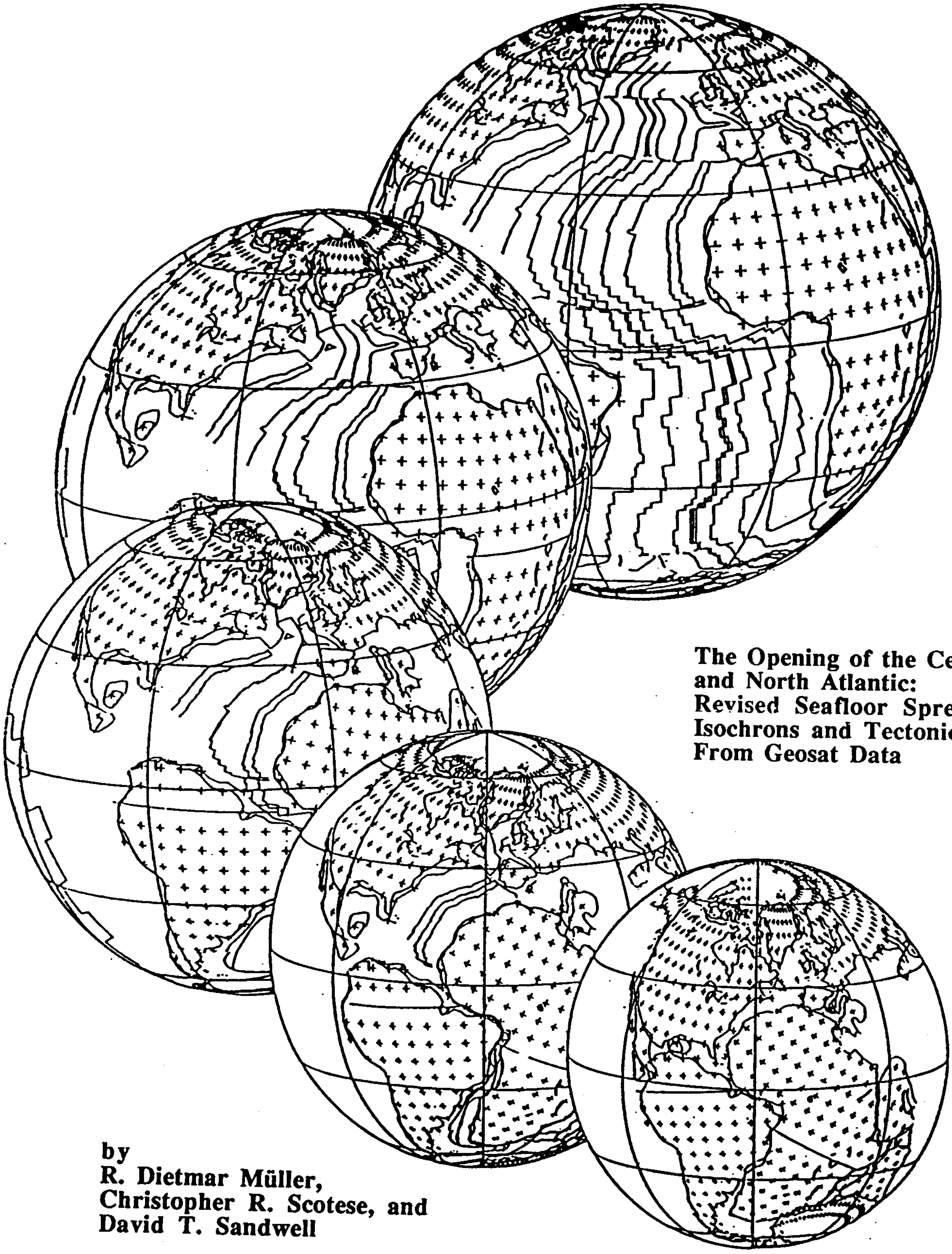
PALEOCEANOGRAPHIC MAPPING PROJECT
PROGRESS REPORT No. 39 - 0888



The Opening of the Central and North Atlantic: Revised Seafloor Spreading Isochrons and Tectonic Map From Geosat Data

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University of Texas Institute for Geophysics Technical Report No. 91

Abstract

Plate reconstructions for the opening of the Central and North Atlantic were made by combining Geosat altimetry and magnetic anomaly data. Geosat deflection of the vertical (horizontal gravity) data, which reflect the short wavelength basement topography of the ocean floor, allowed us to construct a much improved map of fracture zones in the Central and North Atlantic. The fabric of prominent fracture zones, as interpreted from Geosat deflection of the vertical data, was utilized to constrain the fits of corresponding magnetic anomaly lineations by using an Evans and Sutherland 3-D graphics computer system. For example, we have used the trace of the Charlie-Gibbs Fracture Zone to better constrain the spreading history between the North American and Eurasian plate. Movements of smaller plates such as in the Canadian Arctic and the western Mediterranean were tied to the relative motion of the major plates by applying a hierarchical plate analysis technique. Our tectonic model served as a base to construct a self consistent isochron chart of the Central and North Atlantic ocean floor.

Introduction

During the last 17 years, at least 7 models for the opening history of the Central Atlantic (Francheteau, 1970; Pitman and Talwani, 1972; Sclater et al., 1977; Olivet et al., 1984; Savostin et al., 1986; Klitgord and Schouten, 1986) and at least 10 models for the opening of the North Atlantic (Francheteau, 1970; Pitman and Talwani, 1972; Sclater et al., 1977; Unternehr, 1983; Savostin et al., 1986; Srivastava and Tapscott, 1986; Rowley and Lottes, in press) have been proposed. The increasing complexity of the plate tectonic models reflects the addition of new magnetic data and improved modeling techniques. Until now it has not been possible to evaluate the quality of synthetic flowlines as proposed by plate models, because the coverage and availability of fracture zone bathymetry data for different parts of the ocean floor is highly variable. Geosat satellite data provide a more complete picture of the tectonic fabric of the ocean basins. We used Geosat altimetry data to produce a map of the vertical deflection along-track of the ocean surface from the equator to 72°N. Lineations apparent in the Geosat profiles reflect morphologic features of the ocean floor such as fracture zones, volcanic ridges and the shelf edge.

Data

Magnetic anomaly data used in this study are from Srivastava (1978) (Labrador Sea), Hagevang et al. (1983) (eastern Norwegian Sea), Nunns (1983) (Norwegian, Iceland and Irminger Sea), Klitgord and Schouten (1986) (Central and southern North Atlantic), Srivastava and Tapscott (1986) (Eurasian Basin) and Vogt (1986a) (Eurasian Basin) (Figure 1). Ages of magnetic anomalies correspond to the time scale of Kent and Gradstein (1986). The interpreted boundaries between oceanic and continental crust around the North Atlantic are subject to much controversy. The debate concentrates on the location of the continental/oceanic crust boundaries along dipping-reflector sequences (seaward directed basalt flows), that characterize large parts of the passive margins around the North Atlantic (White, 1987). The Faeroe-Shetland Escarpment, bounding a dipping reflector sequence, was originally proposed to delineate the continental/oceanic crust boundary (Talwani and Eldholm, 1977). Other authors suggested that the boundary is located further westward (Smythe, 1983; Nunns, 1983). Similar controversies revolve around the interpreted boundaries of the Greenland and Vøring Plateau dipping-reflector sequences. White (1987) pointed out that it is impossible to define a precise boundary in a region of fragmented continental blocks and newly emplaced igneous rocks.

Interpretations of the crustal character of Davies Strait and Baffin Bay are controversial as well. A continental crustal character for both Davies Strait and Baffin Bay was proposed by Grant (1975, 1980). However, Keen et al. (1972, 1974), Srivastava (1978), Jackson et al. (1979), Srivastava et al. (1981) and Rice and Shade (1982) argued that parts of Baffin Bay is floored by oceanic crust, although well defined magnetic anomalies are absent (Srivastava et al., 1981).

The Jan Mayen microcontinent is thought to be underlain by crust of continental character, as indicated by seismic reflection data (Nunns, 1983) and a deep seismic survey (Gebhardt and Weigel, 1988). Bott (1987) tentatively interpreted the boundaries of the microcontinent as being defined by magnetic anomaly 24 in the western Norway Basin, by a change in character of the magnetic anomalies east of the Kolbeinsey Ridge, and by the Faeroe Transform Fault to the south.

The continental/oceanic crust boundaries included in our database were taken from Srivastava (1978) (Labrador Sea) , Rice and Shade (1982) (Baffin Bay), Eldholm and Thiede (1987) (Norwegian shelf), Emery and Uchupi (1984) (southern North Atlantic and West Africa), Larsen (1984) (West Greenland shelf), Reksnes and Vågnes (1985) (Eurasian Basin), Sawyer (1986) (East Coast of North America), and Bott (1987) (Jan Mayen plate) (Figure 1). Continental margins reconstructed to their predrift positions (Dunbar and Sawyer, in prep.) were used to constrain the fit reconstructions of Greenland, the Ireland/Rockall Plateau margins and Africa relative to North America.

Fracture zone lineations

We have used Geosat altimetry data to better determine the location of fracture zones in the Central and southern North Atlantic. The filtered first derivative of the geoid height from Geosat data was formed to construct maps of the vertical deflection or horizontal gravity (Sandwell, 1984a) along track from the Equator to 72°N in the Central and North Atlantic (Figures 2 and 3). To determine the relation between the location of fracture zones and the lineations in the deflection of the vertical field, the relationship between specific geoid signals and the bathymetric expression of a fracture zone must be known.

The short wavelength topography of the ocean surface (between 50 and 200 km) reflects the uncompensated topography of fracture zones (Mulder and Colette, 1984). The vertical deflection of the Geosat geoid data enhances the short wavelength component of the signals, amplifying the expression of fracture zone signals. Fracture zones in the Pacific are usually characterized by a large age/depth step that is often retained even in the oldest parts of the sea floor (Sandwell, 1984b). In contrast to the Pacific, fracture zones in the Atlantic exhibit a more complex morphology (Colette, 1986). In the Atlantic the expected depth/age step is commonly overprinted by the fracture zone morphology (Colette et al., 1984; Colette, 1986; Fox and Gallo, 1986; Potts et al., 1986; Roest and Colette, 1986). This is due to the relatively slow spreading in the Atlantic ocean. A characteristic feature of Atlantic fracture zones is a central valley (van Andel, 1971; Colette, 1986; Fox and Gallo, 1986), resulting in a prominent geoid low across the fracture zone. In the deflection of the vertical field, a fracture zone valley is expressed as a lineated peak and trough, reflecting the positive and the negative slope of the valley. The inflection point of the vertical deflection signals locates the bottom of fracture zone valleys. A comparison of bathymetric data and magnetic lineations with the vertical deflection data showed that many fracture zones in the North and Central Atlantic can be traced from the present-day ridge back to the magnetic quiet zone by using the described relation between deflection of the vertical and fracture zone morphology. We then interpreted lineations apparent in the Geosat profiles, as shown for the Charlie-Gibbs Fracture Zone on Figures 5 and 6, and drew a map of lineations in the deflection of the vertical field (Figures 7 and 9). Continuous and dashed lines on Figures 7 and 9 delineate negative and positive slopes of the sea surface, respectively, as viewed from south to north. Uninterrupted pairs of lineations, however, are only present for medium to large-offset fracture zones such as the Fifteen-Twenty, Kane, Atlantis, Oceanographer and Charlie-Gibbs fracture zones. This indicates that the morphology and the geoid expression of a fracture zone becomes more pronounced with increasing age-offset.

Fracture zone lineations north of the Azores triple junction are generally not as distinct and continuous as in the Central Atlantic. Small offset fracture zones with complex morphologies dominate this area as a result of its proximity to the pole of relative motion between North America and Eurasia. Small age-offset fracture zones do not have a large topographic expression and consequently do not have a strong expression in the geoid. The Charlie-Gibbs Fracture Zone is the only fracture zone between North America and Europe that is characterized by a large offset (350 km). Information about this tectonic flowline is essential for constraining plate motions between

North America and Europe. We have interpreted the trend of the Charlie-Gibbs Fracture Zone from Geosat data (Figure 8), using additional information about its location from bathymetric and magnetic data.

A detailed survey of the Charlie-Gibbs Fracture Zone was published by Olivet et al. (1974). It revealed that this unusual double fracture zone is characterized by two parallel east-west trending troughs that are separated by a median ridge. This morphology, however, becomes obscured with increasing age of the adjacent ocean floor. Bathymetric data alone do not allow the tracing of the fracture zone to the continental margins. A clear, continuous deflection of the vertical pattern delineates the western limb of the fracture zone as well as the westernmost half of its eastern branch. Here a series of 4 lineations outline the slopes of the two median troughs. This signature is in good accordance with the bathymetric contours for the fracture zone after Olivet et al. (1974). The bathymetry as well as the deflection of the vertical pattern of the easternmost part of the fracture zone is more complex. East of 27°W the central ridge and the two median valleys disappear (Olivet et. al., 1974). However, offsets of the magnetic anomaly lineations (Figure 7) and positive as well as negative magnetic anomaly axes parallel to the fracture zone trend (Olivet et. al., 1974) allow the fracture zone to be traced to the southern margin of the Rockall Plateau. We interpret a positive magnetic anomaly axis (Figure 7) trending east-west between 23° and 21°W (Olivet et al., 1974) to represent the eastern prolongation of the northern valley. An equivalent central positive magnetic anomaly has also been described for the Kane Fracture Zone (Twigt et al., 1983). The positive magnetic anomaly of the Charlie-Gibbs Fracture Zone merges eastward into a negative WNW-ESE trending magnetic anomaly (Figure 7) that is interpreted as an edge effect of the boundary between continental and oceanic crust (Olivet et al., 1974). It appears to mark the paleo-transform margin of the southern Rockall Plateau. A negative magnetic anomaly seems to delineate the eastward continuation of the southern central trough east of 27°W (Figure 7). Our interpreted flowline of the northern Charlie-Gibbs Fracture Zone (Figure 8) abuts the Rockall Plateau to the south and merges into the large offset of the Canadian continental margin north of Grand Banks.

Geosat data could not be utilized to better locate fracture zones in the Labrador Sea. Here the prominent signature in the deflection of the vertical data follows the gravity low over the extinct ridge axis as described by Srivastava (1978). Fracture zones in the Labrador Sea included in this study were taken from Srivastava (1978).

In the Norwegian Greenland Sea, the Old Jan Mayen and Senja fracture zones are visible as distinct lineations in the deflection of the vertical field (Figure 9). Multiple lineations parallel to the Old Jan Mayen Fracture Zone outline a succession of ridges and troughs that are characteristic for this fracture zone (Grønlie and Talwani, 1982). The "Senja Fracture Zone" as identified by Talwani and Eldholm (1972, 1977) is problematic, since it cannot be regarded as a typical oceanic fracture zone. Its eastern part separates continental crust to the north from oceanic crust to the south and represents a paleo-transform margin. It is outlined by a positive gravity anomaly that is thought to be due to dense mantle intrusions after the onset of transtension between the Senja and Greenland margins (Eldholm et al., 1987). The positive gravity anomaly is characterized by two distinct lineations in the deflection of the vertical field, delineating the two slopes of the feature (Figure 9). The Senja Fracture Zone was recently reinterpreted to be located at the eastern flank of the gravity anomaly (Eldholm et al., 1987) instead of on top of the anomaly as inferred by Talwani and Eldholm (1977). Vogt (1986b) pointed out that incompletely compensated, rapidly deposited late Cenozoic sediments could also be the cause for the observed gravity high. Thus the relation between the gravity anomaly and the location of the fracture zone is not clear.

The Greenland Fracture Zone, which is regarded as the counterpart of the Senja Fracture Zone, is also delineated by a positive, elongated gravity anomaly (Talwani and Eldholm, 1977). A gravity low accompanied by a sediment filled trough is present south of the gravity high (Vogt, 1986b). The relationship between topography, gravity and the location of the Greenland Fracture zone is as ambiguous as that of the Senja Fracture Zone. Both fracture zones are anomalous with respect to the usual fracture zone morphology in the Central and North Atlantic. Hence we conclude that, based on the data available, these two tectonic features can not be used as reliable constraints for reconstructing the relative motion between Greenland and Eurasia.

Derivation of rotation poles

Plate reconstructions were made using interactive computer graphics to determine finite poles of rotation that best fit a pair of corresponding magnetic anomalies and fracture zone lineations. We started with published rotation poles for the Central and North Atlantic, evaluated the fit and, if necessary, adjusted the poles to achieve the best overall match of both the magnetic anomalies and fracture zone lineations. Most of Klitgord and Schouten's (1986) reconstruction poles for the Central Atlantic well satisfy the constraints by the data. The poles for anomalies 5, 13, 21, 25 and 30 were slightly modified, to better fit major fracture zone lineations.

Europe was reconstructed relative to North America by determining the best match for magnetic anomaly pairs and the interpreted flowlines of the Charlie-Gibbs Fracture Zone. We found that all previous models for the relative motion between Eurasia and North America do not satisfy the constraints as imposed by the Charlie-Gibbs Fracture Zone, particularly for reconstruction times between An13 and An25. A related problem in the reconstructions is overlap of the continental/oceanic crust boundaries between Svalbard and Greenland in reconstructions for Chron 20 and older. Those models, which focus on reconstructions of the Norwegian-Greenland Sea (Vogt et al., 1981; Nunns, 1983; Unternehr, 1982; Talwani and Eldholm, 1977), do not show large overlaps between Greenland and Svalbard. However, these models can not be reconciled with the tectonic fabric the Charlie-Gibbs Fracture Zone, if reconstructions are attempted that fit all magnetic and fracture zone data in the three plate system of North America/Greenland/Eurasia. As noted by Srivastava and Tapscott (1986), reconstruction poles determined for two plate systems like Greenland/North America, Greenland/Eurasia and Eurasia/North America usually fit the regional data, but fail to comply with the constraints of the entire three plate system, if used collectively.

Specific problems arise for reconstruction times An25 and An21. If the Lomonosov Ridge is considered to have been fixed to North America, reconstructions for these times either result in large overlaps of magnetic anomalies in the Eurasian Basin (Srivastava, 1978; Kristoffersen and Talwani, 1977) or south of the Charlie-Gibbs Fracture Zone (Vink, 1982, 1984; Srivastava and Tapscott, 1986). For our reconstructions for chrons 21 and 25 we tried to find the best fit for all magnetic anomaly and fracture zone data north of the Charlie-Gibbs Fracture Zone and allowed a misfit of magnetic anomalies south of the Charlie-Gibbs Fracture Zone. This misfit may be due to deformation during the northward movement of Iberia with respect to Eurasia prior to Chron 13 and can be accounted for by defining a separate plate ("Porcupine Plate") for this region (Srivastava and Tapscott, 1986).

After finding new poles for the relative motions between North America and Europe, we reconstructed Greenland to North America by evaluating the fit of magnetic anomalies in the Labrador Sea as well as the resulting fit between Greenland and Europe. Subsequently the rotations of the microcontinent Jan Mayen relative to Europe and of Iberia relative to North America were determined. The concept of a "correction pole", put forward by Srivastava and Tapscott (1986), for relative motions of Iberia was evaluated with interactive computer graphics. According to Srivastava and Tapscott (1986) anomalies between Iberia and Newfoundland older than A6 can be fitted by using the poles for Africa relative to North America. A correction pole restores Iberia's position to bring it in the Africa-North America frame. We found that this model fulfills the requirements of the data quite well. Hence we kept Iberia rigidly fixed to Africa for reconstructions prior to Chron 13.

Defining isochrons

After the best fitting rotations were determined, finite rotation poles were calculated for every stage for the reference frames of all major plates in the model (Table 1). A stage is defined by the time interval between two adjacent anomaly lineations used in a reconstruction. Subsequently reconstructions for all time slices as listed in Table 1 were plotted, keeping North America fixed. These plots included superimposed magnetic anomaly lineations for the reconstruction time as well as the older anomaly lineations. Lineations in the deflection of the vertical field and calculated small-circles for the stage bounded by the next older anomaly pair were also plotted on the maps. Continuous isochrons (which can be viewed as of "idealized ridge segments") were drawn and connected by transforms. The paleo-ridge segments were drawn by finding the best average lines for superimposed magnetic lineations. The position of transforms between paleo-ridge segments were determined by offsets in magnetic lineations. The deflection of the vertical lineations served as additional constraints for the location of fracture zones, especially where magnetic data are sparse.

The fracture zone segments for different stages were drawn as synthetic flowlines, which are defined by small circles for the stage poles. This procedure yielded isochrons for the plate that was kept fixed for the reconstructions. A complete set of isochrons (Figure 20) was derived by rotation of each isochron from the fixed plate to its corresponding position on the opposite plate by applying the finite reconstruction poles as shown in Table 1, with the angle of opening reversed.

Reconstruction maps

All plate reconstructions for the North Atlantic are plotted with superimposed magnetic lineations for the reconstruction time and fracture zones, permitting the evaluation of the quality of the fit for every reconstruction time. Areas of overlap between the continental/oceanic crust boundaries are stippled. The entire Arctic Ocean region was included in the reconstruction maps to illustrate the predicted tectonic regime between the Eurasian and North American plates in the Bering Sea region. All reconstructions for the North and Central Atlantic are plotted with North America fixed.

Fit Reconstruction (175 Ma, Bathonian, Figure 10)

Our fit reconstruction for Africa, Eurasia and Greenland relative to North America is constrained by the fit of continental margins reconstructed to their predrift position (Dunbar and Sawyer, in prep.). Poles and rotation angles for the fits were obtained by determining the rms "best fits" for the margins. The rms misfits are 64 km between the African and North American margins, 25.6 km between Labrador and Greenland and 69.7 km between Labrador-Newfoundland and Rockall-Ireland (Dunbar and Sawyer, in prep.). The fit between Labrador-Newfoundland and Rockall-Ireland was used to better constrain the predrift position of Eurasia relative to North America. The fit of these two plates is now well constrained in the area for which the margins have been restored. However, the predrift position of the entire Eurasian plate cannot be reliably estimated without reconstructing the margins around the Norwegian Greenland Sea.

A problem seemingly inherent to North Atlantic fit reconstructions, controversially discussed for decades, is the "Nares Strait problem". It consists of a gap and dextral offset between Greenland and the Canadian Arctic observed in pre-Oligocene reconstructions for Greenland relative to North America and implies considerable left-lateral transpression during the opening of the Labrador Sea.

To find the fit position of Ellesmere Island relative to Greenland we used the boundary between the lower Paleozoic Arctic Platform and the Precambrian Shield after Kovacs et al. (1986). We infer about 120 km of strike slip between Ellesmere Island and Greenland based on restoration of the two branches of the suture. Closure of the Labrador Sea by matching the restored margins of Southwest Greenland and Labrador (Dunbar and Sawyer, in prep.) requires an additional amount of strike slip between Greenland and North America. This problem can be resolved by including rifting within the Canadian Arctic Islands in the plate model. Hamilton (1983) proposed 100 km of extension in the Hudson Strait. Young normal faults cut through southern Baffin Island and indicate Tertiary extension (Hamilton 1983). Cretaceous and Paleogene sediments in the Northwest Passage (Daae and Rutgers, 1975) and extensional faulting in its eastern part (Kerr, 1980) give evidence for crustal stretching across the strait. Closing the Hudson Strait, Lancaster Sound, Jones Sound and the eastern Northwest Passage accounts for about 200 km of total offset between Greenland and North America during the Upper Cretaceous/Tertiary and solves the Nares Strait problem.

A variety of tectonic models has been suggested for the tectonic development of the Canada Basin. The stratigraphic and structural evidence for the rotational model of Arctic Alaska that we favor has been summarized by Harland et al. (1984). This model has been incorporated into our work. It proposes that the North Slope Block of Alaska and the Chukotka block rotated away from Arctic Canada about a pole in the Mackenzie Delta. The model is supported by recent paleomagnetic data from cores from the North Slope, which indicate significant rotation between North America and the North Slope Block (Halgedahl and Jarrard, 1987). Motion of the North Slope Block is assumed to have occurred between 130 and 100 Ma, causing the Brookian Orogeny when Arctic Alaska collided with the North American plate (Halgedahl and Jarrard, 1987). The Yukon-Koyukuk region presumably consists of trapped Jurassic or older oceanic crust (Churkin and Trexler, 1980). The South Anyuy suture is interpreted to have been the plate boundary between the North American and Eurasian plates in the Bering Sea region (Parfenov and Natal'in, in prep.) The suture consists of a highly compressed fold belt (Shilo and Til'man, 1981) that records collision from Late Jurassic to Neocomian (Parvenov and Natal'in, in prep.). We used a schematic outline of this suture zone to illustrate motions along this plate boundary following Harbert et al. (1987).

The gap shown west of Ellesmere Island schematically outlines the total amount of compression between Greenland and the Canadian Arctic Islands in the Upper Cretaceous/Tertiary. The compression was actually taken up by three distinctive thrust belts on Ellesmere Island (De Paor, pers. com.). The North Sea grabens were closed in our fit reconstruction (Figure 10) by assuming 50% extension (Jarvis and McKenzie, 1980). For our fit reconstruction in the Iberian region we used the reconstruction pole from Srivastava and Tapscott (1986).

We have included the restored margins of Italy and the Alps of southern Europe, from Hill and Hayward (1988) in our reconstructions from the fit to Chron 34. Following Hill and Hayward (1988), we assume that Italy moved attached to Africa during the Mesozoic. Corsica, Sardinia and Calabria have been restored to their predrift position in accordance to a 60° Oligocene-Miocene clockwise rotation of Corsica/Sardinia (Montigny et al., 1981; Rehault and Bethoux, 1984). The orientation of Calabria follows the fit by Hill and Hayward (1988) that implies subduction along its southern margin and a transform to the east. The fit position of Sicily corresponds to a 15° counterclockwise rotation in the Pliocene (Besse et al., 1984). The Florida Straits Block was rigidly attached to Africa during the Middle Jurassic, when rifting in the Central Atlantic propagated into the Gulf of Mexico along the North Bahamas Fracture Zone through central Florida (Klitgord and Popenoe, 1984).

Chron M10N (131.7 Ma, Valanginian, Figure 11)

Middle/Upper Jurassic movements in the North and Central Atlantic were dominated by rifting in the North Sea and the onset of seafloor spreading in the Central Atlantic. Rifting in the Central and Viking grabens was related to right lateral wrench movements in the Fennoscandian Border Zone. The Tornquist zone formed the main southwestern boundary of the Fennoscandian-Russian Platform (Pegrum, 1983). It extends from the southwestern USSR to the southern Baltic, southwest Sweden and the Oslo Graben (Ziegler, 1982). Pegrum (1984) and Pegrum and Ljones (1984) suggested its westward extension into the North Sea, regarding the Horda and East Shetland platforms as former parts of the Fennoscandian platform. The East Shetland platform was separated from the Fennoscandian platform by Late Carboniferous/Early Permian rifting in the proto-Viking Graben, and the Horda Platform was uncoupled by Perotriassic rifting along the Horda Fault Zone (Pegrum and Ljones, 1984). The southwestern part of the Fennoscandian platform is separated from the Norwegian/Danish Basin and the Rinkkøbing-Fyn High to the south by the Fjerritslev Fault Zone, which is regarded as a western extension of the Tornquist zone (Pegrum and Ljones, 1984). The Ringkøbing-Fyn/Pompeckj block was offset from the Rhenish-Bohemian Massif to the south by a second major transform (Ziegler, 1982). The major rifting event in the North Sea is interpreted to have occurred between the Bathonian and Berriassian, following Badley et al. (1984). Assuming rigidity of the Fennoscandian/East European Craton, rifting in the North Sea accompanied by right-lateral strike-slip movements in the Fennoscandian Border Zone must have resulted in extension between Greenland and Svalbard in the Upper Jurassic. This model is in good accordance with evidence for enhanced subsidence accompanied with faulting, intrusions and volcanic activity in the Upper Jurassic of Svalbard (Steel and Worsley, 1984).

As a consequence of continuing seafloor spreading in the Central Atlantic, opening between Iberia and Newfoundland started in the Lower Cretaceous at about Chron 11 (Srivastava and Tapscott 1986). Subsequently the rift propagated northward between Labrador and Greenland. The subsidence history, as interpreted from a well on the northern Labrador shelf (Hinz et al., 1979), shows that subsidence in this area started as early as about 130 Ma. Sub-aerial basaltic lava flows of Berriasian to Hauterivian age up to 260 m thick on the Labrador shelf (Hinz et al., 1979) provide additional evidence for an Early Cretaceous onset of rifting in this area. This extensional tectonic regime initiated rift basins north of Newfoundland from the Rockall Trough to the western margin of Norway (Price and Rattey, 1984).

Chron M0 (118.7 Ma, Aptian, Figure 12)

During the Cretaceous Quiet Period, rifting started to separate Rockall Bank from Eurasia (Kristoffersen, 1978). Relative motion between Eurasia and North America during the opening of the Rockall Trough implies transtension between Greenland and Svalbard and slight compression in the Bering Sea area in the Upper Cretaceous. No Upper Cretaceous sediments are preserved on Svalbard due to an uplift and slight tilting of the Barents shelf at that time (Atkinson, 1963; Nagy, 1970). Steel and Worsley (1984) interpreted the uplift as part of the doming related to subsequent transtensional tectonics between Svalbard and Greenland. The uplift might have been the predecessor of the Upper Cretaceous transtension as result of this first rift propagation northward along the Caledonian suture between Greenland and the Baltic shield. Italy, which is considered to have been attached to Africa, started to collide with Eurasia at about 95 Ma, giving rise to crustal shortening and the emplacement of ophiolites (Dewey et al., 1973).

Different flowline patterns have been suggested for the Cretaceous Quiet Zone (Slootweg and Colette, 1985; Klitgord and Schouten, 1986), where fracture zones cannot be traced by offsets in magnetic anomalies. A uniform flowline direction for this period, as proposed by Klitgord and Schouten (1986) cannot be reconciled with the Geosat lineations between magnetic anomalies M-0 (118.7 Ma) and 34 (84 Ma). The lineations rather suggest that the trend in seafloor spreading between anomalies M-4 (126.5 Ma) to M-0 continued until 100 Ma. Between 100 and 95 Ma, we propose a clockwise change in spreading direction that was followed by a counterclockwise change which established a direction of spreading that was maintained until Klitgord and Schouten's Chron 30o (80.2 Ma). Slootweg and Colette (1985) found a very similar flowline pattern for the Cretaceous Quiet Zone in the Madeira abyssal plain. Their findings, based on seismic and magnetic data, confirm our interpretation. At the same time, at about 100 Ma, the Caribbean plate started to move into the opening gap between the North American and the South American continents, subducting proto-Caribbean crust (Ross and Scotese, in prep.).

The Fifteen-Twenty Fracture Zone as shown on Figure 1 reveals that its branch on the African plate partly deviates from the flow direction to the north. The clockwise shift of seafloor spreading between Africa and North America after 100 Ma resulted in divergence between the Fifteen-Twenty Fracture Zone and the fracture zones to the north. Despite the counterclockwise change in spreading direction in the Central Atlantic approx. 95 Ma, a divergent trend between the Fifteen-

Twenty Fracture Zone and the Central Atlantic spreading direction was maintained until Chron 30. This implies that this fracture zone acted as a plate boundary during this time. We propose that a triple junction developed at the Fifteen-Twenty transform after 100 Ma, which resulted in the continuous growth of the ridge segment between the Fifteen-Twenty and the Jacksonville Fracture Zone to the north (Figure 20).

Chron 34 (84 Ma, Campanian, Figure 13)

At this time seafloor spreading started in the southern Labrador Sea and west of the Rockall Plateau. The oldest identified magnetic anomaly north of the Charlie-Gibbs Fracture Zone and in the southern Labrador Sea is anomaly 34. Since spreading in the Labrador Sea and south of the Charlie-Gibbs Fracture Zone between North America and Europe proceeded with slightly different directions, small differential movements resulted between Greenland and Eurasia. The opening between the North American and the Eurasian plates between Chron 34 and 30 induced significant left-lateral transpression in the Bering Sea region. It was probably taken up within the South Anyuy Fold Belt. According to Parvenov and Natal'in (in prep.), plate convergence occurred along this boundary in the Upper Cretaceous. Upper Cretaceous transpression in this area is also in accordance with a counterclockwise bending of western Alaska at that time (Harbert et al., 1987).

The counterclockwise rotation of Greenland relative to Ellesmere Island and Svalbard induced the first phase (oblique compression) of the Eurekan orogeny in the Canadian Arctic Islands (Miall, 1984). Dextral transpression between Greenland and Svalbard as implied by our model is in accordance with the formation of pull-apart basins along the Trolle Land Fault System in northeast Greenland (Håkansson and Pedersen, 1982).

Chron 30 (67.5 Ma, Maestrichtian, Figure 14)

At Chron 30 seafloor spreading had propagated into the northern Labrador Sea. The overlap of the oceanic/continental boundary in the Baffin Bay (from Rice and Shade, 1982) had decreased significantly and oceanic crust may have formed in central Baffin Bay. Geologic evidence suggests that the plate boundary between Greenland and Svalbard jumped from the Trolle Land Fault System in northeast Greenland to the Hornsund Fault Zone west of Svalbard at about the Cretaceous/Tertiary Boundary. Lower Tertiary sediments are generally absent on northeast Greenland (Håkannson and Pedersen, 1982). On Svalbard, where Upper Cretaceous sediments are absent, the Central Tertiary Basin began to subside in the Lower Paleocene (Steel and Worsley, 1984; Steel et al., 1985).

Half spreading rates in the Labrador Sea between Greenland and North America increased gradually from 5 to 9 mm/year from the onset of spreading to Chron 25 (Figure 22a). In contrast, half spreading rates between North America and Eurasia increased drastically from 10 to 17 mm/yr at Chron 30 (Figure 21a). This change in rates induced transtension between Greenland and Norway and left lateral strike slip between Greenland and Svalbard between chrons 30 and 25. This model is in good accordance with a short sinistral strike-slip period in the earliest Paleocene for Svalbard relative to Greenland suggested by Kleinspehn et al. (in prep.) based on application of paleostress stratigraphy. At the same time (in the Lower Paleocene), subsidence of the Central Tertiary Basin on Svalbard was initiated (Steel et al., 1985). The direction of spreading between North America and Eurasia resulted in continuing transpression along the South Anyuy suture in the Bering Sea region until Chron 25, assuming Eurasia behaved as a rigid block.

Chron 25 (59.2 Ma, Thanetian, Figure 15)

A clockwise change of spreading direction between North America and Eurasia after Chron 25 changed the tectonic regime between Norway and Greenland from transtensional to extensional and from extensional to strike slip between Greenland and Svalbard. Rifting propagated from the

Charlie-Gibbs Fracture Zone to the Eurasian Basin (Figure 12). This model suggests that the Central Tertiary Basin on Svalbard changed its nature from extensional rifting in the Lower Paleocene to strike slip in the Thanetian.

The plate reorganization between North America and Eurasia after Chron 25 caused a switch of the strike slip regime in the Bering Sea region from sinistral to dextral. Slow right lateral transtension prevailed in this region until Chron 13. This observation correlates well with the subsidence and formation of pull-apart basins along the Bering margin (Harbert et al., 1987).

A number of volcanic rises and plateaus were formed during this plate reorganization, i.e. the Thulean Rise (Vogt and Avery, 1974) and the Greenland Scotland Ridge, volcanics on the Morris Jessup Rise and Yermak Plateau (Vogt et al., 1979) and on the Vøring Plateau and Faroer Islands (Talwani and Eldholm, 1977). Anomaly 24 is doubled north of Jan Mayen (Hagevang et al., 1983), giving evidence for a ridge jump between Chrons 24 and 23. The stage pole for fitting these anomalies results in an age of 55.2 Ma for the jump.

Chron 24 (56.1 Ma, Ypresian) to Chron 21 (50.3 Ma, Lutetian) (Figures 16, 17)

In the time between the initial opening of the Norwegian Greenland Sea (Chron 24b, Kovacs et al., 1985) and Chron 21, the seafloor spreading direction between Greenland and Eurasia was parallel to the Senja Fracture Zone. A change of motion between Eurasia and Greenland (Figure 17) caused propagation of seafloor spreading into the area between Senja Fracture Zone and Hornsund Fault after Chron 21.

The Jan Mayen plate is inferred to have started rifting away from Greenland at Chron 24 (56.1 Ma.). The counterclockwise rotation of Greenland relative to North America after Chron 21 initiated the second phase of the Eurekan Orogeny in the Canadian Arctic Islands (Miall, 1984). The tectonic regime between Greenland and Svalbard changed from pure strike slip to transpression during the time period Chron 24 to 20, according to our model. Figures 15, 18, 20 and 22 illustrate a continuously growing overlap between the margins of Svalbard and Greenland during this time. This correlates well with the main Tertiary folding phase of Spitsbergen which is of Eocene age (Steel and Worsley, 1984; Steel et al., 1985). Transpression as predicted by our model would have persisted throughout the Ypresian and Lutetian. The eastward prograding foldbelt caused crustal buckling along the western margin of Svalbard, giving the Central Tertiary Basin a foreland basin character (Steel et al., 1985). We suggest that the main progradation of the fold belt was related to continuous transpression from Chron 24 to 20, which implies a Lower/Middle Eocene age for the Spitsbergen orogeny.

Kings Trough began to form after Chron 21 along the plate boundary between Iberia and Eurasia as a result of divergence between the African and Eurasian plate margins (Srivastava and Tapscott, 1986). The amount of overlap (stippled area, Figure 14) along the plate boundary between Iberia and Eurasia (after Searle and Whitmarsh, 1978) represents the successive extension along the plate boundary after Chron 21.

Chron 13 (35.9 Ma, Rupelian) to Chron 5 (10.6 Ma, Tortonian) (Figures 18, 19)

Spreading in the Labrador Sea ceased between Chron 20 and Chron 13. As a result, the direction of motion between Greenland and Eurasia changed, initiating the onset of seafloor spreading between Greenland and Svalbard along the Knipovich Ridge. Seafloor spreading between Jan Mayen and Greenland is inferred to have started at Chron 13, leading to simultaneous spreading east and west of Jan Mayen along the Aegir and Kolbeinsey ridges. Anomaly 13 west of Jan Mayen is not included in our data set, although it is now identified (Klitgord, pers. com.). The plate reorganization at Chron 13 resulted in renewed compression in the Bering Sea region. This convergence seems to be expressed in anticlinal deformation of sediments in the Anadyr and Khatyrka basins (Harbert et al., 1987).

Iberia began to move with Eurasia between chrons 13 and 6 and the Azores triple junction formed between Iberia and Africa. The amount of extension along the Azores plate boundary (after Searle, 1980) after Chron13 is displayed by a stippled area (Figure 18). The total amount of overlap along the boundary corresponds to the extension after Chron 6. Iberia is inferred to have moved independently for a short period of time. By applying the rotations for Africa relative to North America, the magnetic anomalies older than An6 west of Iberia can be fitted only if we assume an independent clockwise rotation of Iberia relative to Africa between chrons 13 and 6. In the same time period spreading ceased between Jan Mayen and Eurasia in the Norwegian Sea. After Iberia became attached to Europe, the entire North Atlantic north of the Azores triple junction opened as a two plate system.

In the Oligocene compression between Italy and Europe continued, but Italy now acted as an independent plate, rotating counterclockwise 25° to 30° with respect to Africa (Vandenberg, 1983). Corsica/Sardinia/Calabria started to rift away from France in the Oligocene, initiating back-arc rifting and Later formation of the Ligurian Sea north of the subduction zone that was located south of Corsica/Sardinia/Calabria (Hill and Hayward, 1988). Starting in the Early Miocene the rotation of Corsica/Sardinia/Calabria caused collision with western Italy and with northern Tunisia and Sicily (Hill and Hayward, 1988). Sardinia is assumed to have rotated away counterclockwise by at least 30° from Africa in the Early Miocene from 22 to 19 Ma based on paleomagnetic data and potassium-argon dating of Tertiary volcanics in Sardinia (Montigny et al., 1981). Between 20 and 10 Ma the Corsica/Sardinia/Calabria block became locked between Italy and Sicily, initiating the major deformation phase of the Appenines. Subduction from the southeast continued beneath Calabria until the Late Miocene (Hill and Hayward, 1988). Subsequently a back arc basin was initiated between Calabria and Corsica/Sardinia, resulting in the formation of ocean crust in the Tyrrhenian Sea. The Miocene-/Pliocene rotation of Sicily initiated formation of the Pantelleria Graben between Sicily and Africa (Hill and Hayward, 1988).

Spreading directions and rates in the North Atlantic

Figures 21 and 22 illustrate spreading directions and half spreading rates for Europe and Greenland relative to North America for our plate model and the model of Srivastava and Tapscott (1986), respectively. Spreading direction and rates are shown for two synthetic flowlines starting at two points along the mid-Atlantic ridge. Half spreading rates were calculated using the finite rotation poles in Table 1 and poles from Srivastava and Tapscott (1986).

Our model suggests a gradual change of seafloor spreading direction between Eurasia and North America as reflected in the direction of the Charlie-Gibbs flowline (Figure 8). We predict that the spreading direction varied within a range of approximately 15 degrees from the breakup to present day in accordance with tectonic flowline evidence. Our predicted flowline for the Charlie-Gibbs Fracture Zone is shown on the isochron chart for the North Atlantic (Figure 20). The histogram for spreading direction (Figure 21a) displays a two stage tectonic development for motion between Eurasia and North America, interrupted by the major plate reorganization at Chron 25.

The plate model by Srivastava and Tapscott (1986) (Figure 21b) shows variations of spreading direction within a range of 30 degrees along the Charlie-Gibbs Fracture Zone, which are not reflected in the Charlie-Gibbs flowline. Spreading directions between Greenland and North America (Figure 22) show a three stage development in our model as well as in Srivastava and Tapscott's (1986) model. We consider the sharp change in spreading direction between chrons 25 and 24 (after Srivastava and Tapscott, 1986) as shown on Figure 22b to be unlikely.

Table 1: Plates and Platelets of the North Atlantic region

Tectonic Element Number	Alphabetic Code	Name
101	NAM	NORTH AMERICA
102	GRN	GREENLAND
103	NSL	NORTH SLOPE BLOCK
106	ELS	ELLESMERE ISLAND
107	BIS	BAFFIN ISLAND
119	TLB	TROLLE LAND BLOCK
120	CAI	CANADIAN ARCTIC ISLANDS
233	FSB	FLORIDA STRAITS BLOCK
301	EUR	EURASIA
304	IBR	IBERIA
306	CSD	CORSICA/SARDINIA
307	ITL	ITALY
318	RKL	ROCKALL PLATEAU
320	BAL	BALEARES
322	CAL	CALABRIA
323	SIC	SICILY
330	RFB	RINGKØBING-FYN BLOCK
331	GBF	GREAT BRITAIN/FRANCE
407	CHK	CHUKOTKA
714	AFR	AFRICA
907	JMN	JAN MAYEN MICROPLATE

Table 2: Finite reconstruction poles for the plates according to Table 1
(If the source of a rotation pole is not specified, the pole refers to the plate model in this paper)

Mobile Plate	Age	Lat.	Long.	Angle	Ref. Plate	Description
101	0.0	0.00	0.00	0.00	714	!NAM-AFR PRESENT DAY
101	10.6	80.12	50.80	2.52	714	!NAM-AFR AN 5
101	20.5	79.57	37.84	5.29	714	!NAM-AFR AN 6 KLITGORD and SCHOUTEN 1986
101	35.9	75.37	1.12	10.04	714	!NAM-AFR AN 13
101	50.3	75.30	-3.88	15.25	714	!NAM-AFR AN 21
101	59.2	79.68	-0.46	18.16	714	!NAM-AFR AN 25
101	67.5	82.90	4.94	20.76	714	!NAM-AFR AN 30
101	71.7	81.35	-9.15	22.87	714	!NAM-AFR AN 32 KLITGORD and SCHOUTEN 1986
101	74.3	80.76	-11.76	23.91	714	!NAM-AFR AN 33y KLITGORD and SCHOUTEN 1986
101	80.2	78.30	-18.35	27.06	714	!NAM-AFR AN 33o KLITGORD and SCHOUTEN 1986
101	84.0	76.55	-20.73	29.60	714	!NAM-AFR AN 34 KLITGORD and SCHOUTEN 1986
101	118.7	66.30	-19.90	54.25	714	!NAM-AFR AN M 0 KLITGORD and SCHOUTEN 1986
101	126.5	66.13	-19.00	56.39	714	!NAM-AFR AN M 4 KLITGORD and SCHOUTEN 1986
101	131.7	65.95	-18.50	57.40	714	!NAM-AFR AN M 10N KLITGORD and SCHOUTEN 1986
101	141.9	66.10	-18.40	59.79	714	!NAM-AFR AN M 16 KLITGORD and SCHOUTEN 1986
101	149.9	66.50	-18.10	61.92	714	!NAM-AFR AN M 21 KLITGORD and SCHOUTEN 1986
101	156.6	67.15	-16.00	64.70	714	!NAM-AFR AN M 25 KLITGORD and SCHOUTEN 1986
101	170.0	67.02	-13.17	72.10	714	!NAM-AFR BSMA KLITGORD and SCHOUTEN 1986
101	175.0	66.95	-12.02	75.55	714	!NAM-AFR ECMA KLITGORD and SCHOUTEN 1986
102	0.0	0.00	0.00	0.00	101	!GRN-NAM
102	35.9	0.00	0.00	0.00	101	!GRN-NAM LABRADOR SFS STOPS A13
102	46.2	60.59	-81.31	-1.76	101	!GRN-NAM AN20
102	50.3	60.59	-81.31	-3.20	101	!GRN-NAM AN21
102	52.6	59.73	-89.37	-3.50	101	!GRN-NAM AN22
102	54.7	57.90	-99.00	-3.90	101	!GRN-NAM AN23
102	56.1	56.52	-103.94	-4.18	101	!GRN-NAM AN24
102	59.2	61.97	-103.27	-5.35	101	!GRN-NAM AN25
102	67.5	66.70	-109.80	-7.61	101	!GRN-NAM AN30
102	71.7	68.04	-112.33	-8.77	101	!GRN-NAM AN32
102	74.3	69.89	-111.52	-9.04	101	!GRN-NAM AN33y
102	80.2	69.20	-109.92	-10.63	101	!GRN-NAM AN330
102	84.0	69.70	-109.90	-11.27	101	!GRN-NAM AN34
102	95.0	73.97	-107.20	-13.62	101	!GRN-NAM FIT SRIVASTAVA and TAPSCOTT 86
102	130.0	75.08	-105.10	-15.94	101	!GRN-NAM FIT REST MARG, DUNBAR and SAWYER IN PREP
103	000.0	0.00	0.00	0.00	101	!NSL-NAM
103	100.0	0.00	0.00	0.00	101	!NSL-NAM
103	130.0	70.11	-128.16	-75.00	101	!NSL-NAM FIT, Rotational Model
106	35.9	0.00	0.00	0.00	102	!ELS-GRN KEPT FIXED TO GRN AFTER A13 TIME
106	95.0	67.20	178.50	2.40	102	!ELS-GRN CALCULATED MOTION REL TO GRN
107	35.9	0.00	0.00	0.00	101	!BIS-NAM
107	95.0	-69.79	101.72	5.98	101	!BIS-NAM RIFTING IN HUDSON BAY

Mobile Plate	Age	Lat.	Long.	Angle	Ref. Plate	Description
119	-100	0.00	0.00	0.00	102	!TLB-GRN
119	0.0	0.00	0.00	0.00	102	!TLB-GRN
119	67.5	0.00	0.00	0.00	102	!TLB-GRN JUMP OF PLATE BOUNDARY BETWEEN EURASIA
119	67.5	50.80	127.30	11.86	301	!TLB-EUR AND GREENLAND FROM TROLLE LAND FAULT
119	245.0	50.80	127.30	11.86	301	!TLB-EUR ZONE TO HORNSUND FAULT Z. AT ~67.5 Ma
120	0.0	0.00	0.00	0.00	101	!CAI-NAM
120	35.9	0.00	0.00	0.00	101	!CAI-NAM
120	95.0	57.15	-137.00	-1.07	101	!CAI-NAM RIFTING IN NORTHWEST PASSAGE
233	0.0	0.00	0.00	0.00	101	!FSB-NAM
233	158.0	66.78	-17.54	0.00	101	!FSB-NAM
233	162.0	66.78	-17.54	-1.50	101	!FSB-NAM RIGHT LATERAL STRIKE SLIP BETWEEN
233	164.0	66.78	-17.54	-2.01	101	!FSB-NAM FLORIDA STRAITS BLOCK AND
233	175.0	66.78	-17.50	-6.16	101	!FSB-NAM NORTH AMERICA
301	0.0	0.00	0.00	0.00	101	!EUR-NAM
301	10.6	68.00	137.00	-2.50	101	!EUR-NAM AN5 PIT. AND TALW.1972,SRIV. AND TAPS. 1
301	20.5	68.92	136.74	-4.97	101	!EUR-NAM
301	35.9	67.27	136.95	-7.64	101	!EUR-NAM
301	50.3	67.79	140.59	-11.04	101	!EUR-NAM
301	56.1	62.98	142.91	-12.65	101	!EUR-NAM
301	59.2	63.25	144.00	-13.75	101	!EUR-NAM
301	67.5	69.87	146.12	-17.39	101	!EUR-NAM
301	71.7	71.23	146.96	-18.32	101	!EUR-NAM
301	74.3	72.21	147.60	-19.04	101	!EUR-NAM
301	80.2	74.20	149.07	-20.51	101	!EUR-NAM
301	84.0	75.34	150.12	-21.55	101	!EUR-NAM
301	105.0	79.50	151.92	-25.59	101	!EUR-NAM
301	130.0	83.44	151.92	-32.58	101	!EUR-NAM SRIV and TAPS 1986, CLOSE ROCK.TROUGH
301	145.0	83.44	151.92	-32.58	101	!EUR-NAM FIT OF REST MARG,DUNB. and SAWY. IN PREP
301	145.0	0.0	0.0	0.0	330	!EUR-RFB MIDDLE/UPPER JURASSIC RIFTING
301	170.0	72.80	30.70	-0.87	330	!EUR-RFB IN VIKING GRABEN
304	0.0	0.0	0.0	0.0	101	!IBR-NAM PRESENT
304	10.6	68.00	137.00	-2.50	101	!IBR-NAM AN 5 SRIV and TAPS 1986
304	20.5	68.92	136.74	-4.97	101	!IBR-NAM AN 6
304	35.9	51.07	144.08	-7.13	101	!IBR-NAM AN 13 IBERIA MOVES WITH AFRICA
304	50.3	72.35	130.90	-11.09	101	!IBR-NAM AN 21 PRIOR TO AN 13
304	59.2	73.56	132.58	-14.26	101	!IBR-NAM AN 25
304	67.5	73.84	134.67	-17.08	101	!IBR-NAM AN 30
304	71.7	78.77	132.66	-18.80	101	!IBR-NAM AN 32
304	74.3	80.47	130.08	-19.70	101	!IBR-NAM AN 33
304	80.2	85.49	110.26	-22.41	101	!IBR-NAM AN 330
304	84.0	87.18	57.40	-24.67	101	!IBR-NAM AN 34
304	118.7	71.20	-12.60	-46.11	101	!IBR-NAM AN M0
304	133.2	70.33	-11.08	-51.09	101	!IBR-NAM AN M11 SRIV and TAPS 1986
306	5.0	0.00	0.00	0.00	301	!CSD-EUR OLIGOCENE/MIOCENE ROTATION OF CORSICA/
306	36.0	43.50	9.00	-67.50	301	!CSD-EUR SARDINIA RELATIVE TO EURASIA

Mobile Plate	Age	Lat.	Long.	Angle	Ref. Plate	Description
307	00.0	0.00	0.00	0.00	301	!ITL-EUR
307	21.0	0.00	0.00	0.00	301	!ITL-EUR ITL MOVES WITH EUR AFTER 21 MA
307	21.0	15.33	-15.03	2.34	714	!ITL-AFR TERTIARY ROTATION OF ITL REL. TO EUR
307	65.0	37.60	20.00	-23.00	714	!ITL-AFR ITALY MOVES WITH AFRICA
307	90.0	37.60	20.00	-23.00	714	!ITL-AFR IN THE MESOZOIC
307	175.0	34.30	7.40	-23.00	714	!ITL-AFR
318	0.0	0.00	0.00	0.00	331	!RKL-GBF
318	84.0	0.00	0.00	0.00	331	!RKL-GBF ROCKALL MOVES WITH EURASIA AFTER 84MA
318	84.0	53.50	125.09	-12.56	102	!RKL-GRN RKL MOVES WITH GRN PRIOR TO 84 MA
320	6.0	0.00	0.00	0.00	304	!BAL-IBR MIDDLE/LATE MIOCENE ROTATION OF THE
320	16.0	38.20	-0.80	23.28	304	!BAL-IBR BALEARES RELATIVE TO IBERIA
322	5.0	46.00	13.00	-8.00	306	!CAL-COR LATE MIOCENE BACK-ARC SPREADING
322	10.0	46.00	16.00	-27.70	306	!CAL-COR BETWEEN CALABRIA AND CORSICA/SARD.
323	0.	0.00	0.00	0.00	714	!SIC-AFR PLIOCENE RIFTING BETWEEN SICILY
323	5.0	38.50	8.00	-14.00	714	!SIC-AFR AND AFRICA
330	0.0	0.00	0.00	0.00	331	!RFG-GBF
330	145.0	0.00	0.00	0.00	331	!RFG-GBF MIDDLE/UPPER JURASSIC RIFTING IN THE
330	170.0	24.19	36.20	0.59	331	!RFG-GBF CENTRAL GRABEN
331	0.0	0.00	0.00	0.00	301	!GBF-EUR GREAT BRITAIN/FRANCE MOVES WITH
331	145.0	0.00	0.00	0.00	301	!GBF-EUR EURASIA AFTER NORTH SEA RIFT EVENT
331	145.0	83.44	151.92	-32.58	101	!GBF-NAM FIT REST MARG,DUNBAR and SAWYER IN PREP
407	0.0	0.00	0.00	0.00	103	!CHK-NSL CHUKOTSKY PENINSULA MOVES
407	175.0	0.00	0.00	0.00	103	!CHK-NSL WITH NORTH SLOPE BLOCK
907	0.	0.00	0.00	0.00	301	!JMN-EUR
907	32.9	64.50	-10.20	-3.20	301	!JMN-EUR AN12
907	35.9	64.61	-11.90	-10.20	301	!JMN-EUR AN13 INTERPOLATED.
907	42.2	64.88	-12.20	-22.59	301	!JMN-EUR AN18 RESULTS IN ROTATION OF JAN MAYEN
907	46.2	64.90	-12.30	-31.57	301	!JMN-EUR AN20 RELATIVE TO EURASIA
999	46.2	64.90	-12.30	-27.40	301	!JMN-EUR AN20
907	50.3	64.31	-12.72	-37.30	301	!JMN-EUR AN21
907	52.6	64.04	-12.88	-41.75	301	!JMN-EUR AN22
907	54.7	63.15	-13.49	-40.86	301	!JMN-EUR AN23
907	54.7	74.88	-9.56	-46.17	102	!JMN-GRN AN24 JAN MAYEN MOVES WITH GREENLAND
907	170.0	74.88	-9.56	-46.17	102	!JMN-GRN AN24 PRIOR TO AN 24

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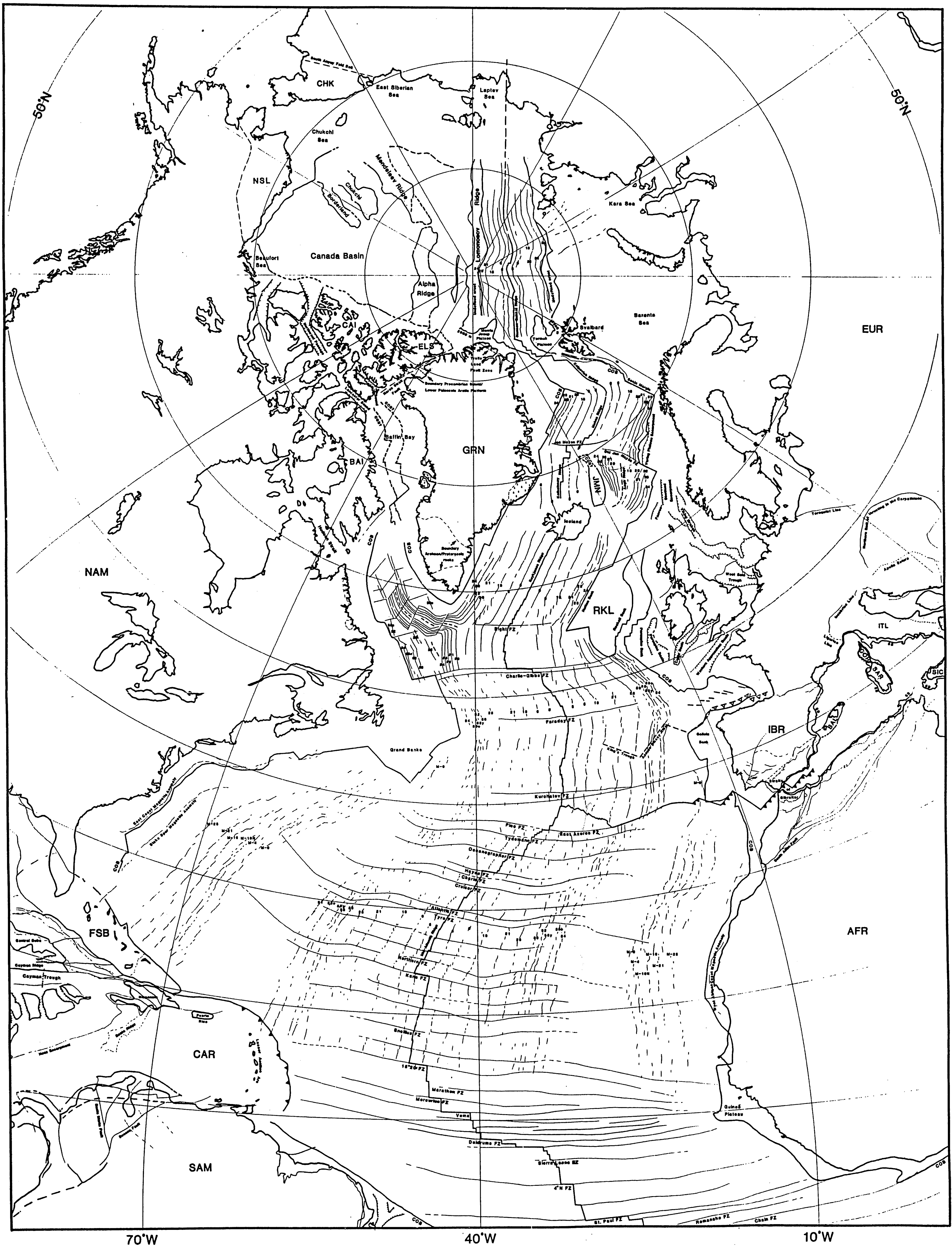

Fig. 1: Magnetic lineations, fracture zones, and boundary between continental and oceanic crust in the North and Central Atlantic.

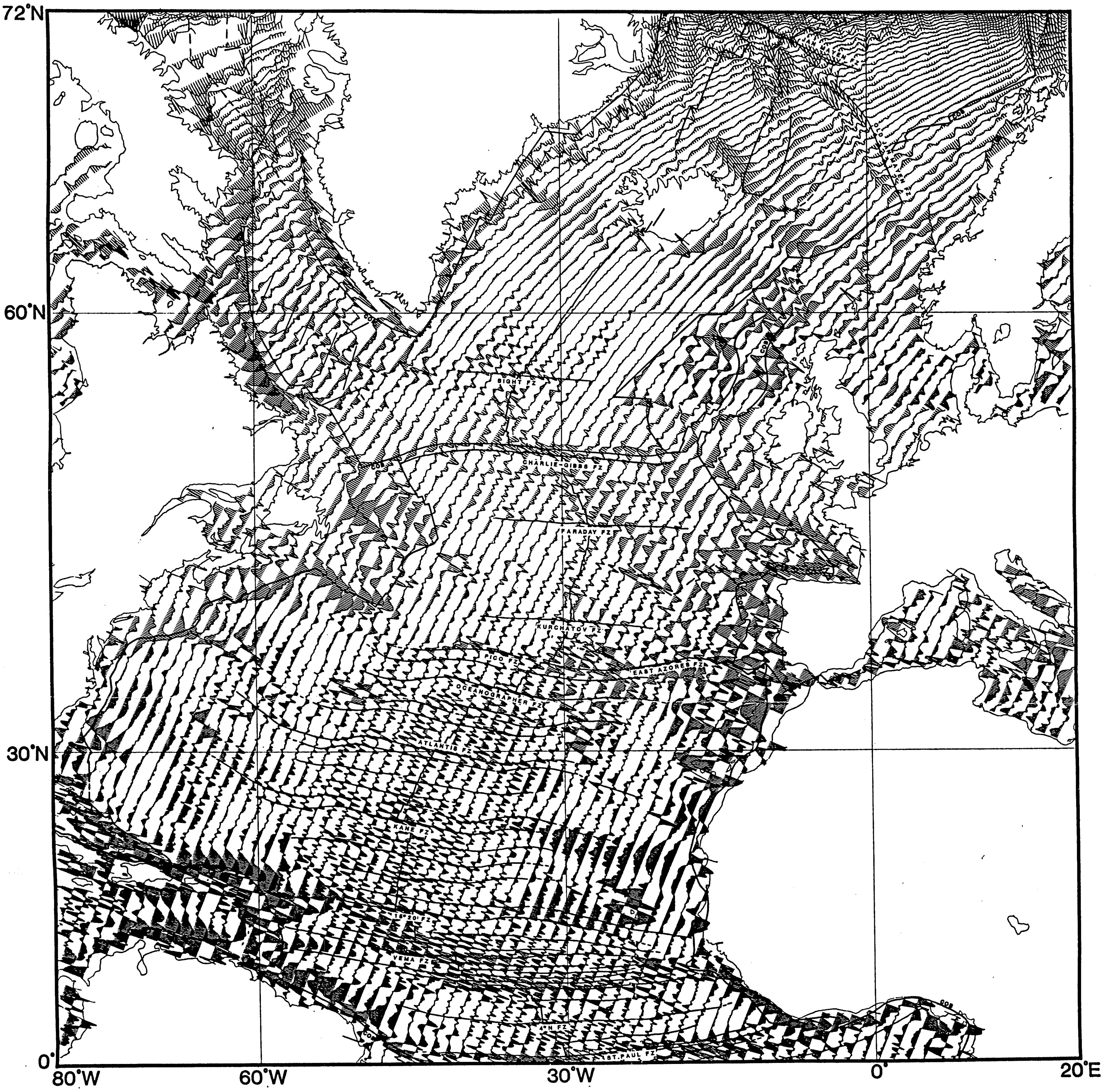

Fig 2: Descending deflection of the vertical data along track from Geosat and fracture zones in the North and Central Atlantic.

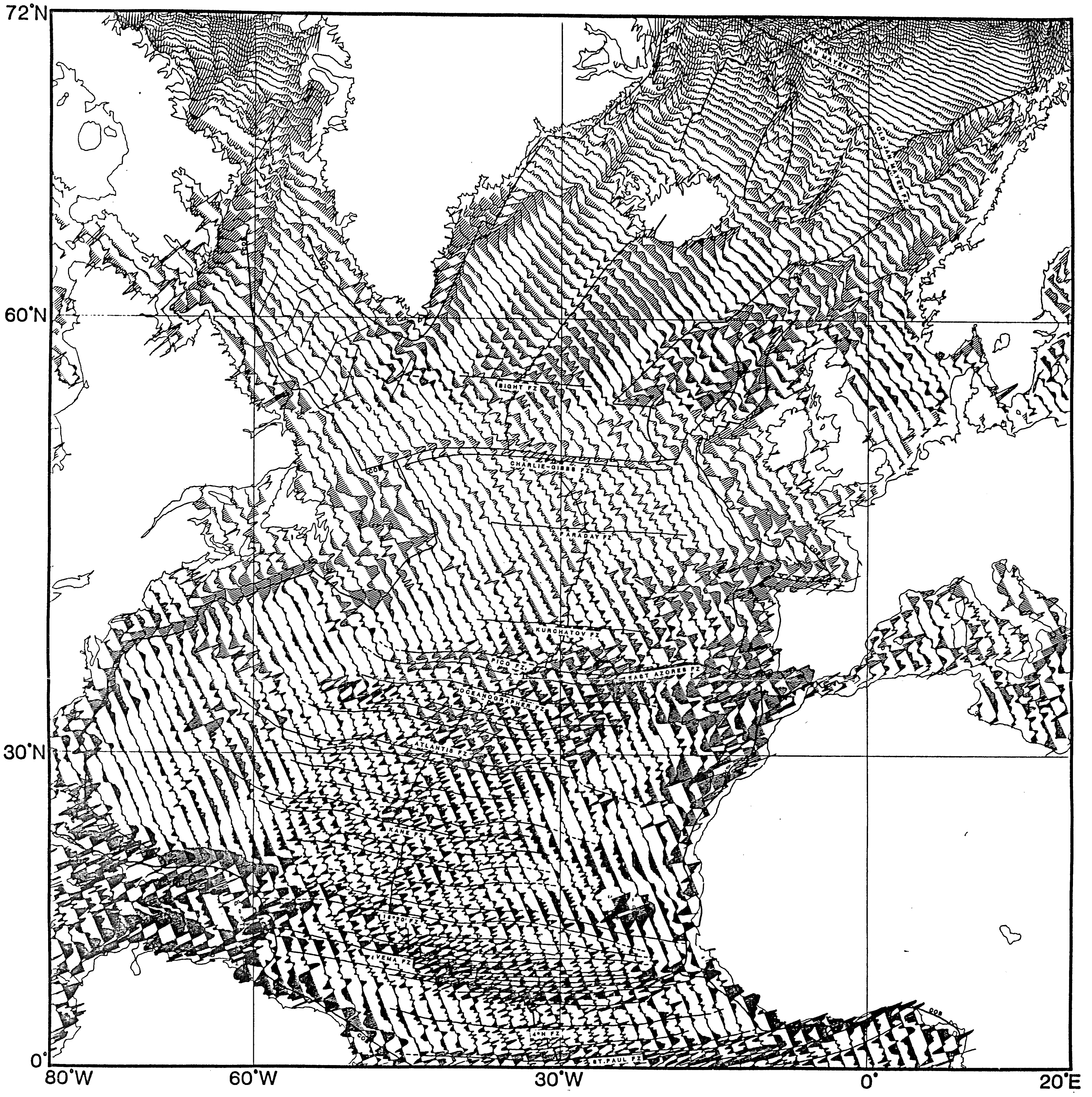

Fig. 3: Ascending deflection of the vertical data along track from Geosat and fracture zones in the North and Central Atlantic.

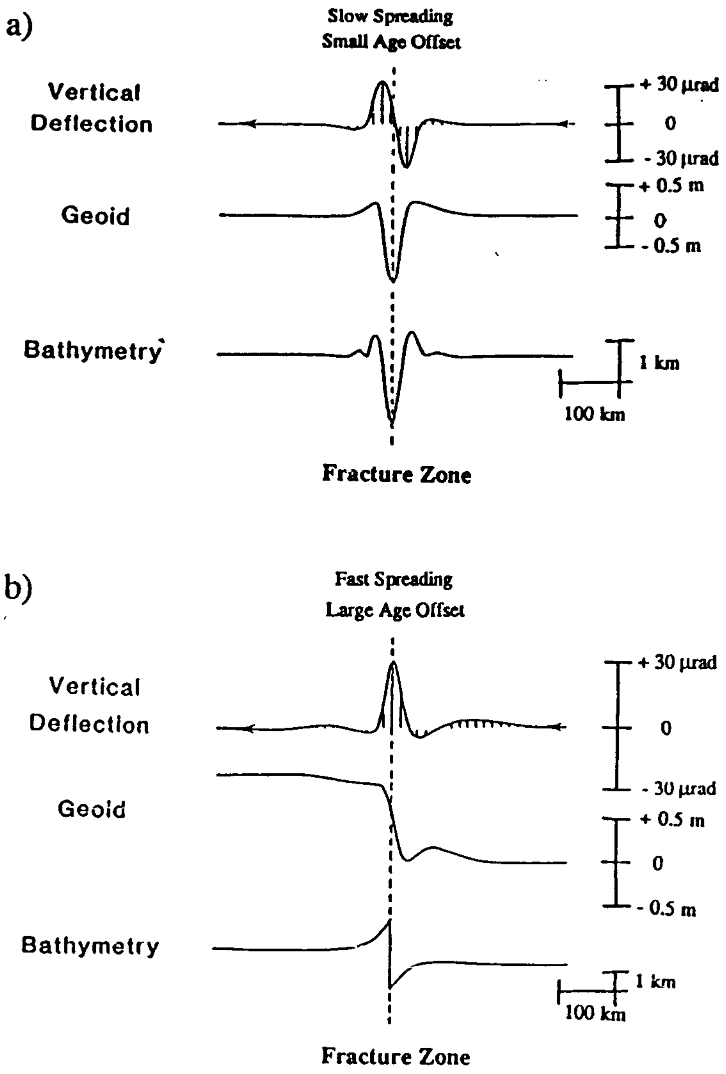

Fig. 4: Relation between vertical deflection, geoid and bathymetry for fracture zones:
a) slow spreading, small age offset
b) fast spreading, large age offset

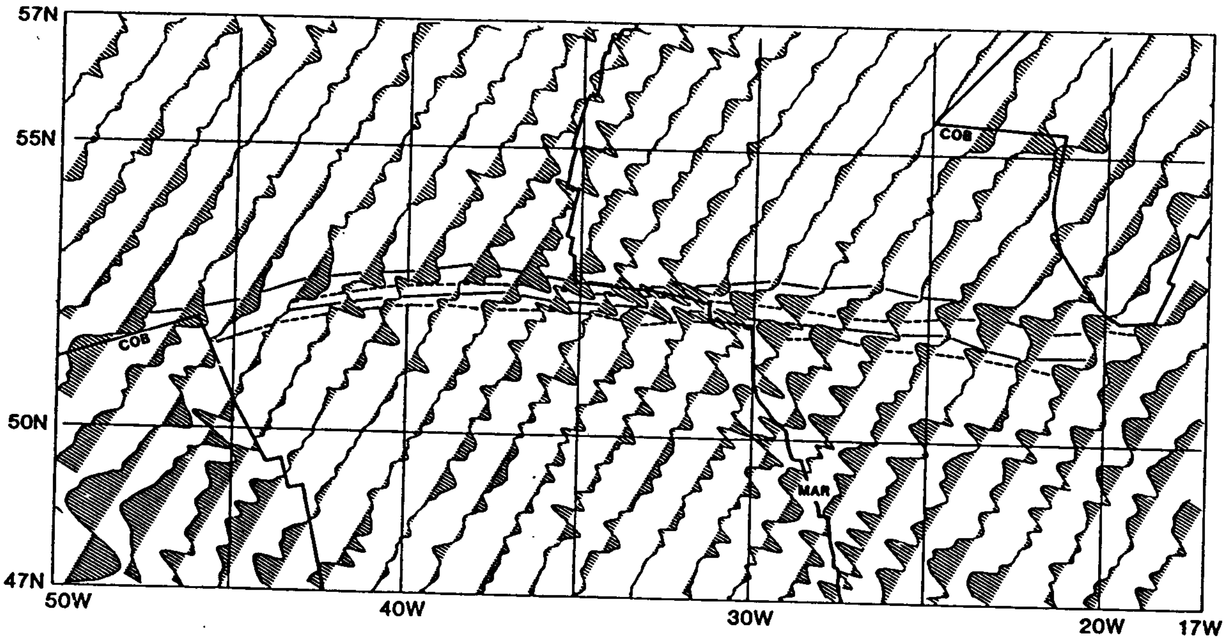

Fig. 5: Descending deflection of the vertical data along track and interpreted lineations in the deflection of the vertical field over the Charlie-Gibbs Fracture Zone.

COB - Boundary between continental and oceanic crust

MAR - Mid-Atlantic Ridge

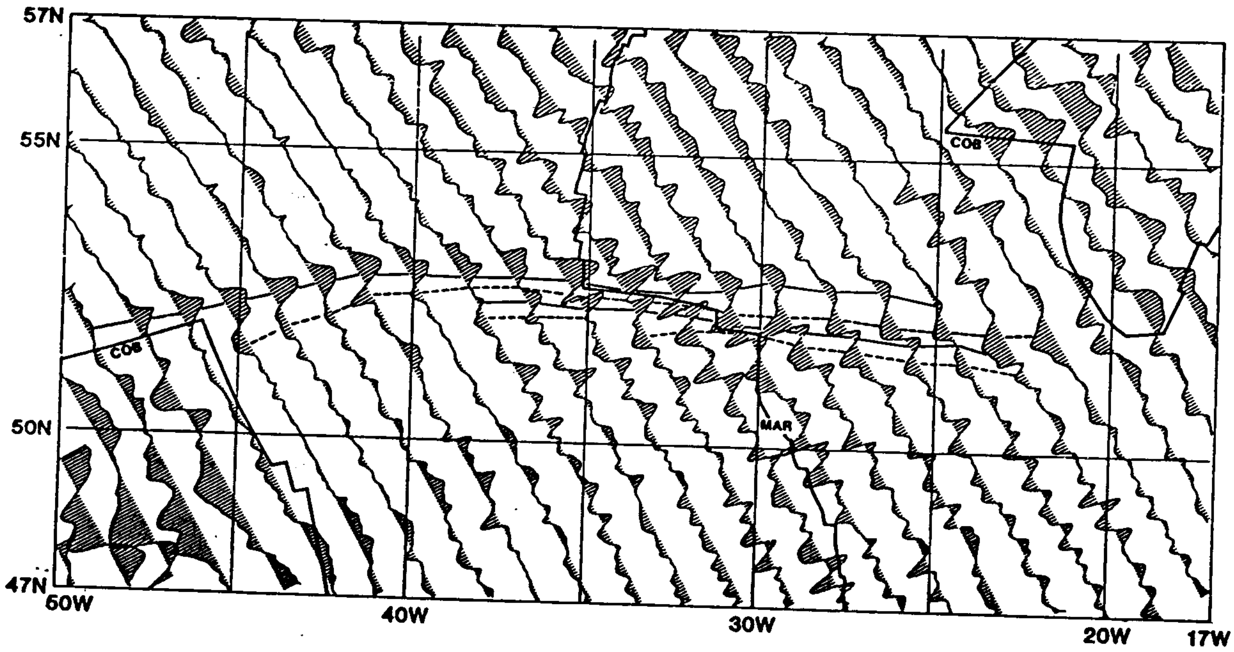

Fig. 6: Ascending deflection of the vertical data along track and interpreted lineations in the deflection of the vertical field over the Charlie-Gibbs Fracture Zone.

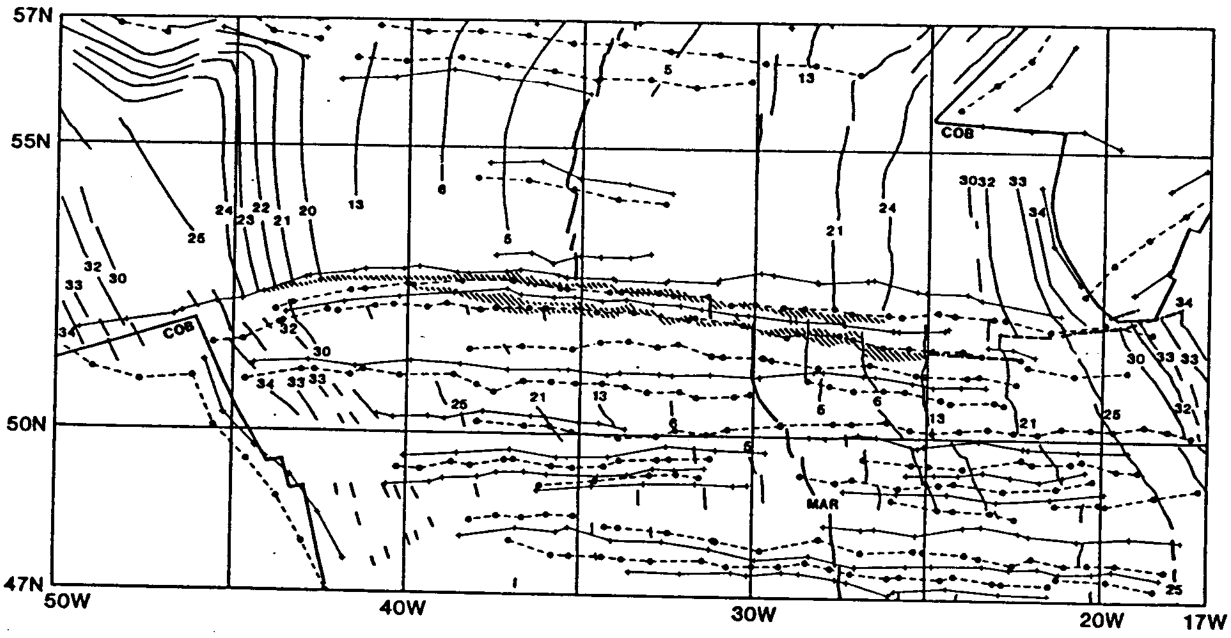

Fig. 7: Lineated peaks and troughs of the vertical deflection from combined ascending and descending tracks, central troughs of the Charlie-Gibbs Fracture Zone (hatched areas) after Olivet et al. (1974), magnetic seafloor spreading lineations and central magnetic anomalies parallel to Charlie-Gibbs Fracture Zone after Olivet et al. (1974) between Grand Banks and the Rockall Plateau.

– – – – positive central magnetic anomalies parallel to Charlie-Gibbs Fracture Zone

– · – · – negative central magnetic anomalies parallel to Charlie-Gibbs Fracture Zone (after Olivet et al. 1974).

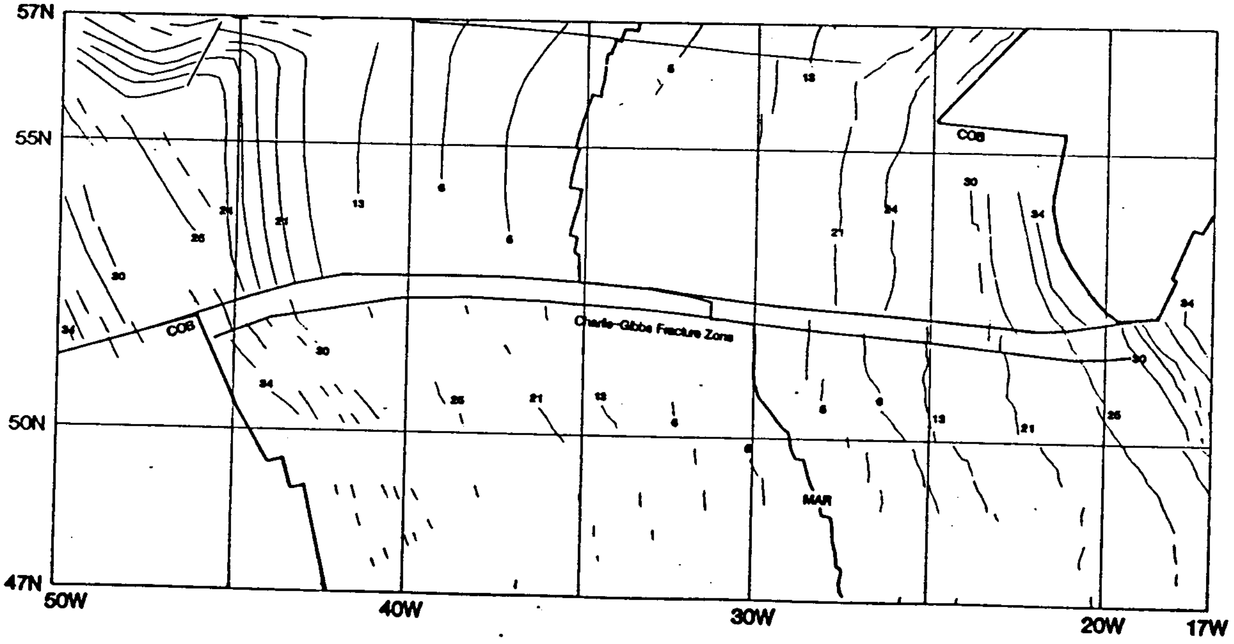

Fig. 8: Interpreted location of the Charlie-Gibbs Fracture Zone from combined ascending and descending deflection of the vertical tracks, central troughs of the Charlie-Gibbs Fracture Zone (hatched areas) after Olivet et al. (1974), magnetic seafloor spreading lineations and central magnetic anomalies parallel to Charlie-Gibbs Fracture Zone after Olivet et al. (1974) between Grand Banks and the Rockall Plateau.

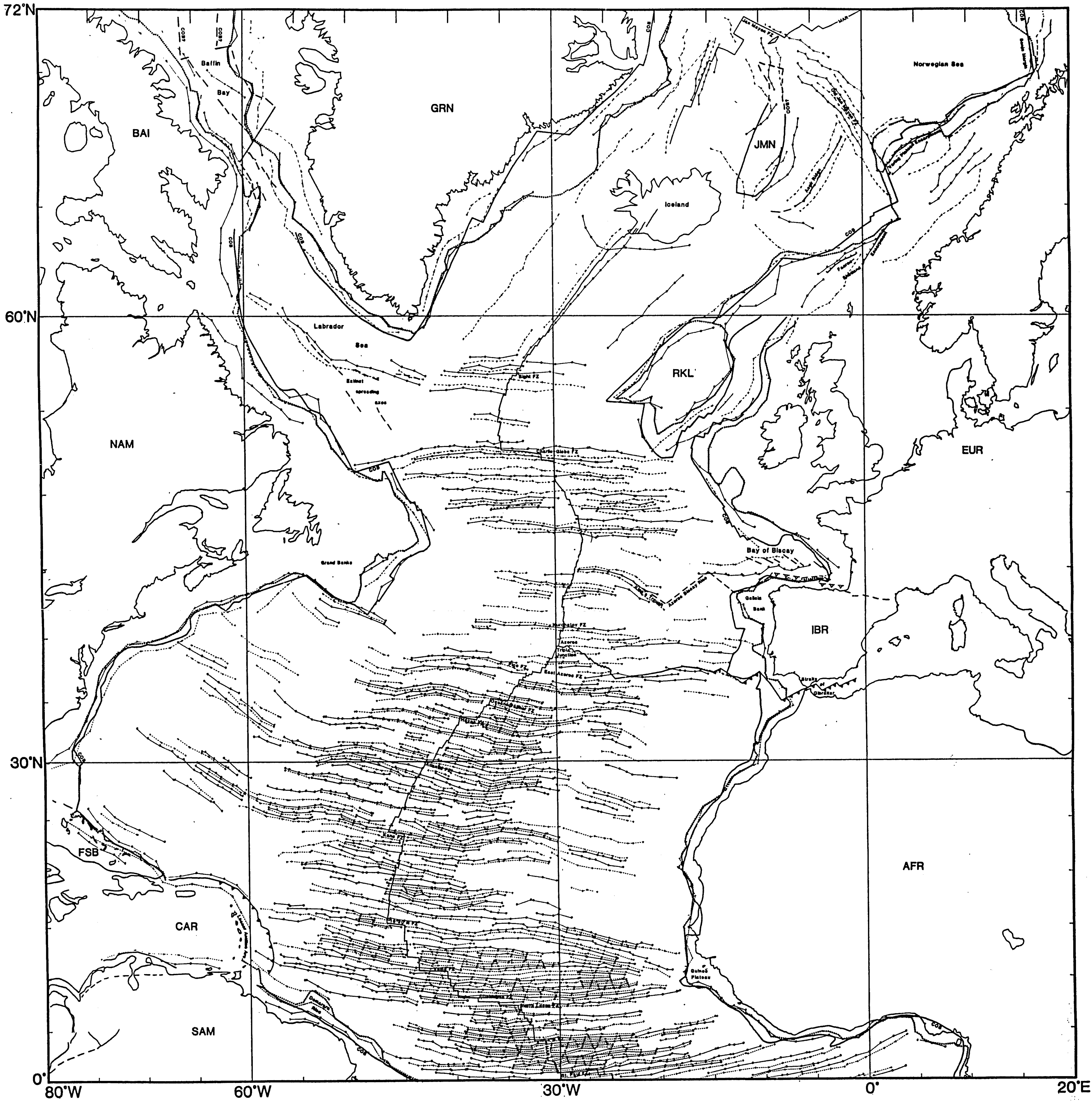

Fig. 9: Lineated peaks and troughs in the deflection of the vertical field in the North and Central Atlantic from combined ascending and descending tracks.

······· shelf break

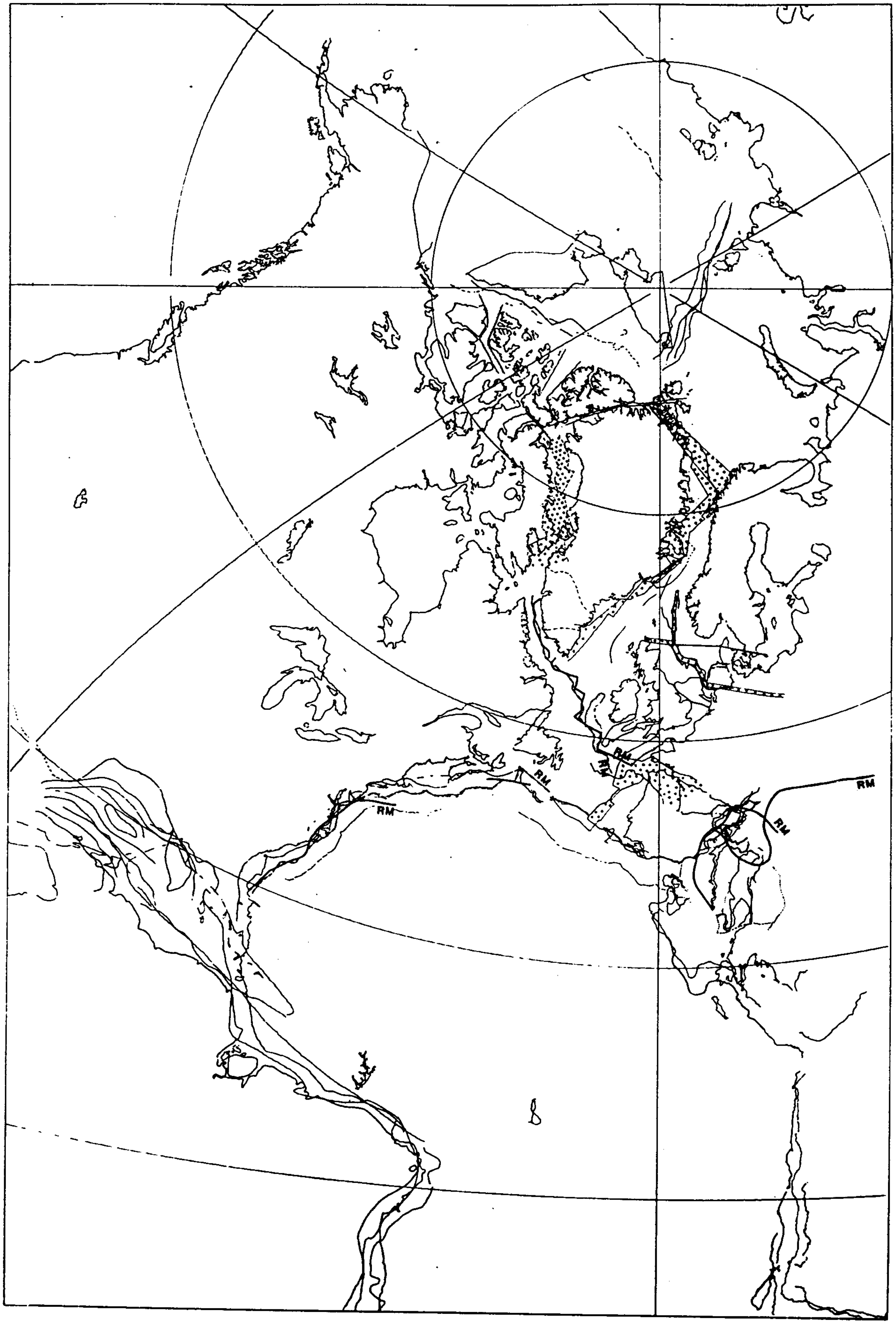

Fig. 10: 175 Ma (Bathonian)

RM - Reconstructed margin ▨ overlaps of oceanic/continental crust

- - - - boundaries of plate boundaries

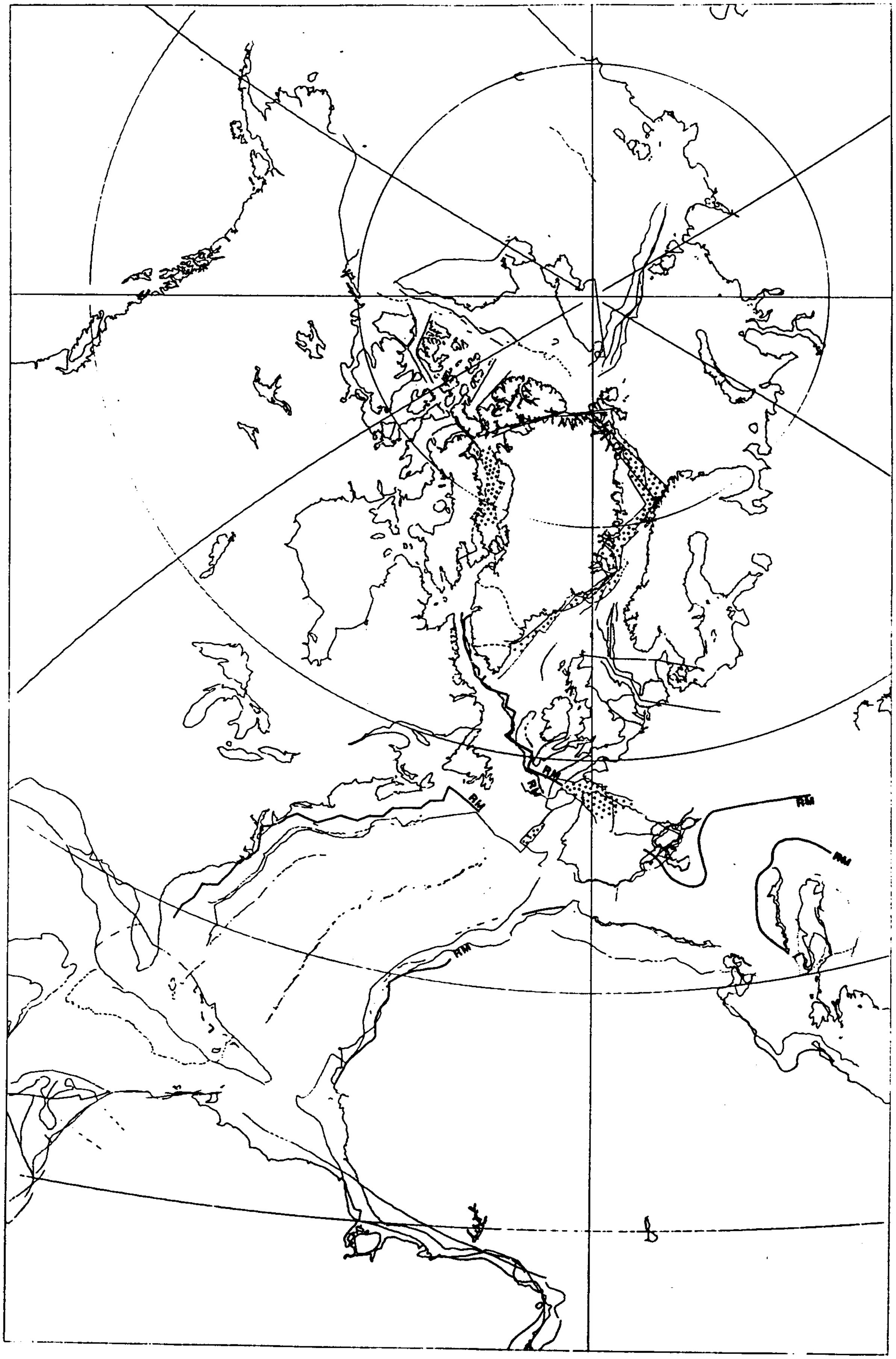

Fig. 11: 130 Ma (Hauterivian)

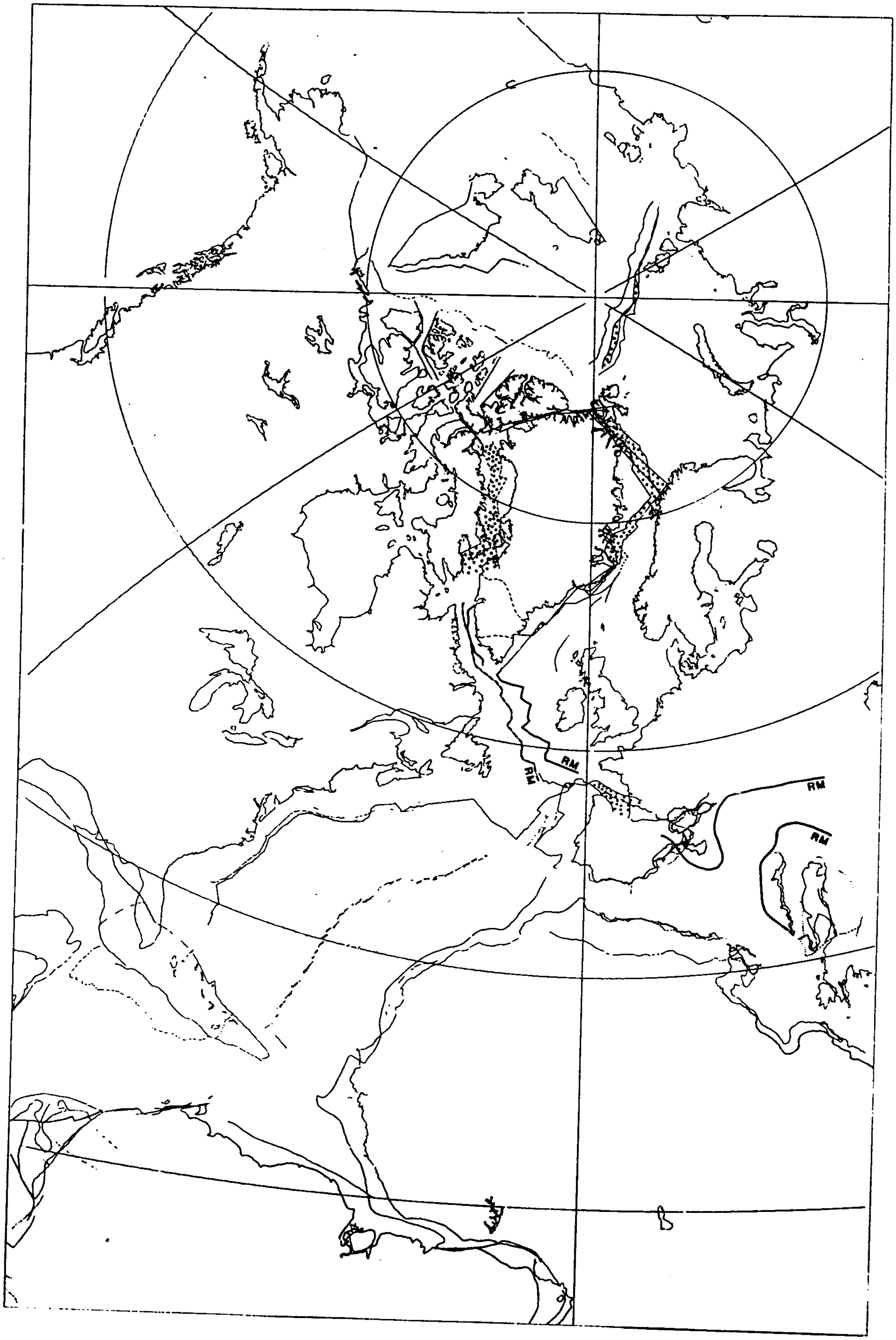

Fig. 12: Chron M-0 (118.7 Ma, Aptian)

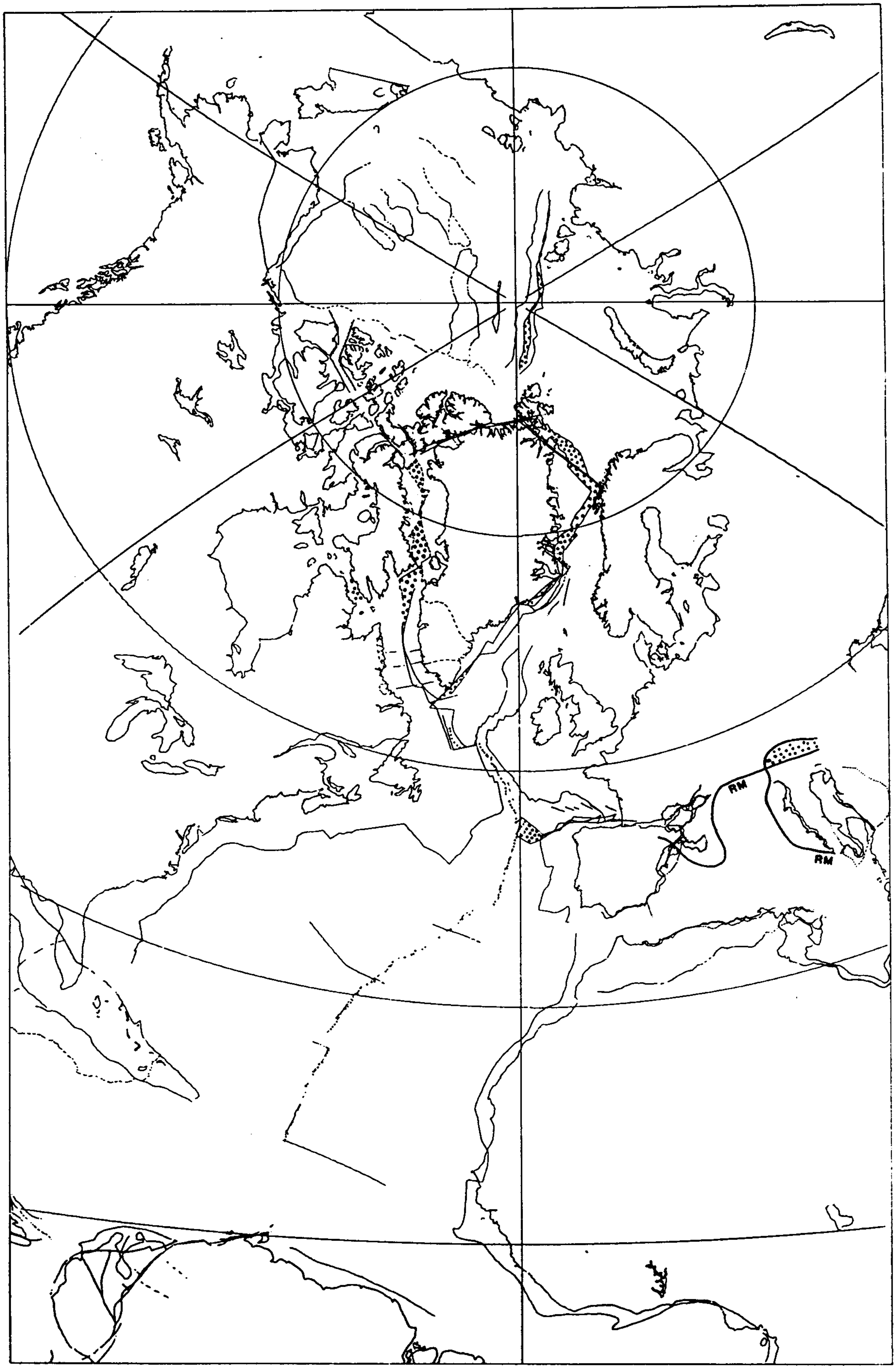

Fig. 13: Chron 34 (84 Ma, Campanian)

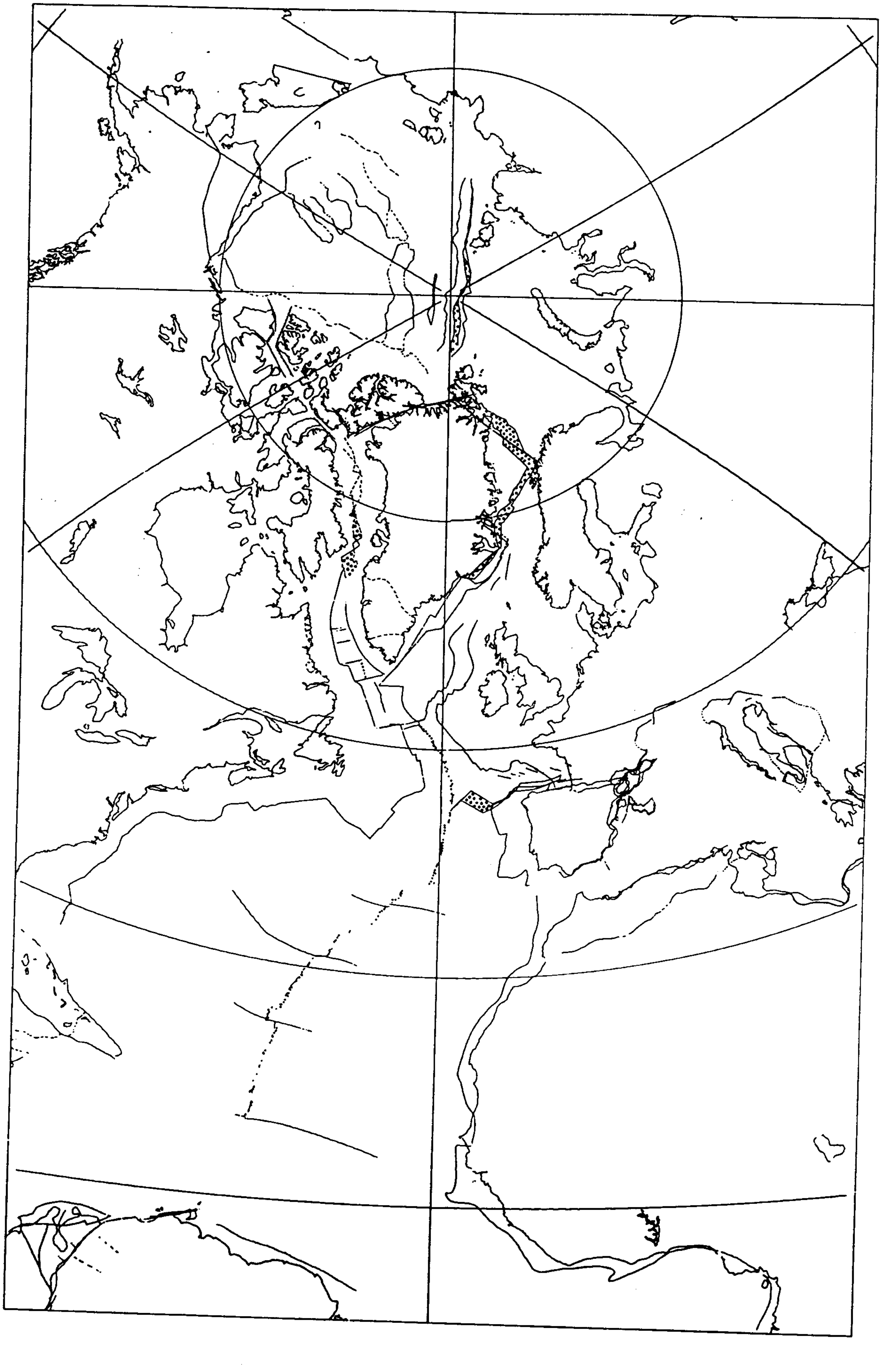

Fig. 14: Chron 30 (68.4 Ma, Maastrichtian)

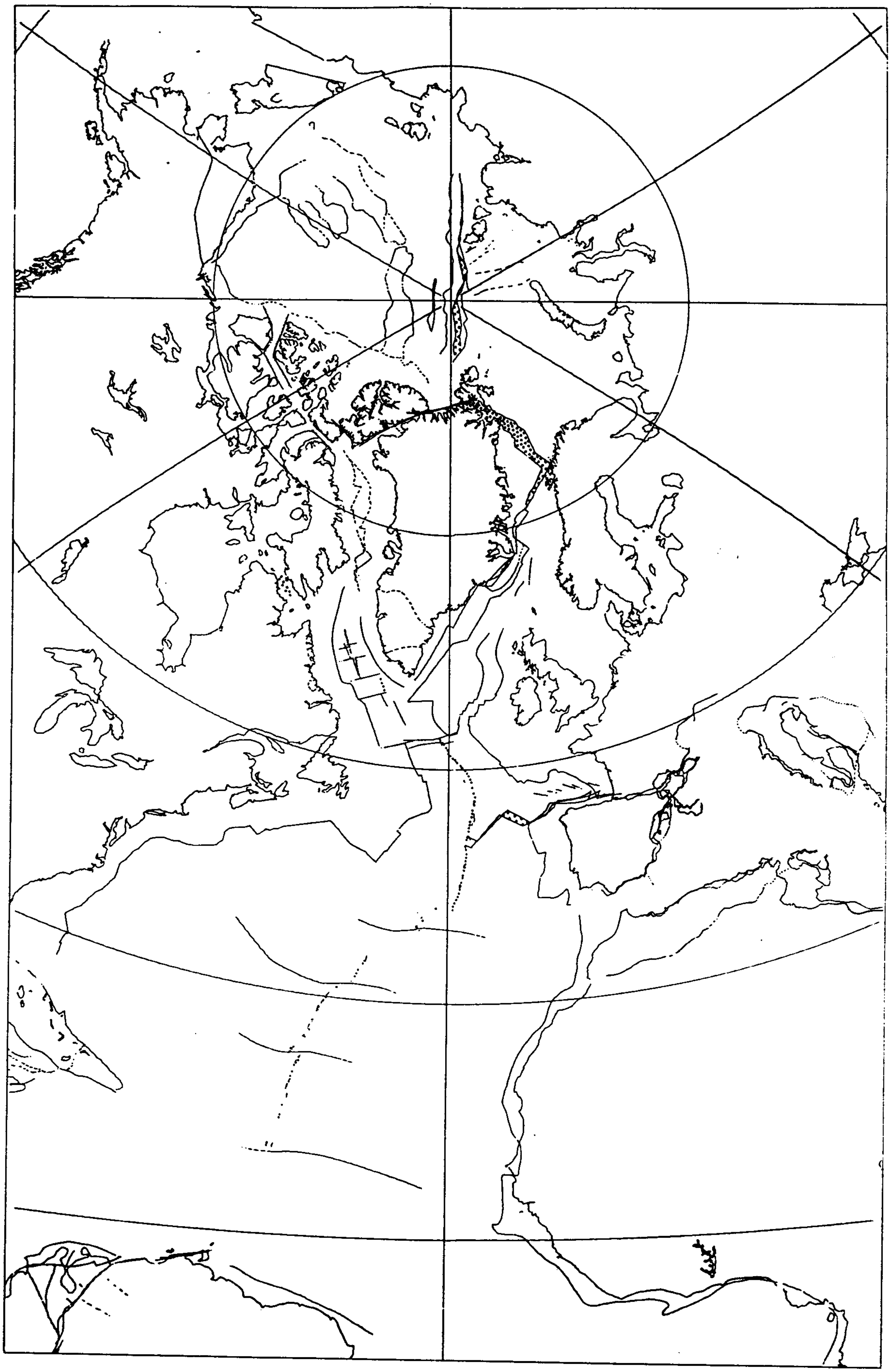

Fig. 15: Chron 25 (59.2 Ma, Thanetian)

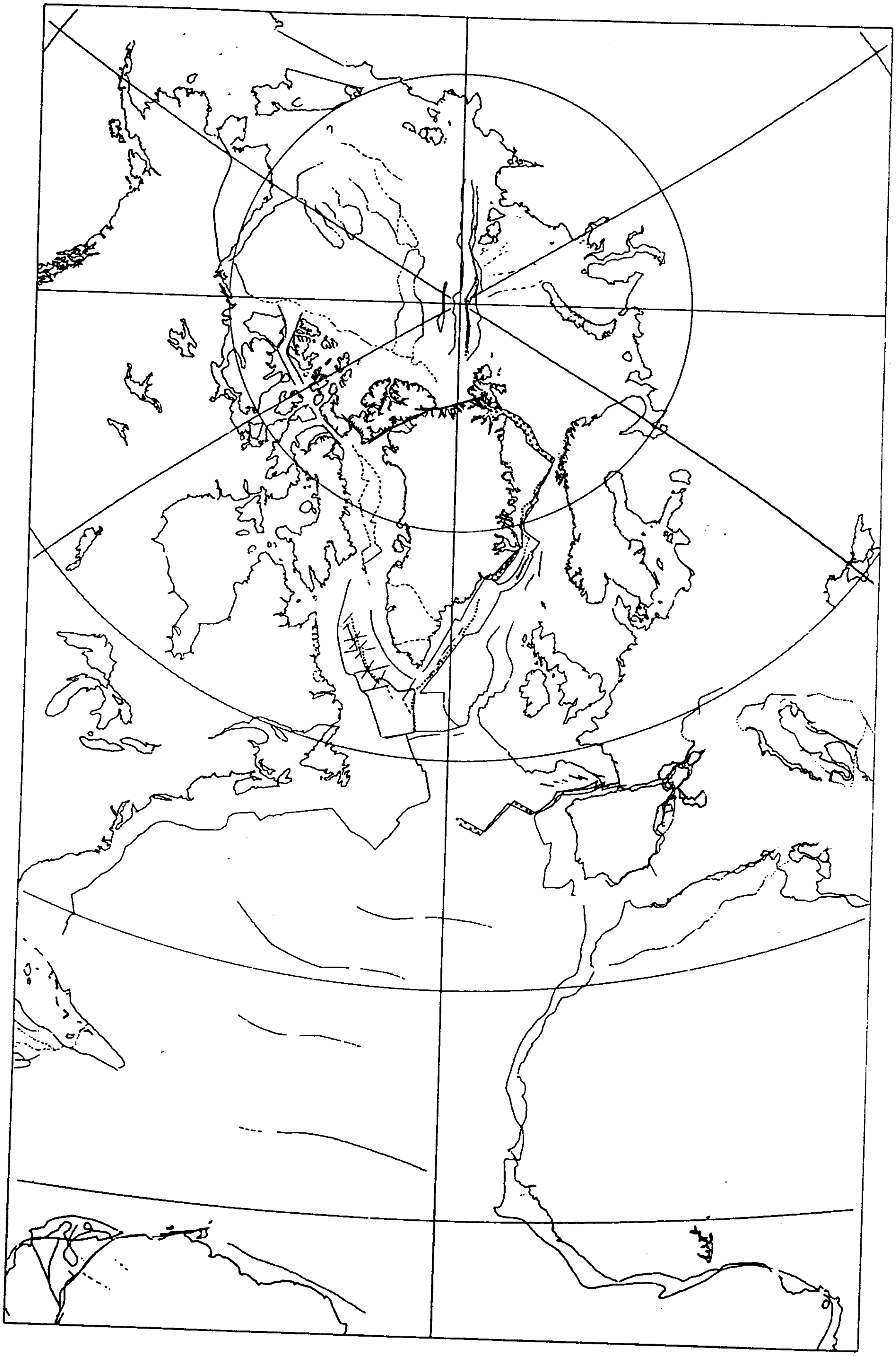

Fig. 16: Chron 24 (56.1 Ma, Ypresian)

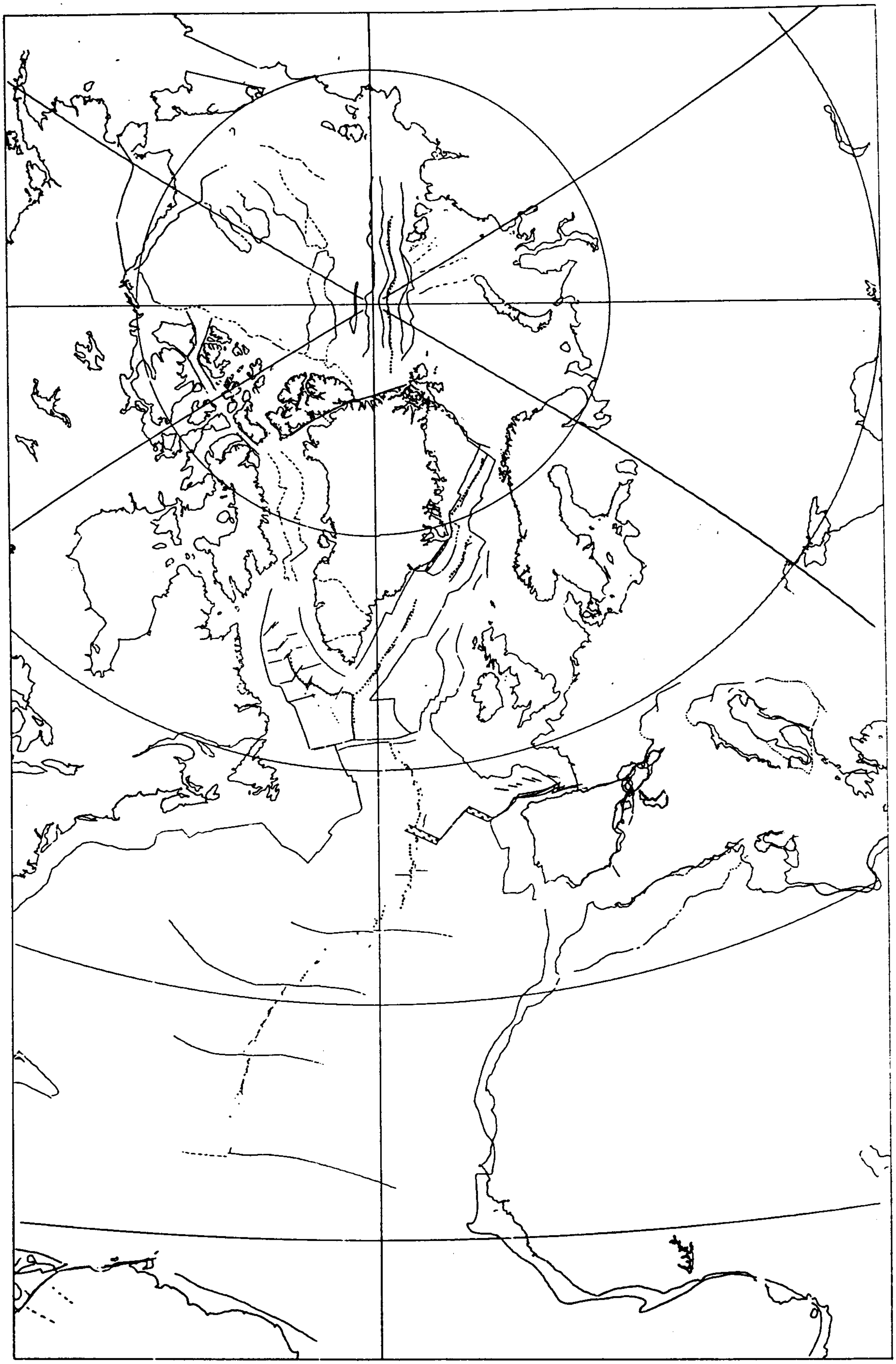

Fig. 17: Chron 21 (50.3 Ma, Lutetian)

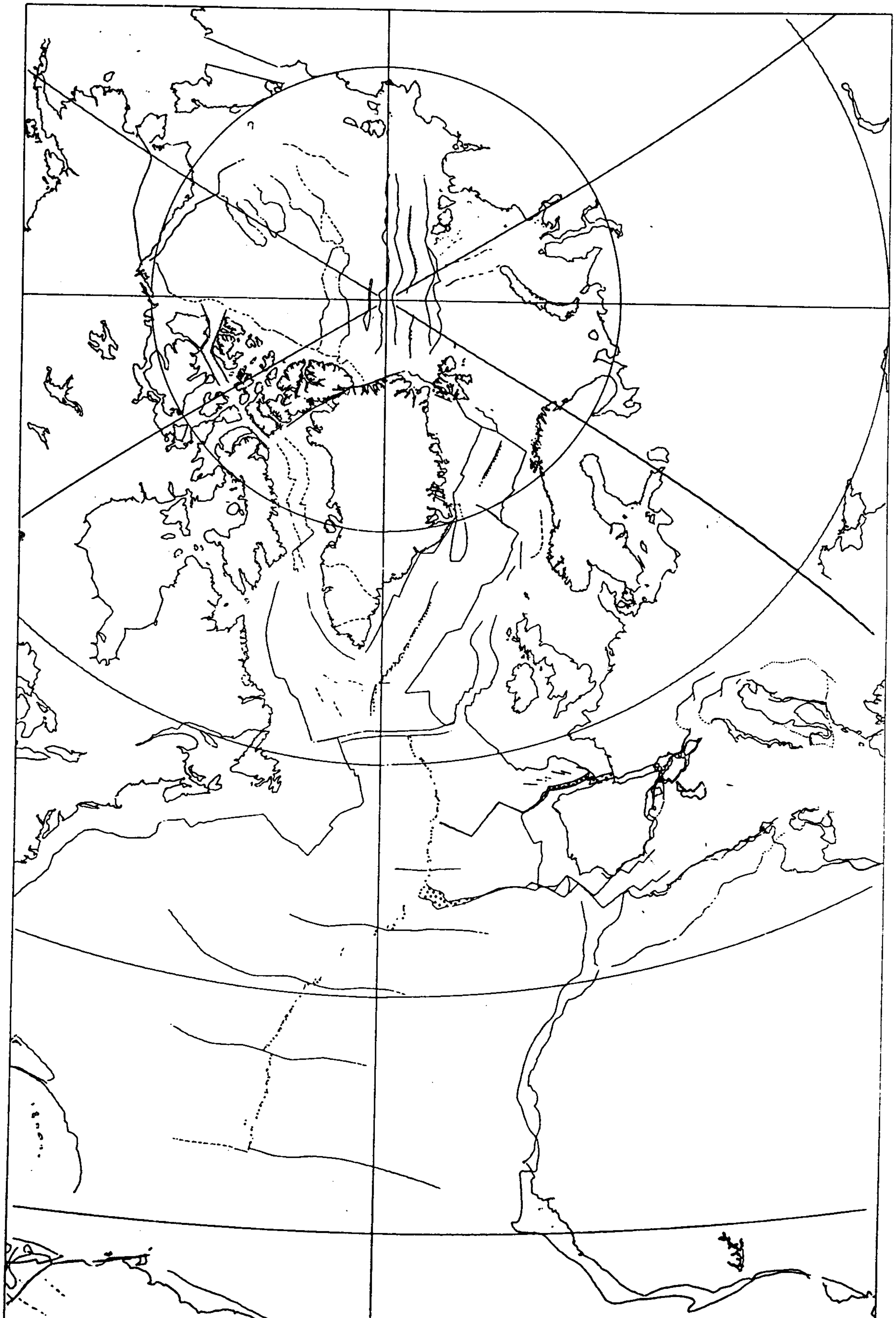

Fig. 18: Chron 13 (35.9 Ma, Rupelian)

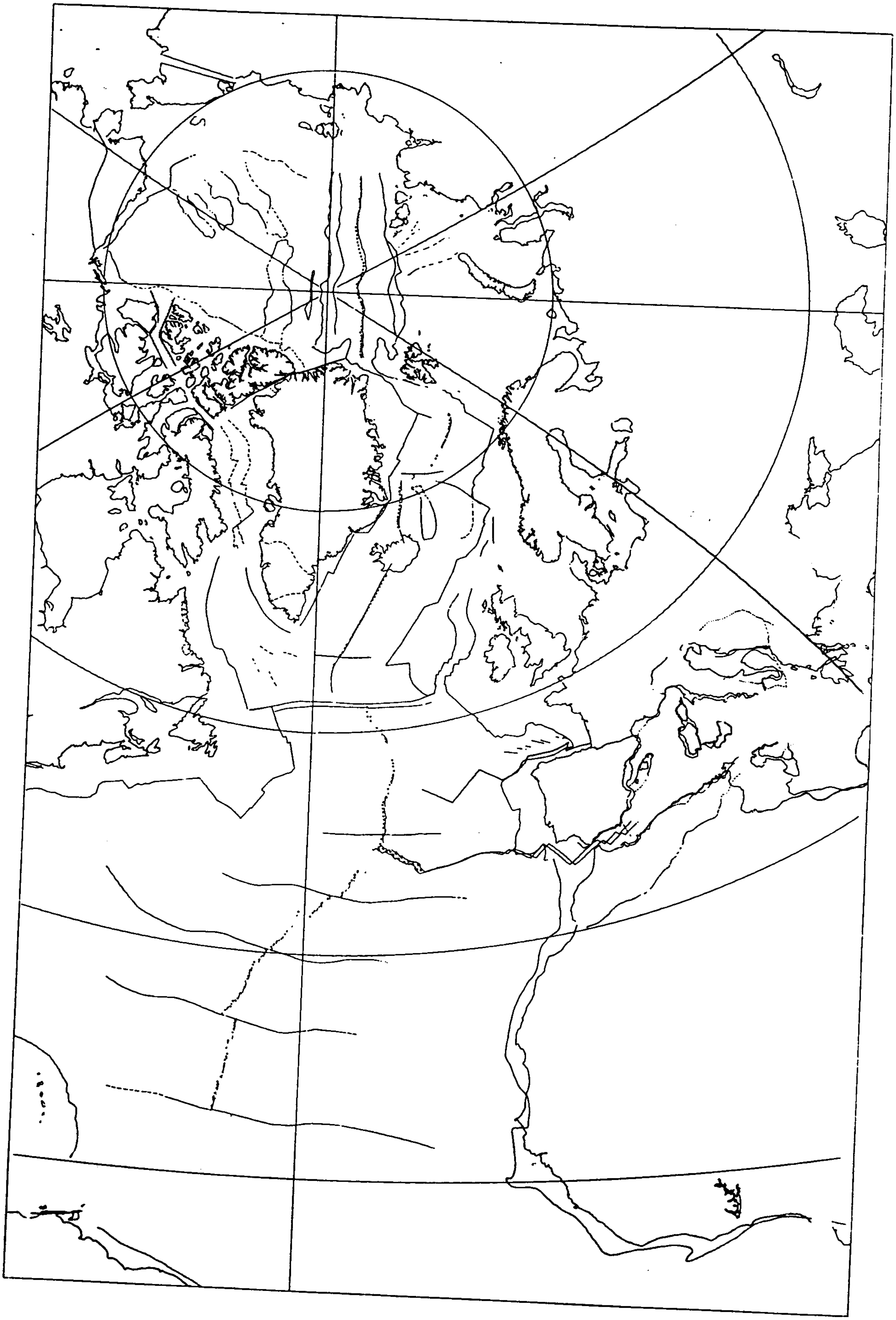

Fig. 19: Chron 5 (10.6 Ma, Tortonian)

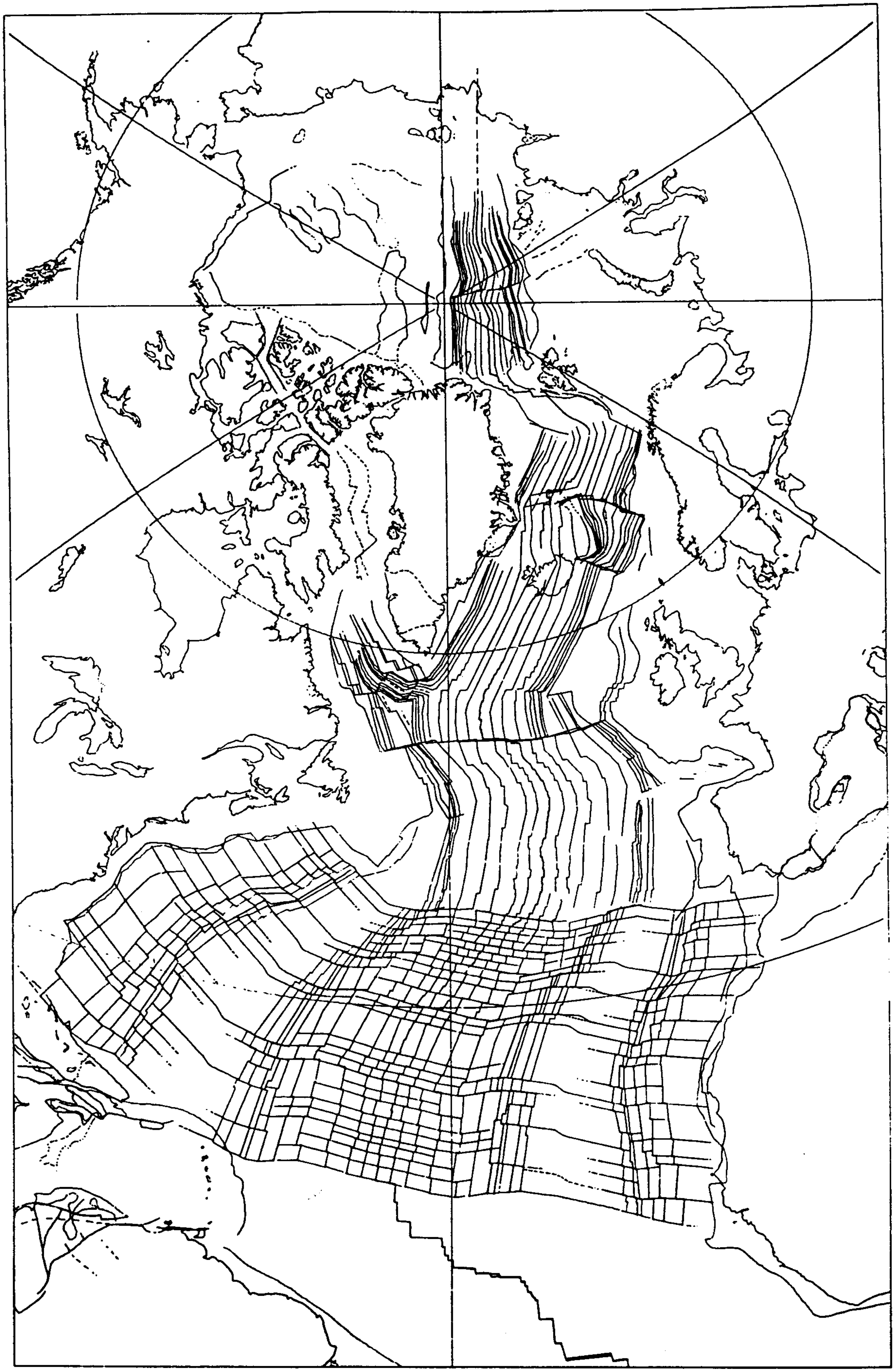

Fig. 20: Isochrons of the North and Central Atlantic ocean floor

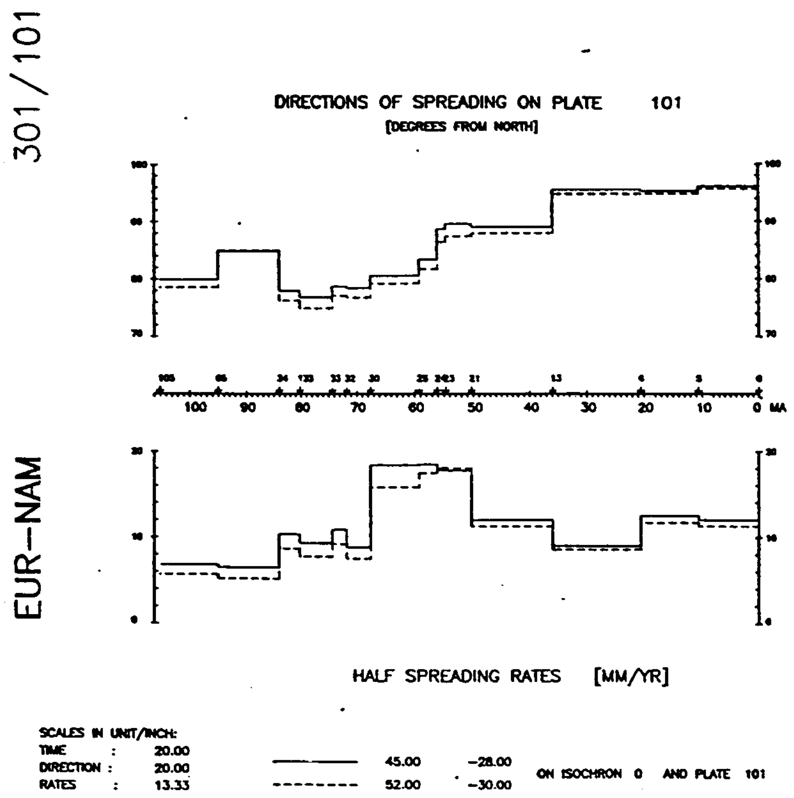

Fig. 21a: Directions and rates of spreading between Eurasia and North America (this paper)

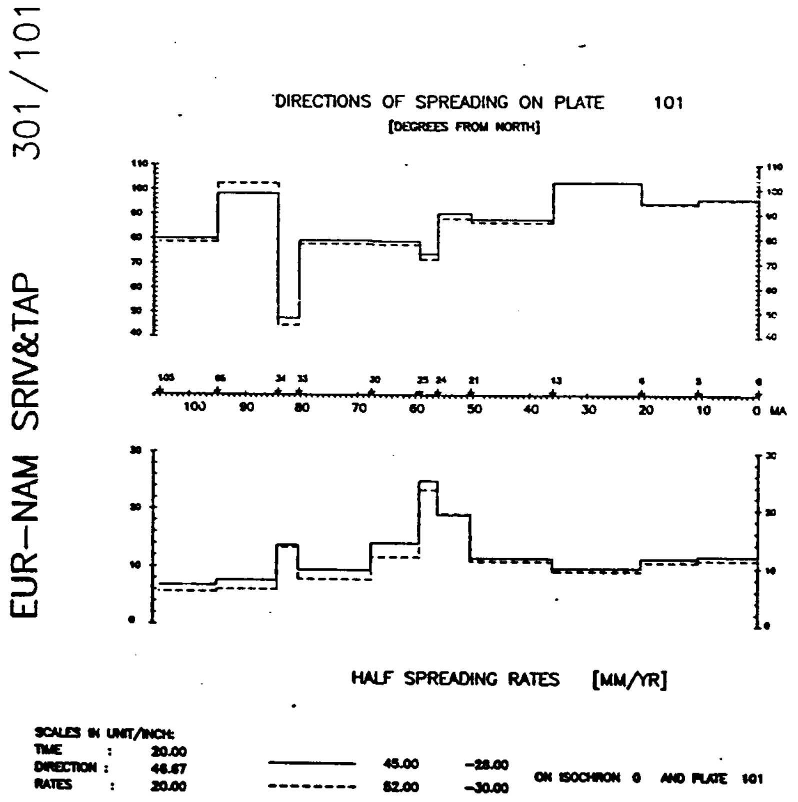

Fig. 21b: Directions and rates of spreading between Eurasia and North America (Srivastava and Tapscott, 1986).

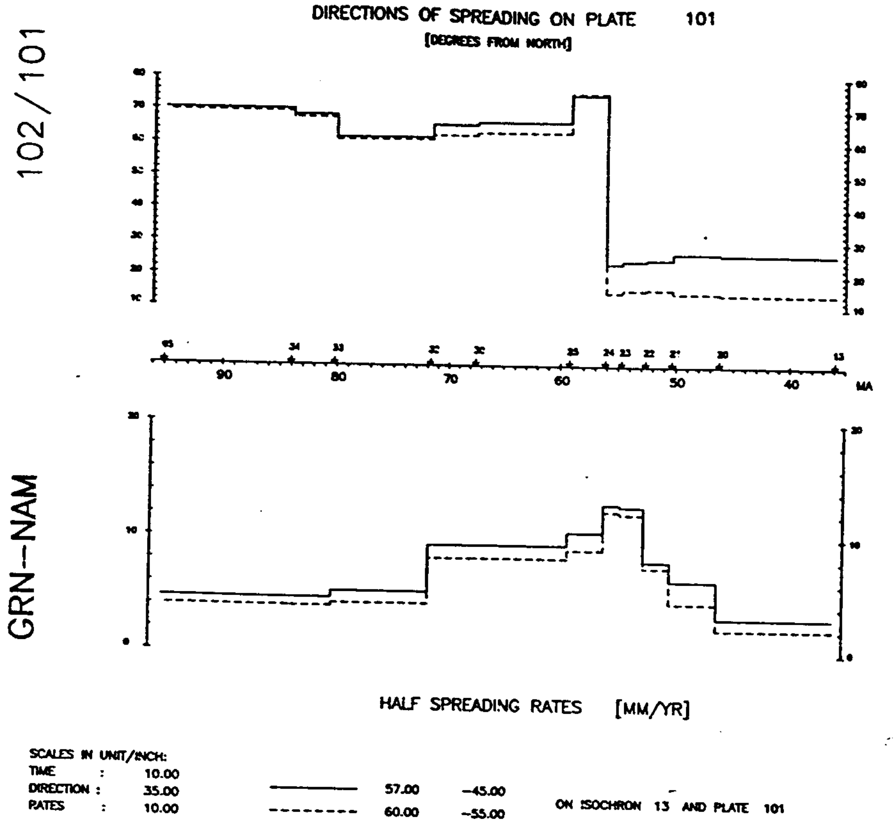

Fig. 22a: Directions and rates of spreading between Greenland and North America (Srivastava and Tapscott, 1986).

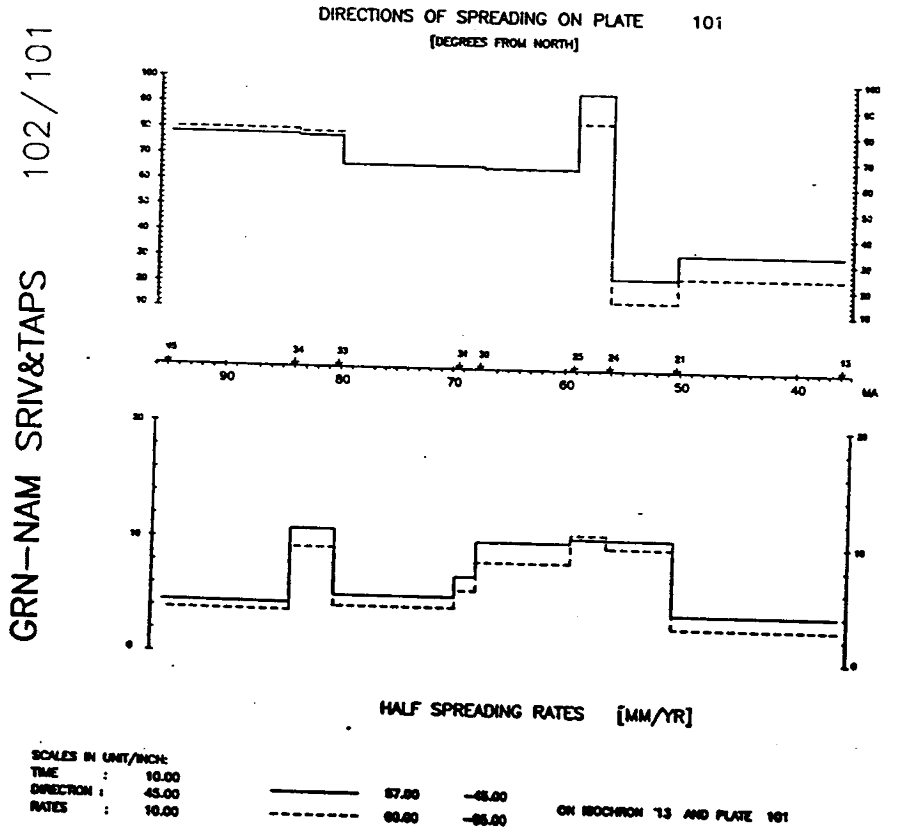

Fig. 22b: Directions and rates of spreading between Greenland and North America (Srivastava and Tapscott, 1986).