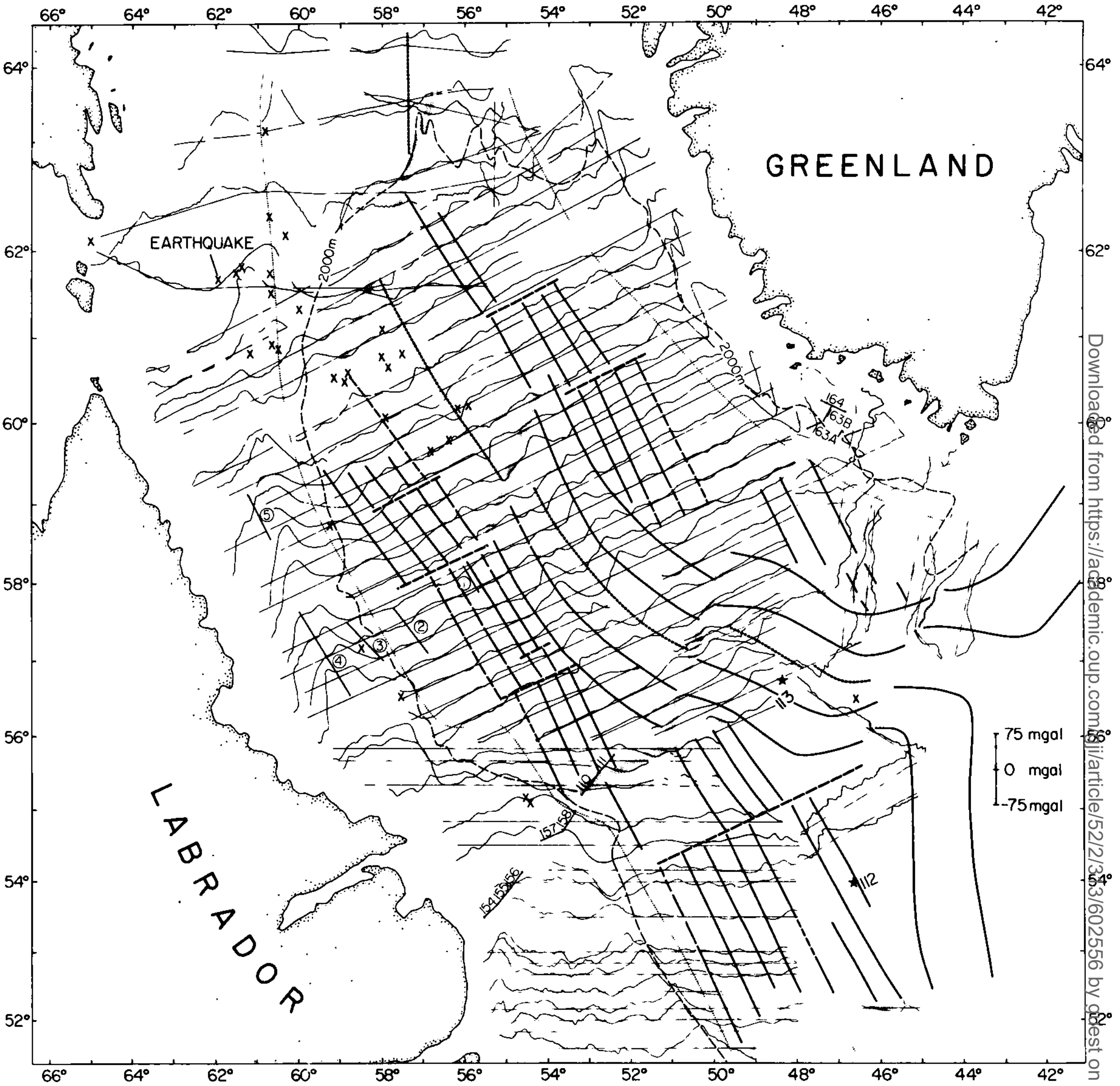

Figure 7. Gravity anomalies plotted along ship's track using the tracks as the base lines. The fracture zones are shown by thick stippled line. The magnetic axis of symmetry coincident with the gravity low is shown by thick dotted line. Also shown are the magnetic lineations obtained from Fig. 4, the location of seismic refraction stations (numbered 110 to 164 after Mayhew *et al.* (1970) and 1–5 after van der Linden (1975b)). the earthquake epicentres as crosses, ocean–continent boundary as thin dotted line and 2000-m water depth contour. Number 112 and 113 refer to DSDP holes.

in compiling a depth-to-basement map (Fig. 10). The basement as interpreted here was recognized as a pronounced reflector that unconformably underlies the sedimentary sequence and constitutes the deepest recognizable primary event on the seismic records. It is devoid of stratigraphic events and has an irregular and undulating surface characterized by the occurrence of numerous hyperbolic reflections. The depth to basement is given in two-way travel time (Fig. 10) rather than in kilometres because of the lack of velocity information

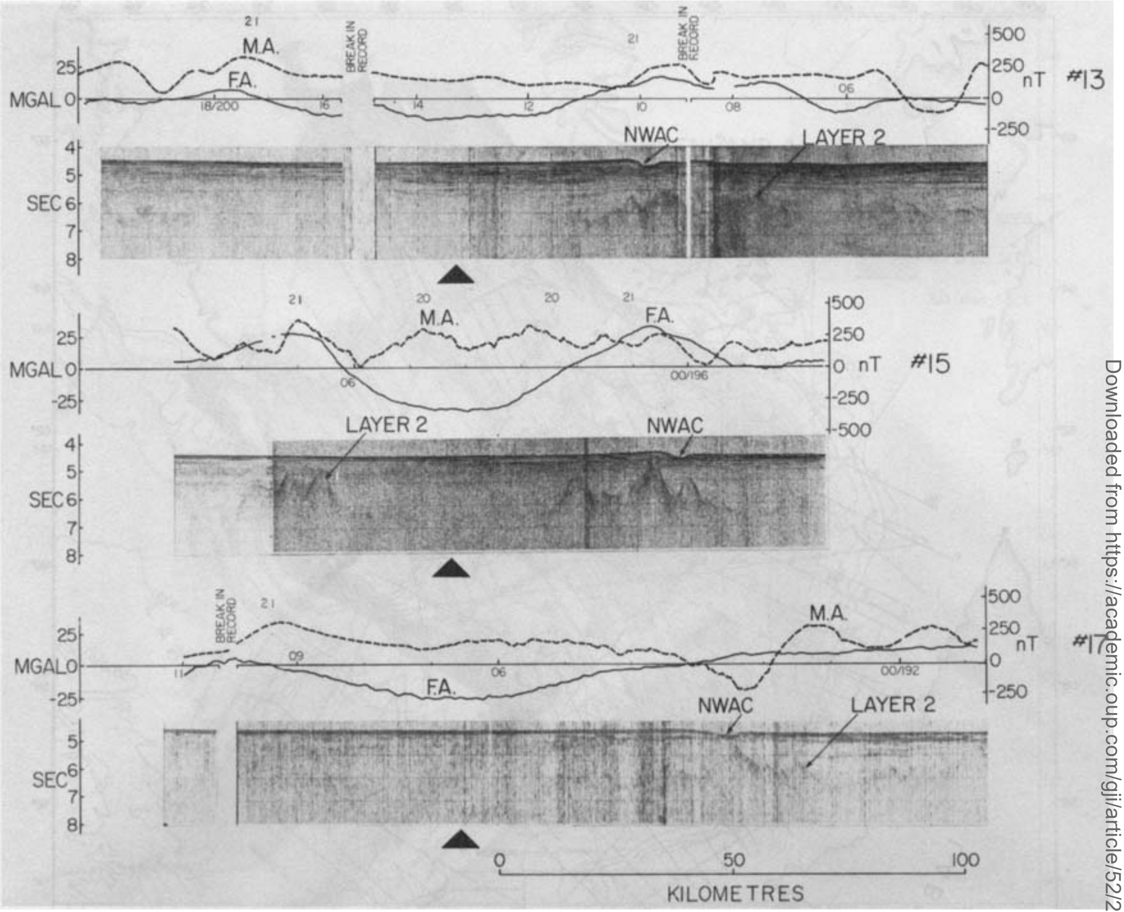

Figure 8. Samples of seismic reflection lines together with free air (F.A.) and magnetic (M.A.) anomalies across the extinct Labrador Sea Ridge. The axis of the ridge is shown by triangles. The location of the profiles are shown in Fig. 9. Numbers on the top refer to anomaly numbers. (NWAC – Northwest Atlantic Channel).

in the Labrador Sea as a whole. Fig. 10 is a simplified map of the basement which shows the broad features together with the magnetic lineations. A detailed map will be published elsewhere. Regions where the basement could not be seen are blank.

The map shows that the Labrador Sea basin is bordered on all sides by basement highs. In the south these highs form a complex pattern of fracture zones and ridges that have been discussed in detail by Egloff & Johnson (1975); Laughton (1972); Kristoffersen & Talwani (1977) and Johnson *et al.* (1973). In the north the basin is bounded by a broad feature with isolated peaks and forms part of the Davis Strait sill. Several fracture zones traverse the Labrador Sea and their positions, as obtained from the dislocation in the magnetic anomalies and the central gravity low, agree well with the overall trends in the basement. Fracture zones in the central and northern Labrador Sea are marked by isolated highs compared to the south where the highs form linear trends in the basement (Leif Fracture Zone) topography. This is partly because the basement in the north is covered by thick sediments (> 2 s) and could not be observed everywhere due to lack of penetration of seismic energy, and partly because of the lack of seismic coverage in these regions which precluded drawing detailed contours around these highs.

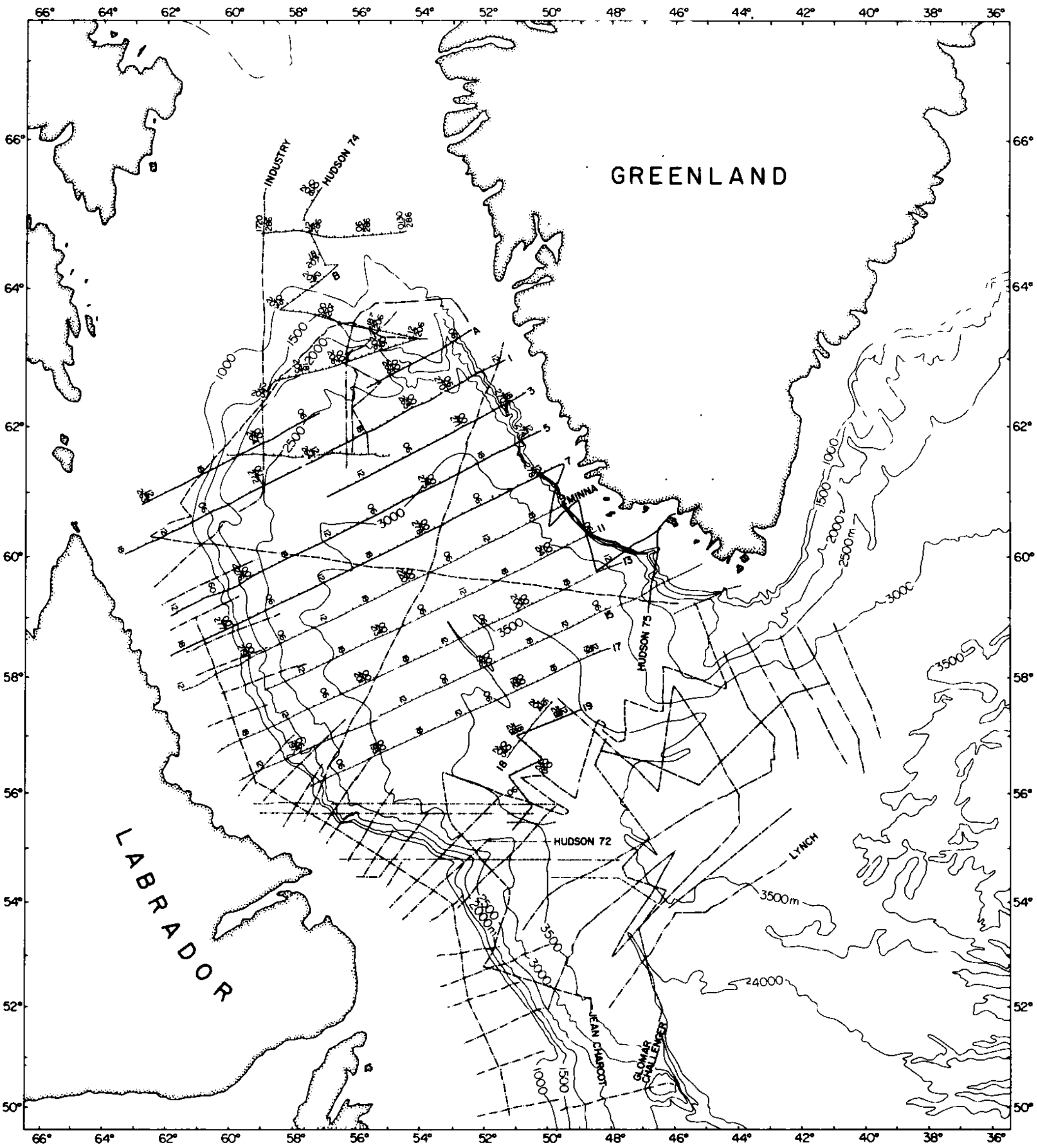

Figure 9. Map showing the ship's track along which seismic reflection data collected in the Labrador Sea have been used in compiling depth-to-basement map shown in Fig. 10. Numbers at the end of the tracks refer to the profile numbers. Some of the tracks whose data have been illustrated here are annotated by day and time.

2.3.1 Labrador Sea Ridge

Seismic observations by Drake *et al.* (1963); Le Pichon *et al.* (1971) and Johnson *et al.* (1969) have shown the existence of a basement high in the middle of the Labrador Sea. This they interpreted as the mid-Labrador Sea ridge. Our data show the presence of a rift valley flanked by two prominent basement highs with reliefs of 1–2 s (Figs 8, 11 and 12). The pronounced gravity low marking the axis of the ridge can be seen in these figures. Two

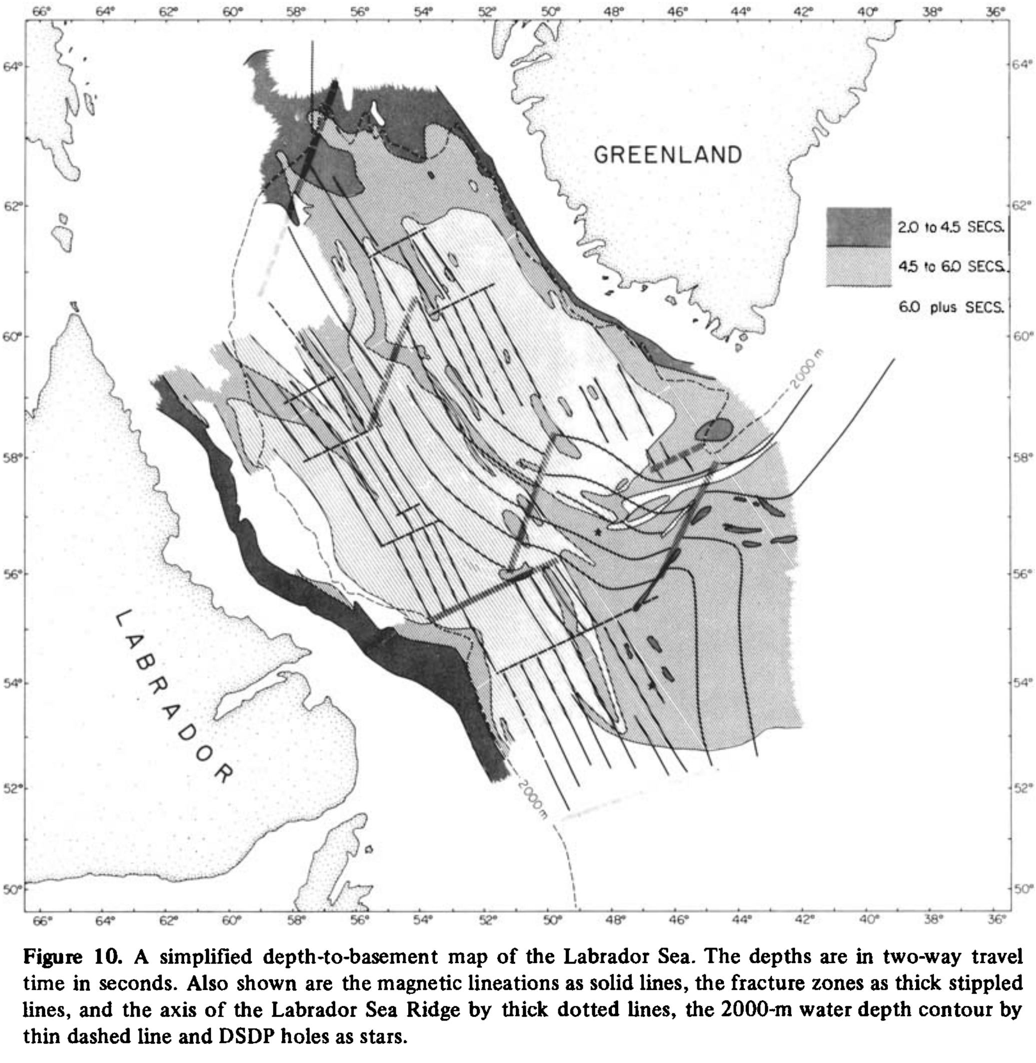

Figure 10. A simplified depth-to-basement map of the Labrador Sea. The depths are in two-way travel time in seconds. Also shown are the magnetic lineations as solid lines, the fracture zones as thick stippled lines, and the axis of the Labrador Sea Ridge by thick dotted lines, the 2000-m water depth contour by thin dashed line and DSDP holes as stars.

isolated basement highs seen under the sediments lie on either side of this gravity low (Fig. 8). The association of these highs with anomalies 20–21 (Fig. 18) shows that they could be related to a major change in the rate of spreading of the Labrador Sea – Fig. 3(a). The basement between the two highs could not be seen in any of the crossings because of the lack of seismic penetration through the overlying sediments. However, a multi-channel seismic record obtained by industry (Fig. 9) shows horizontally layered sediments between the two highs and the basement at a depth exceeding 8-s two-way travel time. The distance between the highs (50–60 km) and size of the gravity low (50–60 mgal) make it an unusually large median valley compared to that observed on present day active ridges. Gravity computation carried out along one of the profiles showed that the base of the median valley has to be at a depth greater than 9 km below sea level to account for the observed anomaly on the basis of topography alone.

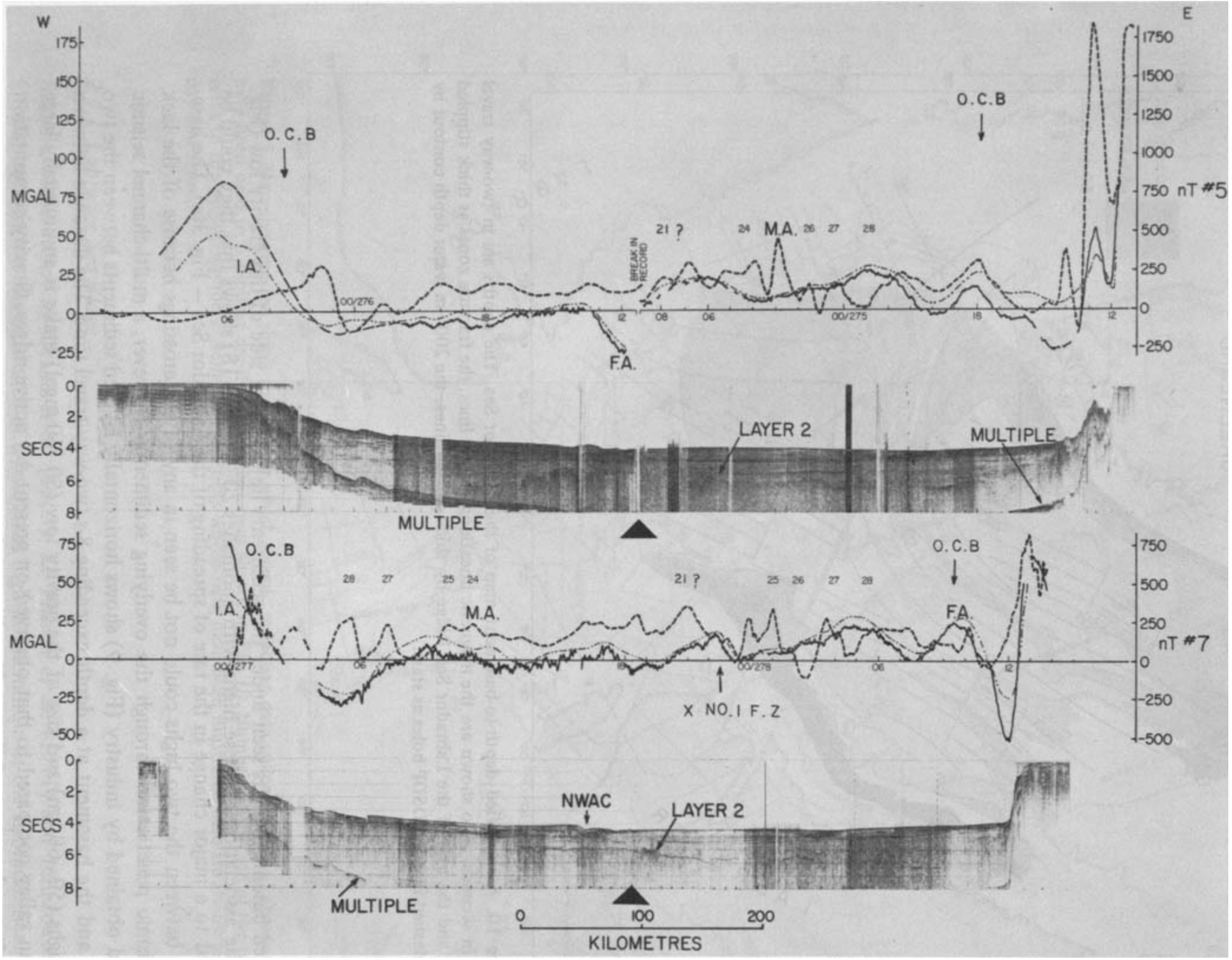

Figure 11. Seismic profiles No. 5 and 7 together with free air (F.A.), isostatic (I.A.) and magnetic (M.A.) anomalies across the Labrador Sea. The locations of the profiles are shown in Fig. 9. Numbers 24–28 refer to anomaly numbers. Solid triangles mark the position of the ridge axis. (NWAC – Northwest Atlantic Channel; OCB – ocean–continent boundary).

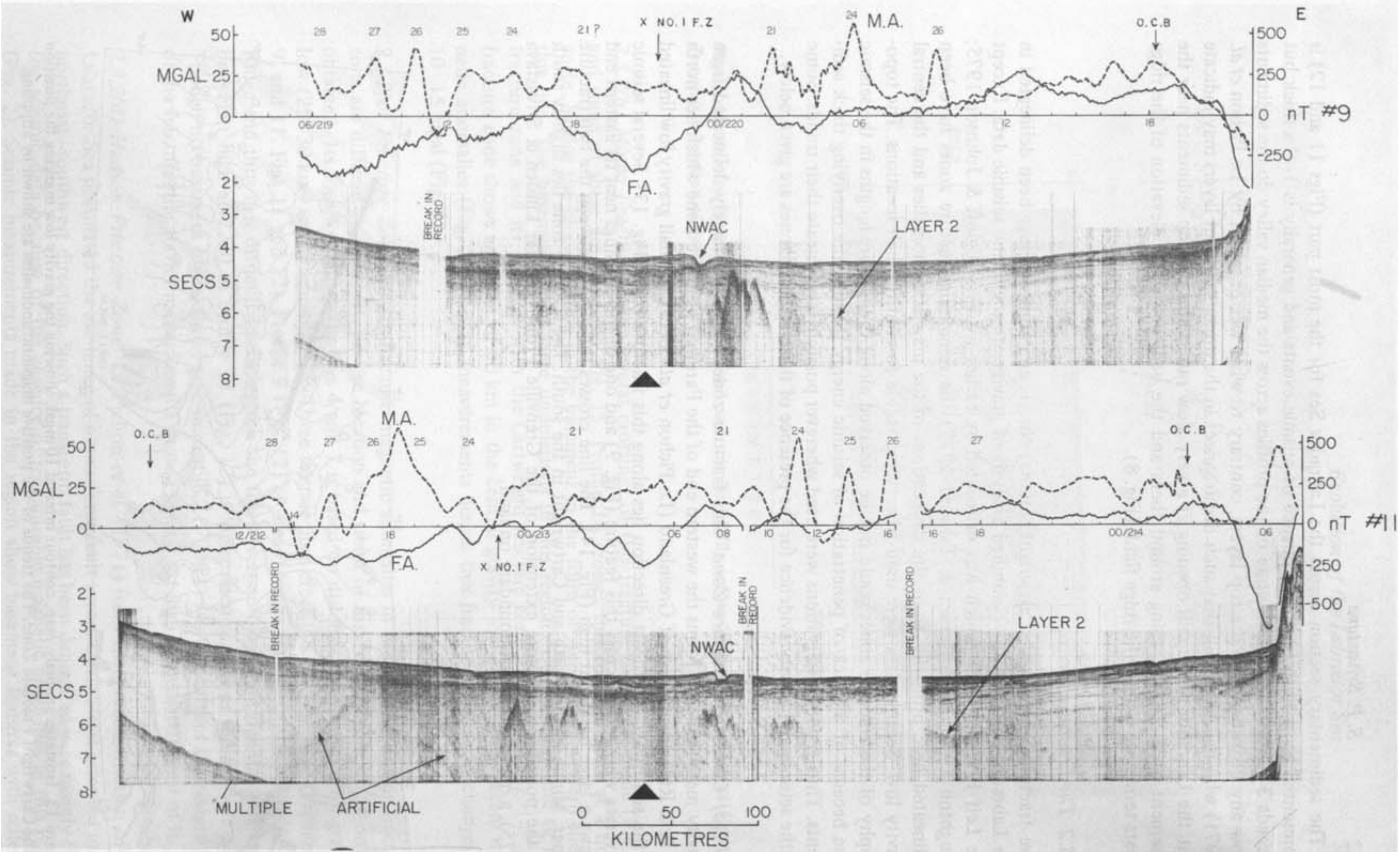

Figure 12. Seismic profiles No. 9 and 11 together with free air (F.A.) and magnetic (M.A.) anomalies across the Labrador Sea. Numbers 21–28 refer to anomaly numbers. The locations of the profiles are shown in Fig. 9. Solid triangles mark the position of the ridge axis. (NWAC – Northwest Atlantic Channel; OCB – ocean–continent boundary.)

The sedimentary section across the Labrador Sea for the most part (Figs 11 and 12) is represented by a fairly regular sequence of seismic events and generally is 1–2 s thick but exceeds 3 s in some areas. In none of the profiles across the median valley do the sediments show any disturbance in the top layers, contrary to what was observed by Le Pichon *et al.* (1971) who had suggested that such disturbances in the upper sediment layers may indicate that the Labrador Sea is still opening at a very slow rate. Only the top sediments near the basement highs show draping around them and the beds below the elevation of the ridge crests terminate against the ridge flank (Fig. 8).

2.3.2 The Fracture Zones

Five fracture zones, Leif, Cartwright, Minna, No. 1, and Hudson, have been delineated in the Labrador Sea from the combined analysis of gravity, magnetic and seismic data. Except the Leif Fracture Zone which was delineated by earlier workers (Egloff & Johnson 1975; Laughton 1972; Kristoffersen & Talwani 1977) the remaining fracture zones have been delineated here primarily from the dislocations of the magnetic anomalies and the central gravity low. Seismic data were used wherever possible to confirm their locations. The topography of the fracture zones could not be observed along their entire lengths in the seismic data because of the lack of penetration of seismic energy through the overlying thick sediments. Thus gravity observations were used wherever possible to delineate their trends. Some of the seismic and gravity evidence for the presence of these fracture zones are given below.

2.3.2(a) Cartwright Fracture Zone. This fracture zone, which was largely delineated from gravity measurements, forms the western end of the Farewell Fracture Zone which lies north of Erik Ridge southwest of Greenland (Le Pichon *et al.* 1971). A small gravity low lineated in the southwest–northeast direction lies along this fracture zone (Fig. 13). Several seismic traverses were made across this feature (Fig. 9) and one of the crossings near its eastern end shows a large basement high (Fig. 14). The line crosses the region between the two fracture zones, Minna in the north and Cartwright in the south. The fracture zone lies slightly south of the postulated offshore extension of the Grenville Front (van der Linden & Srivastava 1975), a major structural boundary on land.

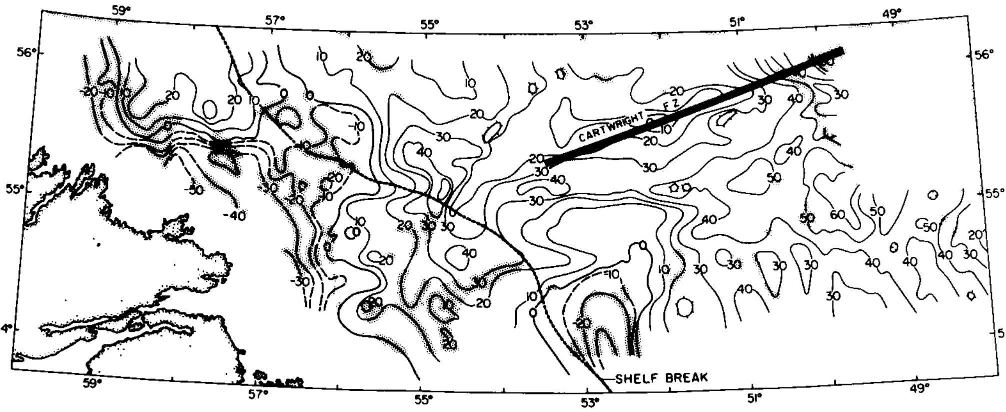

Figure 13. Isostatic anomaly map, contour interval 10 mgal, showing the gravity low marking the position of the Cartwright Fracture Zone. The trends of the positive magnetic anomalies are shown by stippling.

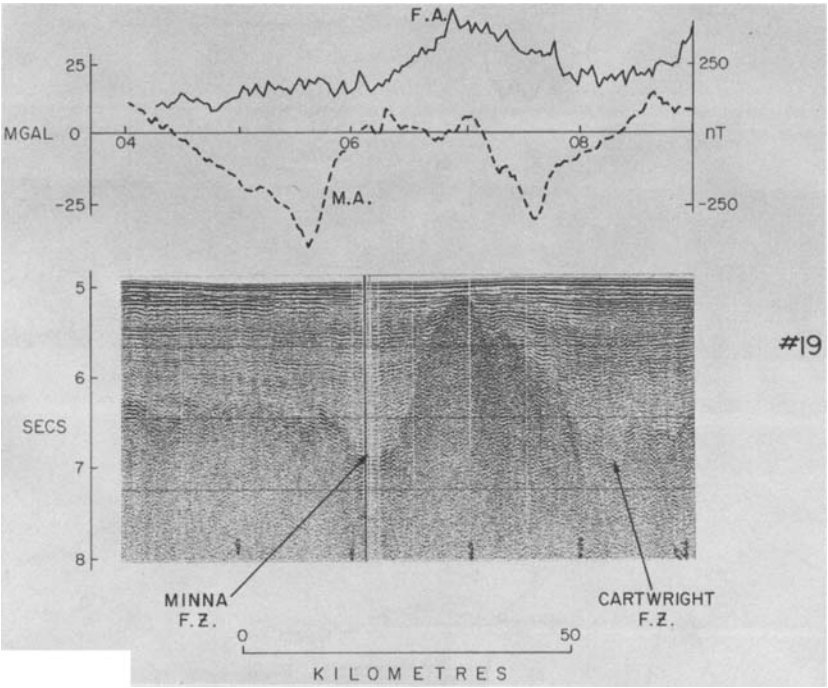

Figure 14. Gravity (F.A.), magnetic (M.A.) and seismic profile across Cartwright and Minna Fracture Zones. For location of profile, see Fig. 9.

2.3.2(b) Minna Fracture Zone. Several crossings of this fracture zone were made (Fig. 9) and some of these are shown in Fig. 15. Profile 18 crosses this fracture zone at a small angle. Notice the block faulting in the basement in the form of steps at the western end of this line. The basement shows large undulations in this region. The southern end of this fracture zone and its junction with the Cartwright fracture zone is shown in Fig. 14. The fracture zone shows an offset of 50 km in the central gravity low and in the adjacent magnetic anomalies (Fig. 7). Gravity measurements across this fracture zone show changes of 10–15 mgal (Fig. 7).

2.3.2(c) Fracture Zone No. 1. Because magnetic anomalies in the vicinity of this fracture zone are difficult to interpret, precise location and trend of this fracture zone could not be obtained. Its location shown in Figs 4 and 7 is based on dislocation of the central gravity low (25–30 km) and of anomaly 24. Three seismic lines cross this fracture zone (Profiles 7, 9, and 11, Figs 11 and 12). Profile 9 (Fig. 12) crosses it in the vicinity of the Labrador Sea Ridge and thus it is difficult to distinguish the fracture zone from the ridge topography. A basement high at 2230 in profile 11 (Fig. 12) is interpreted as part of the fracture zone. Though no basement highs can be seen in profile 7 (Fig. 11) where it crosses the eastern end of the fracture, the gravity measurements show a prominent high immediately west of it.

2.3.2(d) Hudson Fracture Zone. Le Pichon *et al.* (1971) from their reconstruction of the Labrador Sea postulated the existence of a transform fault across Davis Strait oriented in the northeast–southwest direction. Such a transform fault has been delineated here mainly from the seismic data because of the absence of recognizable magnetic anomalies in this region (Fig. 2). Seismic measurements made in the region show basement features with relief of

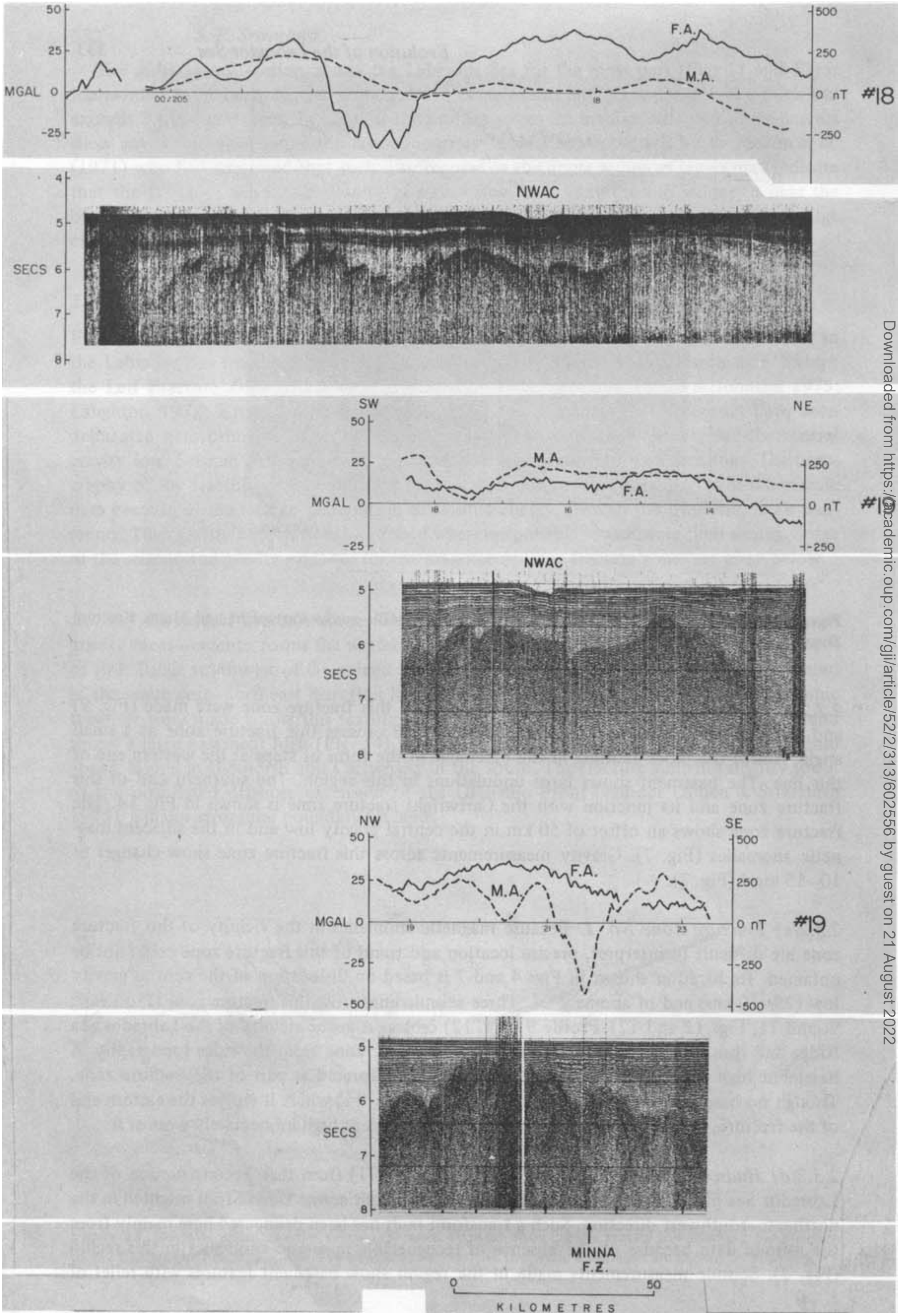

Figure 15. Gravity (F.A.), magnetic (M.A.) and seismic profiles across the Minna Fracture Zone. For location of profiles, see Fig. 9. Profile 18 lies at a small angle to the fracture zone.

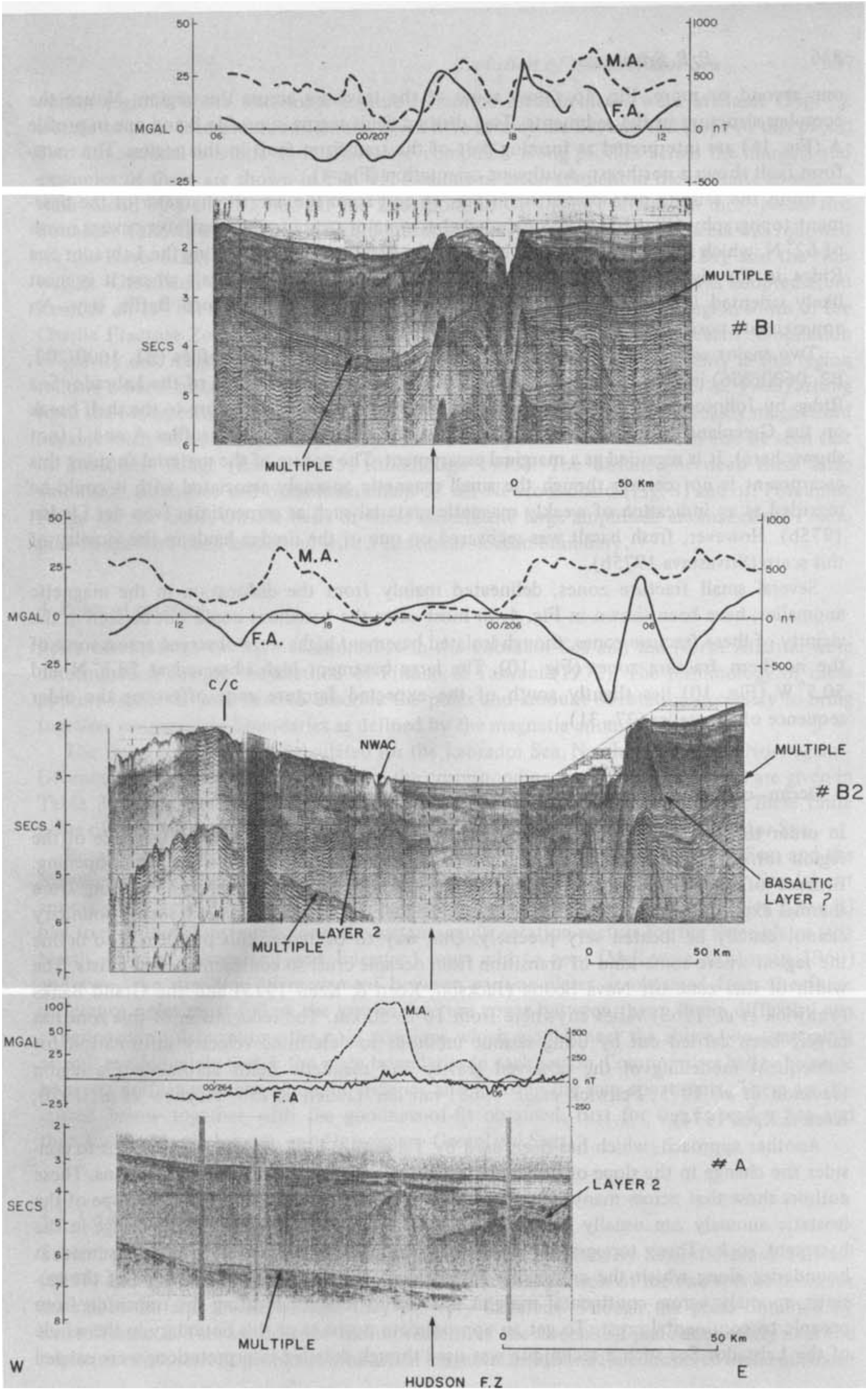

Figure 16. Gravity (F.A.), magnetic (M.A.) and seismic profiles across the Hudson Fracture Zone. For location of profiles, see Fig. 9. The scarp seen at the eastern end of the profiles is interpreted as the marginal escarpment.

one second or more. Fig. 16 shows some of the traverses across this region. Notice the complex structure in the sediments. Two distinct fault scarps in profile B and one in profile A (Fig. 16) are interpreted as forming part of the transform fault in this region. The transform fault shows a northeast–southwest orientation (Fig. 4).

From the seismic data presented in Fig. 16 and from the overall character of the basement topography (Fig. 10) it is concluded that a major structural discontinuity exists north of 62° N, which is interpreted here as the Hudson Fracture Zone offsetting the Labrador Sea Ridge in the right lateral sense. The ridge then enters the Davis Strait where it is most likely oriented in the north–south direction and continues north into Baffin Bay. An approximate position of the fracture zone is shown in Fig. 10.

Two major escarpments can be seen at the eastern end of the profiles (B1, 1600/207; B2, 0600/206) in Fig. 16. These features were interpreted as the crest of the Labrador Sea Ridge by Johnson *et al.* (1969). Because of the proximity of this feature to the shelf break on the Greenland side and its continuation to the south as seen in profiles A and 1 (not shown here), it is regarded as a marginal escarpment. The nature of the material forming this escarpment is not certain though the small magnetic anomaly associated with it could be regarded as an indication of weakly magnetic material such as serpentinite (van der Linden 1975b). However, fresh basalt was recovered on one of the dredge hauls in the vicinity of this scarp (Srivastava 1975b).

Several small fracture zones, delineated mainly from the dislocation in the magnetic anomalies, have been shown in Fig. 4. In most cases the basement could not be seen in the vicinity of these fracture zones, though isolated basement highs were observed across some of the northern fracture zones (Fig. 10). The large basement high observed at 58.5° N and 50.5° W (Fig. 10) lies slightly south of the expected fracture zone offsetting the older sequence of anomalies (27–31).

3 Ocean–continent boundary

In order to carry out any palaeoreconstruction of continents located on either side of the region formed by seafloor spreading, it is necessary to define the line of initial opening. Because of the deformation of this boundary during and after the rifting resulting from thermal expansion and contraction of the lithospheric plates (Sleep 1971), such a boundary cannot usually be located very precisely. One way to overcome this problem is to define the region where some kind of transition from oceanic crust to continental crust exists. The width of this zone off Nova Scotia (Jackson, Keen & Keen 1975) and the Grand Banks (Fenwick *et al.* 1968) varies anywhere from 10 to 50 km. The recognition of this zone has largely been carried out by using seismic methods to determine velocity information for subsequent modelling of the observed gravity and magnetic fields across such a region (Jackson *et al.* 1975; Fenwick *et al.* 1968; van der Linden 1975b; Mayhew *et al.* 1970; Keen & Keen 1974).

Another approach, which has been used by Talwani & Eldholm (1972, 1973), is to consider the change in the slope of the isostatic anomalies across the continental margins. These authors show that across many rifted continental margins a sharp change in the slope of the isostatic anomaly can usually be associated with some kind of escarpment or ridge in the basement rock. These topographic changes in the basement rocks have been assumed as boundaries along which the continents rifted apart. Thus a change in the slope of the isostatic anomaly across continental margins is a useful tool for locating the transition from oceanic to continental crust. To get an approximate position of this boundary in the whole of the Labrador Sea such a technique was used though detailed interpretations were carried out in regions where additional seismic refraction measurements were available (Fig. 7). Details of these interpretations are not given here as they are beyond the scope of this paper. Two-dimensional isostatic anomalies were computed along profiles across the margins and examples of them are shown in Fig. 11. Regions of steep gradient in the isostatic anomalies were joined by a smooth line off the Labrador and Greenland margins. In most places this boundary follows the 2000-m depth contour (Figs 2 and 7). A similar process was followed for the Davis Strait region and the result is shown in Fig. 19. For Baffin Bay and the Norwegian–Greenland Seas the position of the continent–ocean boundary was adopted from Keen *et al.* (1974) and Talwani & Eldholm (1977) respectively. For the region south of the Charlie Fracture Zone the position of this boundary was taken from the recent compilation of gravity and magnetic field of Haworth (1977) for this region. The boundary in this region follows a band of large amplitude positive magnetic anomalies (Fenwick *et al.* 1968) arising from the juxtaposition of highly magnetized continental crust against the weakly magnetized oceanic crust of normal polarity. A similar band of positive anomalies can also be seen east of Porcupine Ridge (Bailey 1975; Riddihough 1975). The distance between these large amplitude anomalies and oceanic anomaly 32 off Newfoundland (Fig. 3) and off Porcupine Ridge are the same. On the basis of these criteria the large amplitude anomalies off Porcupine Ridge have been associated with a continent–ocean boundary.

4 Poles of rotation

Poles of rotations for various anomalies in the Labrador Sea and the North Atlantic were determined following the method of Pitman & Talwani (1972). The terminology of these authors has been used here to describe the poles and amount of rotation necessary to bring together various plate boundaries as defined by the magnetic anomalies.

The finite rotation poles calculated for the Labrador Sea, North Atlantic and Norwegian–Greenland Seas are given in Table 2 and the corresponding finite difference poles are given in Table 3. Anomalies 21, 24, 25, 28, 31, and 32 have been used in calculating these finite poles of rotation primarily because they are the easiest to recognize in the Labrador Sea.

Because of the simultaneous spreading in the North Atlantic, the Labrador Sea, and the Norwegian–Greenland Seas prior to cessation of spreading in the Labrador Sea (about anomaly 13 time) the pole positions determined in each of these regions (Tables 2 and 3) had to meet two constraints: one, the instantaneous rotation vectors for the three plates (the North Atlantic, Greenland and Eurasian) must add to zero (McKenzie & Morgan 1969) and two, the direction of movement between various plates as obtained from the finite difference poles must follow the known fracture zones between them. Some difficulty was experienced in determining the pole positions which would meet the above two constraints as well as adequately match the plate boundaries in each region. Compromises had to be made between perfect matches of the boundaries and meeting the two constraints. These are discussed below together with the goodness-of-fit obtained, first for the Labrador Sea and then for the North Atlantic and Norwegian–Greenland Seas.

4.1 LABRADOR SEA

Table 2 gives the poles of rotation for the Labrador Sea obtained by Kristoffersen & Talwani (1977) and the poles deduced in the present work. Comparison of the two sets of poles for anomalies 21 and 24 shows that they are very different. Though the poles obtained by Kristoffersen & Talwani describe the movement of the Greenland plate adequately near the triple junction, serious problems arise when magnetic lineations are considered in the northern

Table 2. Finite rotations required to rotate anomalies on the west to the east side of various ridges into coincidence. Rotations to the east are considered positive.

Anomalies	Age (Myr)	Lat. of Pole	Long. of Pole	Finite rotation (deg.)
Labrador Sea				
21	53	13.00 N	2.00 E	−1.10
24	60	26.00 N	1.50 E	−2.80
25	63	28.50 N	13.60 W	−3.53
28	68	50.10 N	163.70 W	4.40
31	72	66.00 N	142.90 W	7.68
32	75	69.60 N	133.40 N	9.48
33	78	71.50 N	126.30 N	11.04†
● After Kristoffersen & Talwani (1977)				
21	53	42.20 N	144.20 W	1.15
24	60	54.00 N	116.40 W	3.34
North Atlantic				
13	38	68.00 N	129.90 E	7.78*
21	53	50.77 N	142.80 E	9.78
24	60	40.00 N	145.00 E	11.40
25	63	51.52 N	146.50 E	13.12
31	72	68.40 N	150.00 E	18.89
32	75	70.80 N	150.93 E	20.33
33	78	72.63 N	151.82 E	21.60
Initial opening	90	75.71 N	153.82 E	24.22
● After Pitman & Talwani (1972)				
13	38	65.00 N	133.00 E	7.60
21	53	56.00 N	144.00 E	9.90
25	63	63.00 N	157.00 E	14.00
31	72	77.00 N	160.00 E	20.50
Norwegian Sea				
13	38	68.00 N	129.90 E	7.78*
21	53	55.00 N	135.00 E	9.50
24	60	50.20	130.87 E	10.97
* After Talwani & Eldholm (1977)				
13	38	68.00 N	129.90 E	7.78
21	53	52.40 N	125.90 E	8.79
23	58	46.00 N	125.00 E	9.52

† Based on anomaly identification off Rockall Bank.

Labrador Sea. Admittedly the identification of anomalies 20–24 is difficult in the northern Labrador Sea, as was pointed out earlier, and other interpretations are possible. Nonetheless, when the position of the anomalies older than 24 in this region, which are better developed and easy to identify, are considered, it is found that the pole for anomaly 24 given by Kristoffersen & Talwani (1977) predicts a smaller separation between the older anomalies at the time of anomaly 24 than that actually observed.

If it is assumed that there was no movement between the Greenland and Eurasian plates prior to anomaly 25 time, then anomalies 25 to 31 observed in the Labrador Sea should belong to a similar group of anomalies observed in the North Atlantic south of 55.0° N. In other words, the pole positions determined for the North Atlantic to describe the movement between the North American and the Eurasian plates during anomaly 25–31 time

Table 3. Finite differences of rotations.

Anomalies	Time span (Myr)	Coordinates of pole of rotation					
		Latitude	Longitude	Finite rotation	Latitude	Longitude	Finite rotation
		Reference frame fixed to North America			Reference frame fixed to Greenland		
Labrador Sea							
13 to 21	15	13.00 N	2.00 E	1.10	13.00 N	2.00 E	−1.10
21 to 24	7	34.13 N	0.89 E	1.75	34.15 N	1.37 E	−1.75
24 to 25	3	25.00 N	57.50 W	1.05	27.16 N	58.10 W	−1.05
25 to 28	5	71.50 N	80.00 W	−5.30	74.32 N	77.43 W	5.30
28 to 31	4	71.50 N	80.00 W	−3.80	74.32 N	77.43 W	3.80
31 to 32	3	*72.00 N	68.00 W	−1.96	*75.04 N	63.35 W	1.96
32 to 33	3	*72.00 N	68.00 W	−1.64	*75.04 N	63.35 W	1.64
North Atlantic		Reference frame fixed to North America			Reference frame fixed to Eurasia		
13 to 21	15	5.57 N	150.40 E	−3.42	6.75 N	157.33 E	3.42
21 to 24	7	5.75 N	33.88 W	2.57	4.96 N	25.72 W	−2.57
24 to 25	3	76.00 N	76.00 W	−3.00	79.03 N	30.70 W	3.00
25 to 31	9	78.00 N	76.00 W	−7.40	80.43 N	23.56 W	7.40
31 to 32	3	78.00 N	76.00 W	−1.66	80.43 N	23.56 W	1.66
32 to 33	3	78.00 N	76.00 W	−1.44	80.43 N	23.56 W	1.44
33 to initial opening	12	*78.00 N	76.00 W	−2.90	80.43 N	23.56 W	2.90

*Assumed.

should adequately describe the movement between the North American and the Greenland plates. However, no pole position could be found which would match the plate boundaries in the Labrador Sea and the North Atlantic adequately as well as give the right direction of movement between the plates. Thus, separate poles for the Labrador Sea and the North Atlantic had to be determined (Table 2).

Anomaly 32 is the oldest anomaly which can be recognized in the southern Labrador Sea immediately north of the Charlie Fracture Zone. Its absence in the central and northern Labrador Sea and its proximity to the ocean–continent boundary (Fig. 2) in the south suggests that the initial rifting in the central and northern Labrador Sea started at or just after the time of anomaly 32. Thus the pole of initial opening for the Labrador Sea was determined by assuming that Greenland was not joined to the Eurasian plate at anomaly 32 time and the movement between Greenland and North America was parallel to the Charlie Fracture Zone west of 46° W because it resulted in a better overall fit between the North American and Greenland plates for this time – Fig. 21(d). If it is assumed that Greenland was joined to the Eurasian plate at this time, a serious overlap occurs in the Labrador Sea and Davis Strait.

Within the region where the anomalies have been identified (Fig. 2) the poles for various anomalies do fit well. To demonstrate this the anomalies on the eastern side of the axis of symmetry (shown as filled circles) are rotated to the west and their rotated positions are shown as crosses (Fig. 17). The crosses fall on their respective anomalies on the west side of the axis of symmetry, and this indicates that the opening of the Labrador Sea is represented accurately by the finite rotation poles given in Table 2 for various anomalies. Also shown in this figure are the synthetic flow lines generated from the finite differential poles of rotation, Table 3, and the mean direction of the fracture zones. Parallelism between the flow lines and the fracture zones shows clearly that the movement between the Greenland and the

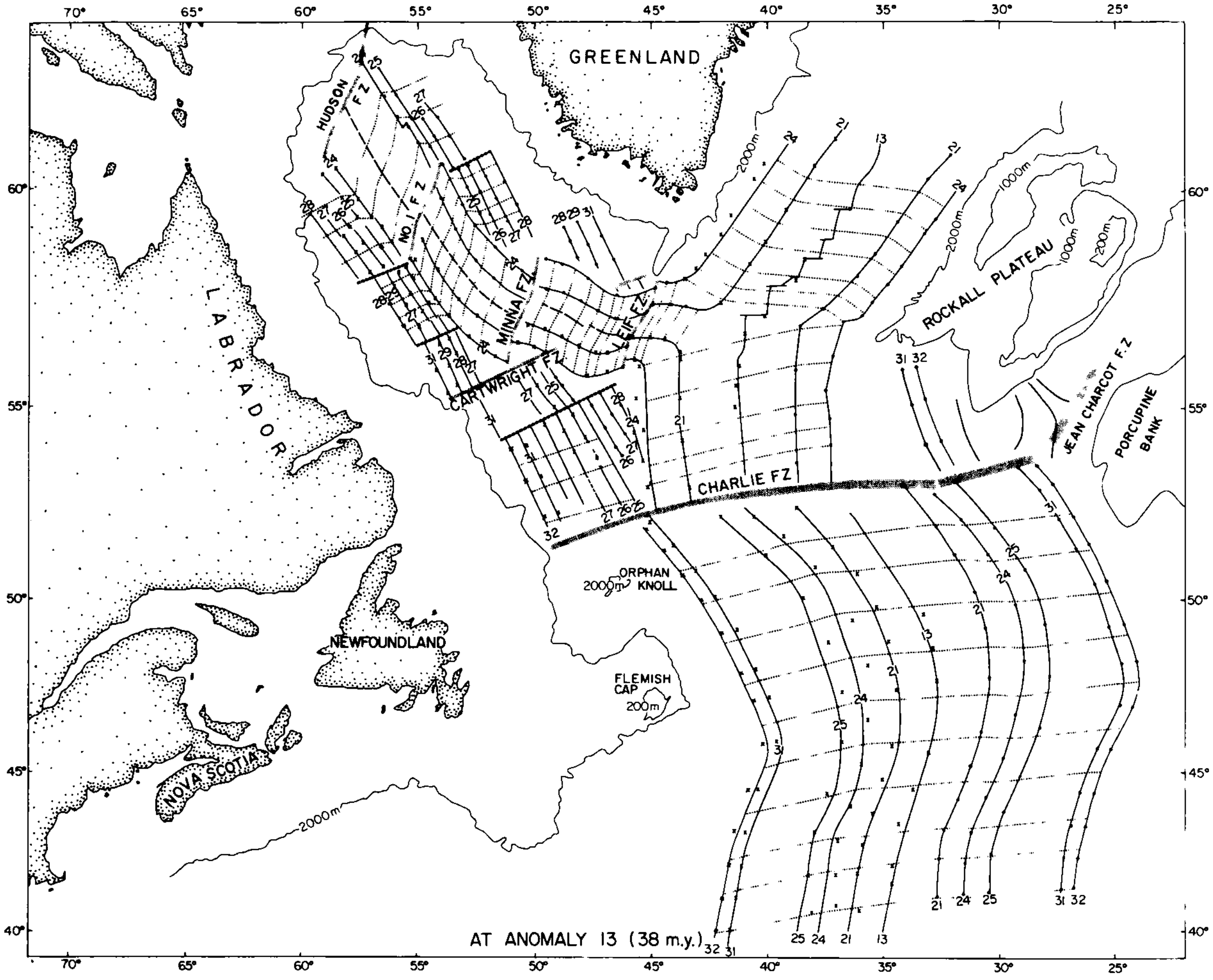

Figure 17. Magnetic lineations in the North Atlantic and the Labrador Sea at the time of anomaly 13. In the reconstruction, North America has been kept fixed. Magnetic lineation 13 to 32 for the Northeast Atlantic were taken from the published work (for details see text) while for the Northwest Atlantic and Labrador Sea they were obtained from those shown in Figs 6 and 2 respectively. The positions of the unrotated anomalies are shown by filled circles and of the rotated anomalies by crosses. The fracture zones are shown by thick stippled lines. The dotted lines indicate flow lines generated from the data in Table 3. The dashed lines indicate dislocation in the magnetic lineations.

North American plates is represented accurately by the poles determined here. Anomalies 20–24 lie at a very steep angle (about 35°) to the flow lines. Such obliqueness in the direction of spreading (Roots 1976) may account for the small amplitudes of the anomalies in the northern Labrador Sea. Why anomalies older than 24 cannot be recognized in the northern Labrador Sea is not certain. Great thicknesses of sediment (10 km or more) lie off the northern Labrador coast (Grant 1975a) and it is possible that anomalies between 25–28 are highly attenuated due to the rapid sedimentation in this region during the time when these anomalies were formed. This would raise the temperature of the magnetic upper layer enough to erase the magnetization (Vogt *et al.* 1970) of the rocks. Such a process was also suggested by Le Pichon *et al.* (1971) for this region.

4.2 NORTH ATLANTIC OCEAN AND NORWEGIAN–GREENLAND SEAS

In determining the poles of rotations for the North Atlantic, the anomaly identifications of Williams (1975); Williams & McKenzie (1971); Pitman & Talwani (1972); Johnson, Vogt & Schneider (1971); Johnson & Vogt (1973) and Vogt & Avery (1974) for the eastern side of the Atlantic were used. The determinations were only carried out for anomalies older than anomaly 13 because just prior to the formation of anomaly 13 the Greenland plate started to move as part of the North American plate (Kristoffersen & Talwani 1977). The poles so determined are listed in Tables 2 and 3.

The pole of rotation for anomaly 13 for the North Atlantic and the Norwegian–Greenland Sea is adopted from Talwani & Eldholm (1977) as it seems to give a reasonable fit when the eastern side of anomaly 13 is rotated to the west (Fig. 17).

The pole of rotation for anomaly 21 given by Pitman & Talwani (1972) for the North Atlantic was modified until a reasonable fit between the rotated and unrotated anomalies in the North Atlantic as well as in the Norwegian Sea could be obtained and the two constraints mentioned earlier were fully met. Similar procedures were followed to determine the pole of rotation for anomaly 24 except that no single North Atlantic pole could be obtained to adequately account for the direction and amount of opening in the North Atlantic as well as provide expected rotations in the Norwegian–Greenland Seas. Kristoffersen & Talwani (1977) also observed this difficulty. Poles of rotation could be determined to match plate boundaries adequately either for the region between the triple junction and the Azores–Gibraltar Fracture Zone (56.6° N, 147.02° W, rotation 11.82°) or for the region north of the Charlie Fracture Zone including the Norwegian–Greenland Seas (35.12° N, 144.65° W, rotation 11.0°). In both cases the constraints imposed for the movement near the triple junction were fully met. In the former instance rotation of anomaly 24 from the eastern to the western side gave a gap of 50 km in the Norwegian Sea with a considerable overlap between Spitsbergen and Greenland, while in the latter instance a similar rotation gave a gap of 100 km for the region south of the Charlie Fracture Zone. This could be due to the erroneous identification of this anomaly in the North Atlantic and in the Norwegian–Greenland Seas.

The identification of anomaly 24 in the Norwegian–Greenland Seas was adopted from Talwani & Eldholm's (1977) identifications and no attempt was made to modify it in the absence of any additional available data. A large amount of aeromagnetic data has been collected recently in the Norwegian–Greenland Seas as well as in the Eurasian Basin (Phillips *et al.* 1976) which may result in a better identification of this anomaly in these regions than has been possible so far. The pole positions determined here are based on the location of the identified anomalies in the North Atlantic and the Norwegian Sea only.

A compromise was thus sought in determining the pole of rotation for anomaly 24 for the North Atlantic (Table 2). The pole so determined matches the plate boundaries well throughout the area except in the south (near 40° N) where a gap of 50 km exists (Fig. 17). Considering the size of the plates involved (44° of latitude or approximately 4840 km in length) and the uncertainty of locating the anomaly in the whole of the North Atlantic precisely, a gap of 50 km can hardly be considered serious. The direction of movement between various plates as obtained from the flow lines between anomalies 21 and 24 agrees well with the known direction of the fracture zones.

Finite poles of rotation for anomalies 25 and 31 were determined (Table 2) for the region between 55° N and 40° N (Figs 2 and 6) in the North Atlantic. The pole positions for these anomalies were determined on the assumption that: (a) the Eurasian plate was not fixed to the Greenland plate during this time (the reasons for this are given earlier), and (b) the direction of movement between the North American and Eurasian plates is adequately described by the trend of the Charlie Fracture Zone west of 46° W (Olivet *et al.* 1974; Vogt & Avery 1974) shown in Fig. 2. It was further assumed that the broad positive anomalies south of the Rockall Plateau in Vogt & Avery's (1974) map form anomalies 31 and 32 whose western counterparts are observed off Labrador (Fig. 5). The finite difference pole of rotation between anomaly 31 and the time of initial opening (Table 3) was assumed to be the same as between 25 and 31.

4.3 IMPLICATIONS OF THE SEA FLOOR SPREADING IN THE LABRADOR SEA TO THE DAVIS STRAIT AND BAFFIN BAY REGION

The origin of Baffin Bay has been the subject of controversy for a long time (Kerr 1967a; McMillan 1973; Keen *et al.* 1974; Beh 1975), mainly because the Bay lacks structure similar to that seen across regions developed by seafloor spreading. Only the velocities determined by seismic measurements (Keen *et al.* 1972; Keen & Barrett 1972) resemble those of an oceanic basin. No basement features in the central Bay that could relate to an extinct spreading centre have been observed, though the detailed gravity measurements of Appleton *et al.* (1975) in the centre of the Bay show a gravity low similar to the one observed over the extinct Labrador Sea Ridge. The width of the gravity low is much smaller (about 30 km) than that seen in the Labrador Sea (75 km). The magnetic anomalies in the centre of the Bay (Hood & Bower 1975) are subdued in amplitude and difficult to correlate, though detailed measurements in a small area show some correlation (Appleton *et al.* 1975).

If the lithospheric plates are considered as rigid plates – an assumption which seems to be valid for the North Atlantic; for details, see Pitman & Talwani (1972) and Talwani & Eldholm (1977) – then the seafloor spreading in the Labrador Sea has direct bearing on the evolution of the region north of it. The question arises how well the gravity and magnetic observations in Baffin Bay and Davis Strait region fit with their expected trends based on the poles of rotation for the Labrador Sea? This is examined briefly here.

Fig. 18 shows the aeromagnetic profiles in Davis Strait and Baffin Bay region from a recent publication by Hood & Bower (1975). Also shown in this figure are the expected positions of anomalies 21, 24 and 25 based on the Labrador Sea poles as well as a computed profile. The ridge axis in Baffin Bay has been assumed to lie in the centre of the Bay along a small gravity low observed in the free air map of this region (Ross 1973; Appleton *et al.* 1975). Two things can be seen from this map. Firstly, large amplitude, high frequency anomalies oriented northeast–southwest lie on either side of Davis Strait. This was interpreted by Hood & Bower (1975) as representing a fracture zone. The location of this zone coincides reasonably well with the transform fault postulated by Kerr (1967a) and McMillan (1973). Secondly, some correlation of anomalies exists among the profiles. Because the

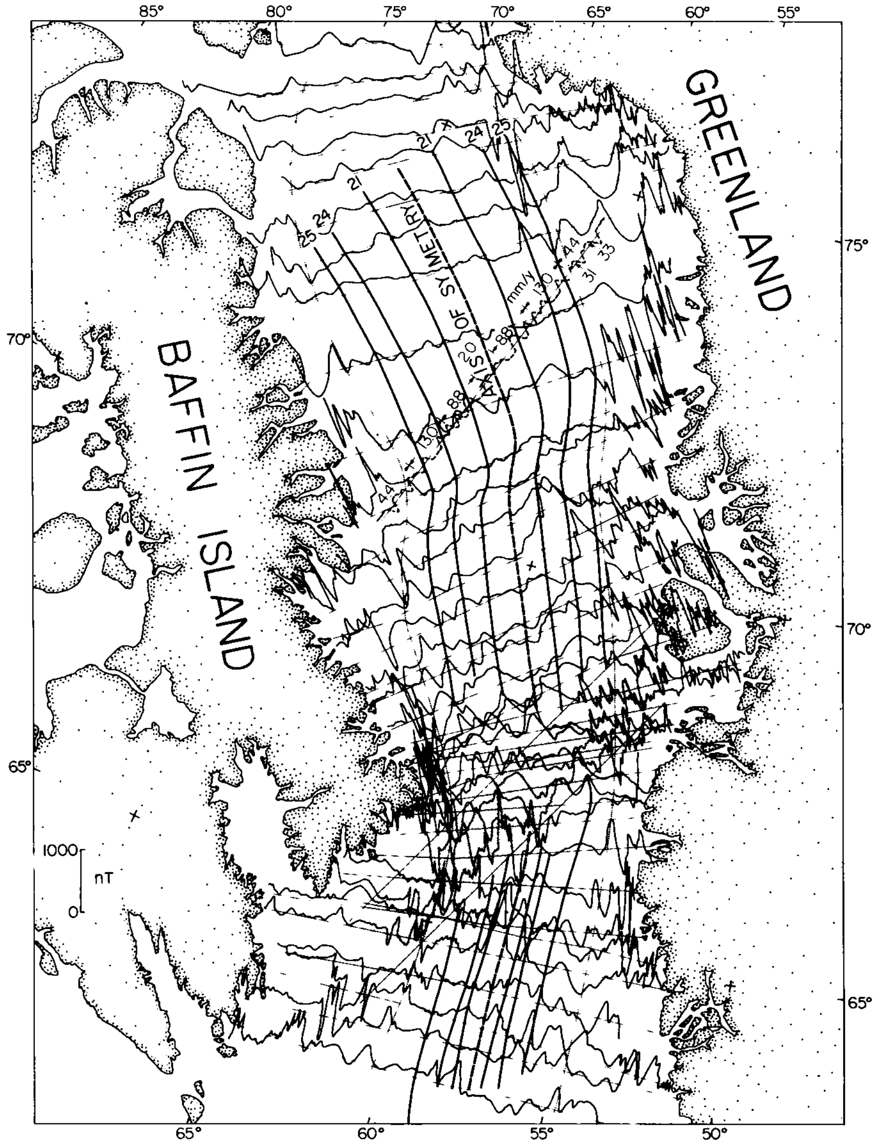

Figure 18. Aeromagnetic profiles plotted along flight path (After Hood & Bower 1975) across Baffin Bay and Davis Strait. Synthetic isochrons showing the correlation of anomalies between tracks were generated from the data given in Tables 2 and 3 for the Labrador Sea. Synthetic profile generated along a flow line through the northern Baffin Bay is shown by dotted line together with the rate of spreading in millimetres per year. The thick stippled area in the south marks the position of a linear feature whose direction coincides with the direction of the plate motions in this region.

anomalies have very subdued amplitudes in most of the Bay and show variations from track to track, other interpretations are possible (Hood & Bower 1973, 1975).

Gravity data collected in the Davis Strait region together with the data in the north (Ross 1973) was contoured at 20-mgal intervals (Fig. 19). A small gravity low oriented north–south along 57° W lies east of a band of gravity highs which is oriented northeast–southwest. Large positive values of gravity anomalies lie in the regions of high-frequency, large-amplitude

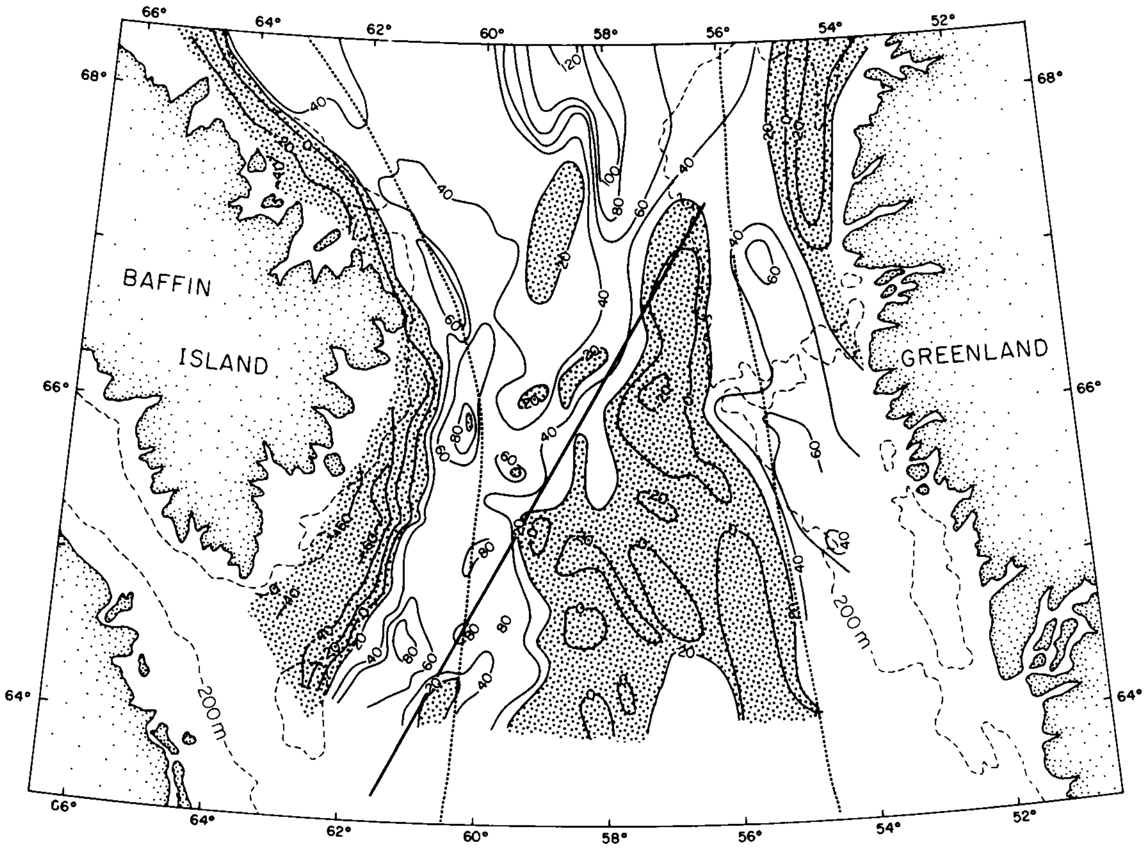

Figure 19. Free air gravity map, contour interval 20 mgal across Davis Strait. Area below 20 mgal is shown by stippling. The direction of high frequency magnetic anomalies as obtained in Fig. 18 is shown by solid line. The ocean–continent boundary is shown by dotted line and the 200-m water depth contour by dashed line.

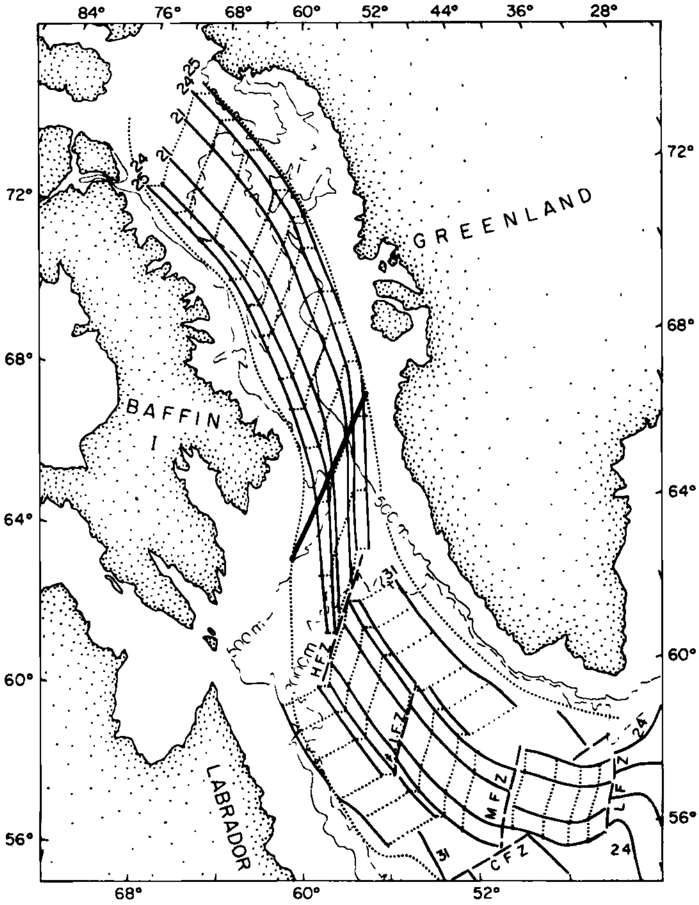

Figure 20. Flow lines (shown by dotted lines) and the synthetic isochrons (shown by solid lines) in Labrador Sea and Baffin Bay generated from the data given in Table 3. Also shown are 500 and 2000-m water depth contours, the ocean–continent boundary as thick dotted line, direction of the linear feature through Davis Strait as thick line, and various fracture zones as thin dashed lines. (L.F.Z. – Leif Fracture Zone; M.F.Z. – Minna Fracture Zone; 1.F.Z. – No. 1 Fracture Zone; H.F.Z. – Hudson Fracture Zone; C.F.Z. – Cartwright Fracture Zone.)

magnetic anomalies (64° N, 61° W and 68° N, 57° W). Also shown in Fig. 19 is the direction of the zone of high-frequency magnetic anomalies as obtained from Fig. 18. Coincidence of the trends in gravity and magnetic data suggest that they are inter-related.

To examine the relation of this feature with the direction of movement of the Greenland plate relative to the North American plate, flow lines were generated for Baffin Bay, Davis Strait, and Labrador Sea (Fig. 20) using the finite difference poles of rotation for the Labrador Sea (Table 3). The parallelism between the flow lines (between anomalies 24) and the lineament (obtained from Figs 18 and 19) clearly indicate that the high-amplitude gravity and magnetic anomalies which lie at either end of this lineament must have formed a continuous band prior to anomaly 24 time. The nature of the material forming such a continuous band is not certain but it could be basalt as postulated by Grant (1975b) for the region off Baffin Island. Tertiary basalt lies on Cape Dyer on the Canadian side and on Disko Island on the Greenland side – Fig. 21(c). Seismic reflection measurements across the Strait (Beh 1975) show that these basalts are not continuous across it, at least as a near surface feature. The offshore extension of these basalts is more pronounced off Disko Island than off Baffin Island (Park, Clarke & Keen 1971; Ross & Henderson 1973; Hood & Bower 1973). It is likely that the excessive basalt giving rise to high-amplitude gravity and magnetic anomalies may have been formed at the time of anomaly 25 when the direction of plate motion changed from east–west to northeast–southwest in this region.

The flow lines in Fig. 20 show that the movement across Davis Strait has been very oblique since anomaly 24 time. The pinching of anomalies from the Labrador Sea into Davis Strait and then their subsequent fanning out in Baffin Bay explains the narrowness of the Strait rather well. They further show that a large portion of Baffin Bay and Davis Strait (about 60 per cent of their present size) is supposed to have formed by seafloor spreading during the later phase of opening of the Labrador Sea (between anomalies 24 and 13) because of the proximity of these regions to the pole of rotation (northern Baffin Bay, Table 3) during the earlier phase. The suggestion of Kerr (1967a) and van der Linden (1975b) that these regions are underlain by subsided continental crust would necessitate a major deformation of the Greenland plate during this time to allow the Labrador Sea to open without opening Davis Strait and Baffin Bay. No geological evidence exists to support this.

5 Palaeogeographic position of the North American, Greenland and Eurasian plates

Figs 21 and 22 show the palaeogeographic positions of North America, Greenland and Europe during the successive stages of evolution of the North Atlantic Ocean, the Labrador Sea, and the Norwegian–Greenland Seas. In all these reconstructions North America has been kept fixed while Greenland and Europe have been rotated to the west using the poles of rotation listed in Table 2. Palaeogeographic positions are shown at the times of anomalies 21, 24, 25, 32, and initial opening. The original reconstructions were carried out on a Lambert conformal projection at a scale of 1 : 6.75 million with standard parallels of 49° and 77° N. The maps as shown in Figs 21 and 22 were obtained by rotating numerous points on the boundaries involved and then tracing out the original outlines to fit between these points.

5.1 RELATIVE MOVEMENT BETWEEN GREENLAND AND NORTH AMERICA

Fig. 21(c) shows that about two-thirds of the Labrador Sea and most of Baffin Bay was closed at anomaly 25 time. This is contrary to what has been obtained previously (Kristoffersen & Talwani 1977; Le Pichon *et al.* 1971). According to the reconstruction of Le Pichon *et al.* (1971, 1977) only one-third of the Labrador Sea was created subsequent to anomaly 25. Furthermore, their reconstructions (Kristoffersen & Talwani 1977; Le Pichon *et al.* 1971) show northward movement of Greenland relative to Ellesmere Island. The present reconstructions, Fig. 21(a–c), show that Greenland moved past Ellesmere Island in the left lateral sense along Nares Strait. Such movement of Greenland along the Strait has been debated for many years (for details, see Dawes 1973) and still no consensus exists whether these movements have or have not taken place. The disagreement on the nature of movement along the Strait arises due to the differences in geometry of the fold pattern present in the Proterozoic to Devonian Strata (Fig. 21) forming part of the Franklinian geosyncline across the Strait as well as the lack of marker horizons on either side of the Strait (Kerr 1967b; Trettin 1971, 1972). However, the boundary between the folded and unfolded rocks of the Franklinian geosyncline is mappable on both sides of the Strait and is generally agreed upon. Whether this boundary should be used in calculation of any relative displacement is again uncertain because of the later diastrophism which seems to have affected the Canadian side differently

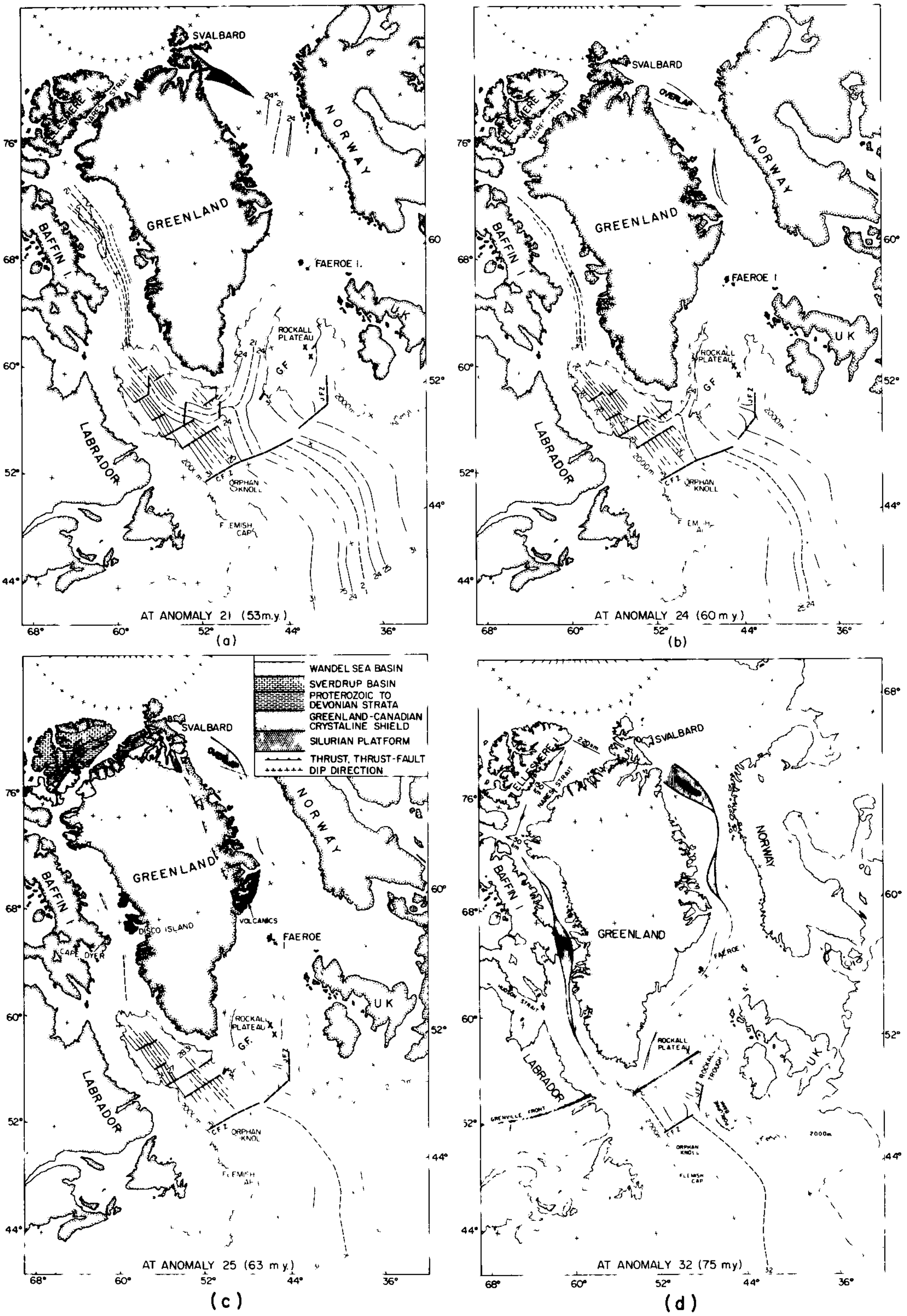

Figure 21. Palaeogeographic positions of Greenland and Europe relative to North America at (a) anomaly 21 time, (b) anomaly 24 time, (c) anomaly 25 time, and (d) anomaly 32 time. These reconstructions were obtained by rotating Greenland and Europe to the west using the data listed in Table 2. The regions of overlaps are shown by stippling. The arrows in figure (d) in Nares Strait show the direction of movement of Greenland relative to North America including Ellesmere Island starting from present to anomaly 32 time. The distances in kilometres refer to the relative movement of Greenland from anomaly 25 to anomaly 32 time. (C.S. – Cumberland Sound; F.B. – Frobisher Bay; C.F.Z. – Charlie Fracture Zone; J.F.Z. – Jean Charcot Fault Zone; G.F. – Grenville Front.)

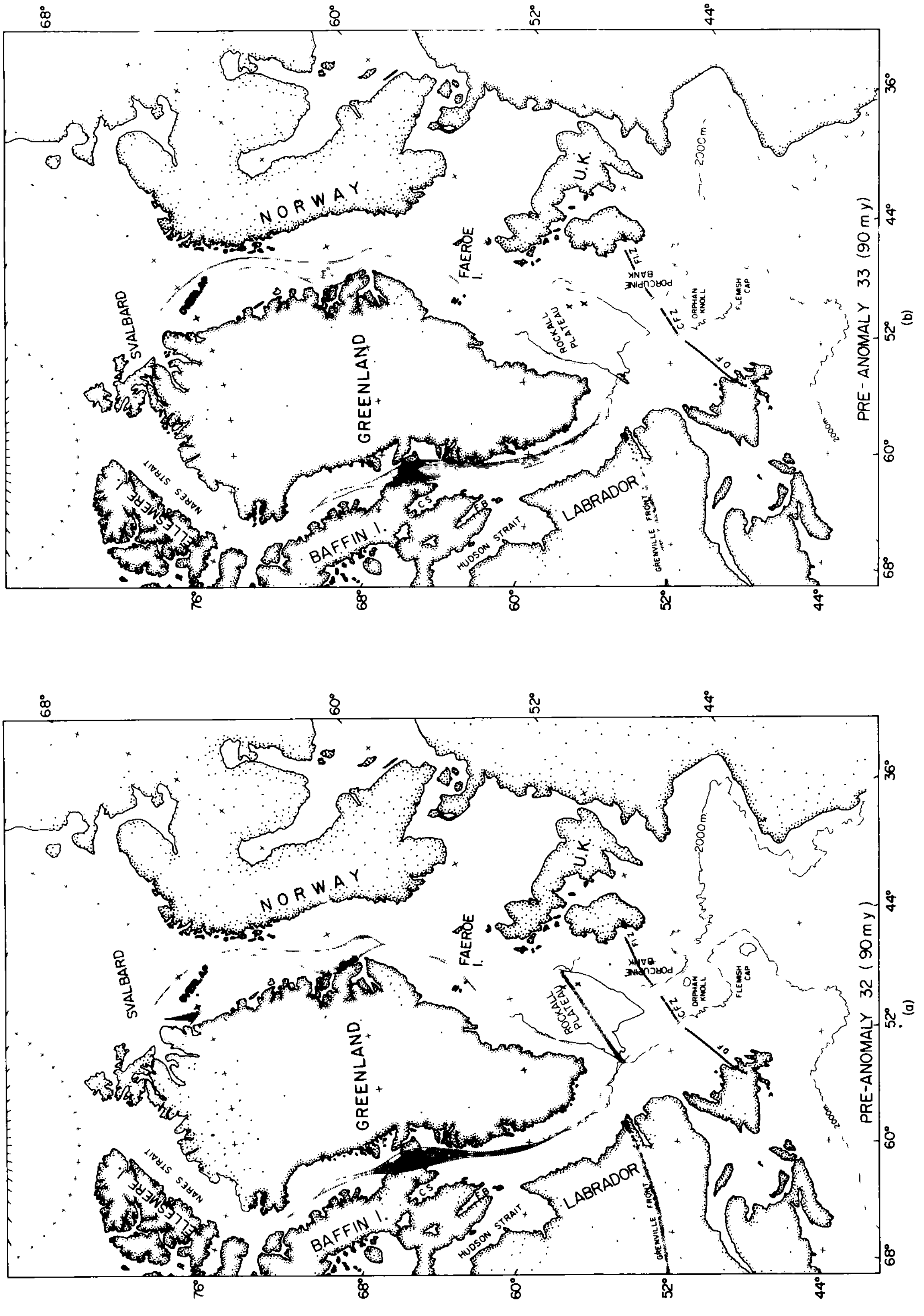

Figure 22. Palaeogeographic positions of Greenland and Europe relative to North America at the time of initial opening. These reconstructions were obtained by rotating Greenland and Rockall Plateau to the west to anomaly 32 time in (a) and to anomaly 33 time in (b) while rotating remainder of the Eurasian plate to the west to the time of initial opening (D.F. – Dover Fault; Fl.Z. – 53° N Flexure Zone).

from the northern Greenland side (Dawes 1973). The reconstruction shown in Fig. 21(c) shows a left lateral displacement of 250 km of Greenland relative to Ellesmere Island along Nares Strait to anomaly 25 time. The alignment of the boundary on either side of the Strait cannot be regarded as proof of its continuity at anomaly 25 time (63 Myr) but it does satisfy earlier speculations (Wilson 1965). It is equally likely that part of this movement may have been taken up by the movements within the Arctic Islands but there is no geological evidence to support this.

The reconstruction in the Labrador Sea to the time of anomaly 25 shows that the Farewell Fracture Zone (Le Pichon *et al.* 1971) off southeast Greenland lies in line with the Cartwright Fracture Zone off Labrador. The dislocation of this fracture zone soon after the formation of anomaly 25 clearly shows the change in the direction of spreading between the various plates involved.

The reconstruction at anomaly 32 time, Fig. 21(d), shows a maximum gap of 220 km between Ellesmere Island and Greenland. What happened to the material present in this gap? Was it subducted under Ellesmere or Greenland or was movement of this magnitude taken up somewhere on land? There is no strong evidence either on Ellesmere Island or northern Greenland to support the subduction of continental or oceanic material under them during the late Cretaceous. Strong evidence, though, exists on the Canadian side to support some diastrophism during this time. Some volcanics do occur in the northernmost part of Greenland, Fig. 21(c), and they have been dated as late Cretaceous and/or Tertiary in age using K/Ar method (Dawes & Soper 1971), though the metamorphic nature and geological setting of the volcanics suggest a post-lower Paleozoic age (Dawes 1973).

On the Canadian side considerable deformation in the Innuitian region took place during Mesozoic and Cenozoic time (Trettin 1972). Stratigraphic, structural and geomorphic evidence suggest that the total uplift in these regions is the cumulative effect of movement that occurred intermittently from the late Cretaceous to the late Tertiary. Uplift during the late Cretaceous and early Tertiary is apparent in sedimentary beds of northern Ellesmere Island which were later folded and faulted in the mid-Cenozoic. It is difficult to relate directly this folding and faulting of beds during the Eurekan orogeny with the deduced compressive motion between northern Greenland and Ellesmere Island, but the sense of motion and overall direction of compression agree.

The reconstruction in Fig. 21(d) further shows that the Labrador Sea is virtually closed and a considerable overlap occurs across Davis Strait and the northern Labrador Sea. Such an overlap can partly be accounted for if we assume that between anomalies 32 and 25 time movement between Baffin Island and Greenland was taken up by crustal stretching rather than by the generation of new sea floor. This may have resulted in the formation of graben and half graben structures in Cumberland Sound, Frobisher Bay, and Hudson Strait on the Canadian side, Fig. 21(d), and in Melville Bay on the Greenland side.

5.2 RELATIVE MOVEMENT BETWEEN GREENLAND AND EUROPE

Based on the poles of rotation obtained here for the Norwegian Sea the position of Europe relative to Greenland has also been shown in Figs 21 and 22. Some overlap occurs between northern Greenland and Svalbard in all of these reconstructions. There is no simple way of avoiding these overlaps without decreasing the goodness of fit obtained between the plate boundaries defined by the magnetic isochrons as mentioned earlier. Poles of rotation obtained by Talwani & Eldholm (1977) for the Norwegian–Greenland Sea (Table 2) give smaller overlaps than those shown here but then their poles do not give the correct direction of motion and the required amount of opening in the Labrador Sea when combined with the poles of rotation for the North Atlantic south of the triple junction. The overlap obtained here could be regarded as an indication of the compressive motion between northeast Greenland and Svalbard margins during the early Tertiary. Some Tertiary deformation exists in the sediments on the west coast of Svalbard (Harland 1969). Similar compressive motion between Svalbard and Greenland was also obtained in the predrift reconstruction of this region by Phillips *et al.* (1976). Other reasons for this overlap could be non-rigid behaviour of the plates involved (Kristoffersen & Talwani 1977) or due to the interaction between more than two plates (Phillips *et al.* 1976).

No overlap between Svalbard and Greenland is obtained by Le Pichon *et al.* (1977) in their predrift reconstruction of this region based on the morphological fit of the continental margins between northern Greenland and Norway and between 2000-m isobaths in the Eurasian Basin. However, their poles of rotation do not satisfy the observations in the Labrador Sea. Until all the geophysical information is available, not only in the Norwegian–Greenland Seas but also in the Eurasian Basin, it is difficult to decipher the exact cause of the overlap obtained between Greenland and Svalbard.

The present reconstruction obtained between Europe and Greenland, Fig. 21(d), differs from the previous reconstructions (Bullard, Everett & Smith 1965; Laughton 1971; Talwani & Eldholm 1977; Vann 1974; Roberts 1974) near Southeast Greenland. A gap of 80 km exists between the margins of Southeast Greenland and the western Rockall Plateau in most of these predift reconstructions and has been interpreted as subsided continental crust (Vann 1974; Featherstone, Bott & Peacock 1977) and as old oceanic crust formed during the initial opening of the North Atlantic (Laughton 1972). The difference between the finite pole of rotations between anomalies 25 and 32 for the Labrador Sea and the North Atlantic supports the latter interpretation and shows a net movement of 63 km at latitude 60° N (southern-most Greenland) to the northwest and 20 km at 74° N (to the east) off the east coast of Greenland. This gives a rate of spreading of 2.5 mm/yr for the southern region and 0.8 mm/yr for the northern region off Greenland. These rates are hardly large enough to give rise to any recognizable anomalies formed during this time except for a negative anomaly between anomalies 24 and 31. Such negative anomalies prior to anomaly 24 have been observed off Southeast Greenland (Featherstone *et al.* 1977; Johnson, McMillan & Egloff 1975b) and off Norway (Talwani & Eldholm 1972).

It is equally likely that such movement between Greenland and northern Europe may have been accommodated by crustal stretching rather than seafloor spreading prior to anomaly 24 time. Some indication of this exists in the increase in the gravity field observed across these regions (Featherstone *et al.* 1977; Talwani & Eldholm 1977) but this needs to be verified by seismic refraction methods.

Another feature in all reconstructions to anomaly 32 time (Fig. 21) is the gap near the Faeroe Islands. Some uncertainty exists as to the location of the ocean–continent boundary near the Faeroe Islands. Bott *et al.* (1974) and Fleischer *et al.* (1974) interpret such a boundary to lie west of the Islands while Talwani & Eldholm (1977) place it east of the Islands (for details see Talwani & Eldholm 1977), the position which has been used here. Because of this uncertainty the position of the Faeroe Islands is shown in all the reconstructions.

5.3 RELATIVE MOVEMENT BETWEEN NORTH AMERICA AND EUROPE AND FORMATION OF THE ROCKALL TROUGH

A predrift reconstruction of North America and Europe which is consistent with the geological trends and marginal offsets across the Atlantic has recently been given by Le Pichon, Sibuet & Francheteau (1977). The predrift position of Greenland given by them differs from that proposed here. Using the present data two reconstructions of the North Atlantic to the time of initial opening were made to determine the position of the British Isles relative to Newfoundland and Labrador – Fig. 22(a) and (b). The reconstructions are based on the assumption that the ridge axis extended into the Rockall Trough during the initial opening of the North Atlantic (Le Pichon *et al.* 1971; Laughton 1972; Roberts 1974, 1975; Kristoffersen *et al.* 1976) prior to anomaly 32 time in one case, Fig. 22(a), and prior to anomaly 33 time in the other case – Fig. 22(b). Though anomaly 32 can be identified, the position of anomaly 33 off Rockall Plateau is assumed between anomaly 32 and 32° W meridian in the magnetic map of the region (Vogt & Avery 1974, Fig. 2(b)) because the width of the anomaly here is twice the distance between anomalies 32 and 33 south of the Charlie Fracture Zone. The reconstructions were made by rotating Greenland and Rockall Plateau to the west to anomaly 32 time in Fig. 22(a) and to anomaly 33 time in Fig. 22(b) while in both cases rotating the remainder of the Eurasian plate to the west to the time of initial opening (90 Myr, obtained by assuming that rate of spreading of 8.0 mm/yr remained constant from the time of initial rifting to anomalies 33 and 34). Fig. 22(a) shows that 80 per cent of the oceanic region in the Rockall Trough – defined by 2s isopachs (Roberts 1975) – is closed while Fig. 22(b) shows that about 60 per cent of it is closed.

Reconstruction in Fig. 22(b) implies that the seafloor spreading continued in the Rockall Trough to anomaly 33 time when the axis shifted to the west, south of Rockall Bank, and occupied two positions, the second of which coincided with the onset of seafloor spreading in the Labrador Sea. The cessation of spreading in the Rockall Trough prior to anomaly 33 time could then account for the absence of recognizable anomalies in the Rockall Trough as they would largely be formed during the Cretaceous normal polarity epoch. The reconstructions in Fig. 22 also imply that 20–40 per cent of the Rockall Trough opened prior to 90 Myr, perhaps during the time when Portugal separated from the Grand Banks of Newfoundland on the lines proposed by Laughton (1972) and Le Pichon *et al.* (1977).

Also shown in Fig. 22 are two tectonic features, Dover Fault (D.F.) and the 53° N Flexure Zone (Fl.Z.), on either side of the Atlantic, which have been delineated from detailed geophysical measurements – Haworth (1977) and Bailey (1975) respectively. The coincidence of these features with the initial position of the Charlie Fracture Zone is noteworthy. The positions of the Grenville Front, an orogenic boundary (Wynne-Edwards 1972), in Labrador and its expected position on the Rockall Plateau based on drilling results (Roberts, Ardus & Dearnley 1973) are also shown in Fig. 22. The predrift reconstruction shows a right-lateral displacement of this boundary, which is contrary to previous work (Roberts 1974; Roberts *et al.* 1973; van der Linden & Srivastava 1975) but in agreement with Lefort (1973). In the reconstruction shown in Fig. 22, the Bay of Biscay has been left open. Even if we close this region on the lines suggested by Williams (1975); Le Pichon *et al.* (1970, 1977) a large gap will still remain between the Grand Banks and Portugal. A complete closure of the North Atlantic must wait until the nature of the crust off Portugal and off Newfoundland (Sullivan & Keen 1977; Hall 1976) is well established and the lines of initial opening are better defined.

6 Summary and conclusion

(1) The results of the compilation of geophysical–geological data in the Labrador Sea show that it was formed by seafloor spreading. Correlation of magnetic anomalies between tracks in the Labrador Sea show two distinct patterns of anomaly limitations, one belonging to anomalies between 25 and 32 and the other to anomalies between 24 and 20. In the

northern Labrador Sea the two groups of anomalies lie parallel to each other while in the southern part of it they lie at angles of 30° or less. Four new fracture zones have been delineated from the gravity, magnetic and seismic data. The fracture zones belonging to the younger group of anomalies (20–24) lie at steep angles to the anomalies showing that the spreading in the Labrador Sea was oblique to the direction of motion between plates. The degree of obliqueness increases from south to north and is maximum in the Davis Strait region.

(2) Compilation of gravity information in the Labrador Sea shows the presence of a pronounced gravity low (50 mgal) in the middle. The position of this gravity low coincides with the axis of symmetry in the magnetic anomalies, thus marking the position of the extinct mid-Labrador Sea Ridge. The seismic observation across the ridge shows two basement highs coincident with magnetic anomalies 21. On the basis of seismic and gravity evidence it is interpreted that in the northern Labrador Sea the ridge changes its orientation from northwest–southeast to north–south and then probably continues north through Davis Strait and Baffin Bay region.

(3) Compilation of magnetic data in the Northwest Atlantic show a northwest–southeast trend for anomalies 13–34 north of 50° N, contrary to that postulated earlier (Pitman & Talwani 1972).

(4) The following sequence of events describing the evolution of the Labrador Sea and North Atlantic Ocean north of Flemish Cap as obtained from the identification of magnetic anomalies and the delineation of fracture zones agrees well with those postulated earlier by Le Pichon *et al.* (1971); Laughton (1971) and Falconer, Srivastava & Johnston (1975) but differs in details.

(a) It is interpreted that seafloor spreading between Newfoundland and the British Isles started around 90 Myr ago. Spreading in the Rockall Trough may have started even earlier. Spreading in the Rockall Trough was perhaps linked to the spreading in the Newfoundland basin, between the Grand Banks and Portugal, by a transform fault running east of Orphan Knoll and Flemish Cap in the northwest–southeast direction. Most of the Rockall Trough is interpreted to have opened from the time of initial opening of the North Atlantic (90 Myr) to anomaly 33 or 32 times (78 to 75 Myr) when the spreading in the Trough ceased and the ridge shifted to the west, south of Rockall Bank. This coincided with the onset of seafloor spreading in the Labrador Sea (anomaly 32 time, 75 Myr).

(b) The initial rifting between Greenland and North America started during the lower Cretaceous though anomaly 32 (75 Myr, Campanian) is the oldest anomaly which can be identified in the southern Labrador Sea. It was during this stage that considerable stretching and block faulting of the crust took place and resulted in the formation of graben and half graben structures off Canada and Greenland. The time of active seafloor spreading in the Labrador Sea varies from north to south, with spreading starting earlier in the south. The absence of anomalies older than 28 and the thinning of the crust in the northern Labrador Sea is interpreted as resulting from stretching of the crust rather than true seafloor spreading during the time when seafloor spreading had already started in the southern Labrador Sea (anomaly 32 time). Spreading started in the northern Labrador Sea during the Maastrichtian (anomaly 28 time). Little or no spreading took place in Baffin Bay during this time.

(c) The differences in the poles of rotation for the North Atlantic and the Labrador Sea show that even though active seafloor spreading between the Greenland and Eurasian plates started in the lower Palaeocene (60 Myr, anomaly 24 time) the rifting between them started as early as the Campanian (75 Myr, anomaly 32 time). Furthermore, the differences in these poles show that prior to the lower Paleocene about 63 km of seafloor might have been generated between Greenland and Rockall Bank at a rate of spreading of 2.5 mm/yr and about 20 km of seafloor might have been generated off northeastern Greenland (74° N) at a spreading rate of 0.8 mm/yr. Alternatively, movement of this magnitude may have been taken up by stretching of the crust rather than true seafloor spreading.

(d) Active seafloor spreading started in the Norwegian Sea in the lower Palaeocene (60 Myr) with the initiation of a triple junction south of Greenland. This resulted in a drastic change in the direction of seafloor spreading in the Labrador Sea.

(e) Baffin Bay and Davis Strait started to open in the lower Palaeocene (60 Myr) and continued to open until upper Eocene (40 Myr) when seafloor spreading ceased in the Labrador Sea.

(f) Spreading has continued to the present in the North Atlantic and Norwegian–Greenland Sea.

(5) Movement between the North American and Greenland plates obtained from the poles of rotation for the first phase of opening of the Labrador Sea (75–60 Myr) show that there was considerable compressive motion between northern Greenland and the Canadian Arctic Islands. Such compressive forces may have been responsible for the deformation of the sediments in the Sverdrup Basin during the Eurkean Orogeny. During the second phase of opening of the Labrador Sea (60–40 Myr) Greenland moved past Ellesmere Island in the left lateral sense along Nares Strait.

(6) The palaeogeographic reconstruction of Greenland and Svalbard between anomalies 31 and 21 show compressive motion between them. Such compressive motion may account partly for the Tertiary deformation observed in the rocks of west Spitsbergen (Harland 1969).

(7) The poles of rotation determined here for the Labrador Sea, North Atlantic and Norwegian Sea describe the relative motions between the three plates adequately everywhere except in the northern Greenland Sea where some overlap occurs between Svalbard and Greenland. Poles of rotation based on the direction of the fracture zones and the magnetic isochrons can be determined separately for the Labrador Sea and Norwegian–Greenland Seas (Talwani & Eldholm 1977) but when these poles are combined to get a consistent solution for the North Atlantic as a whole, problems arise. The overlap obtained between the plate boundaries off northern Greenland and off Svalbard shows this clearly. It could be argued that this arises due to the nonrigid behaviour of the plates (Kristoffersen & Talwani 1977) or due to the interactions of more than two plates (Phillips *et al.* 1976).

(8) The palaeogeographic position of continents at the time of their separation as given here shows considerable overlap between their boundaries. The position of these boundaries is not known with precision everywhere and an accurate description of these boundaries may reduce some of the apparent misfits.

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