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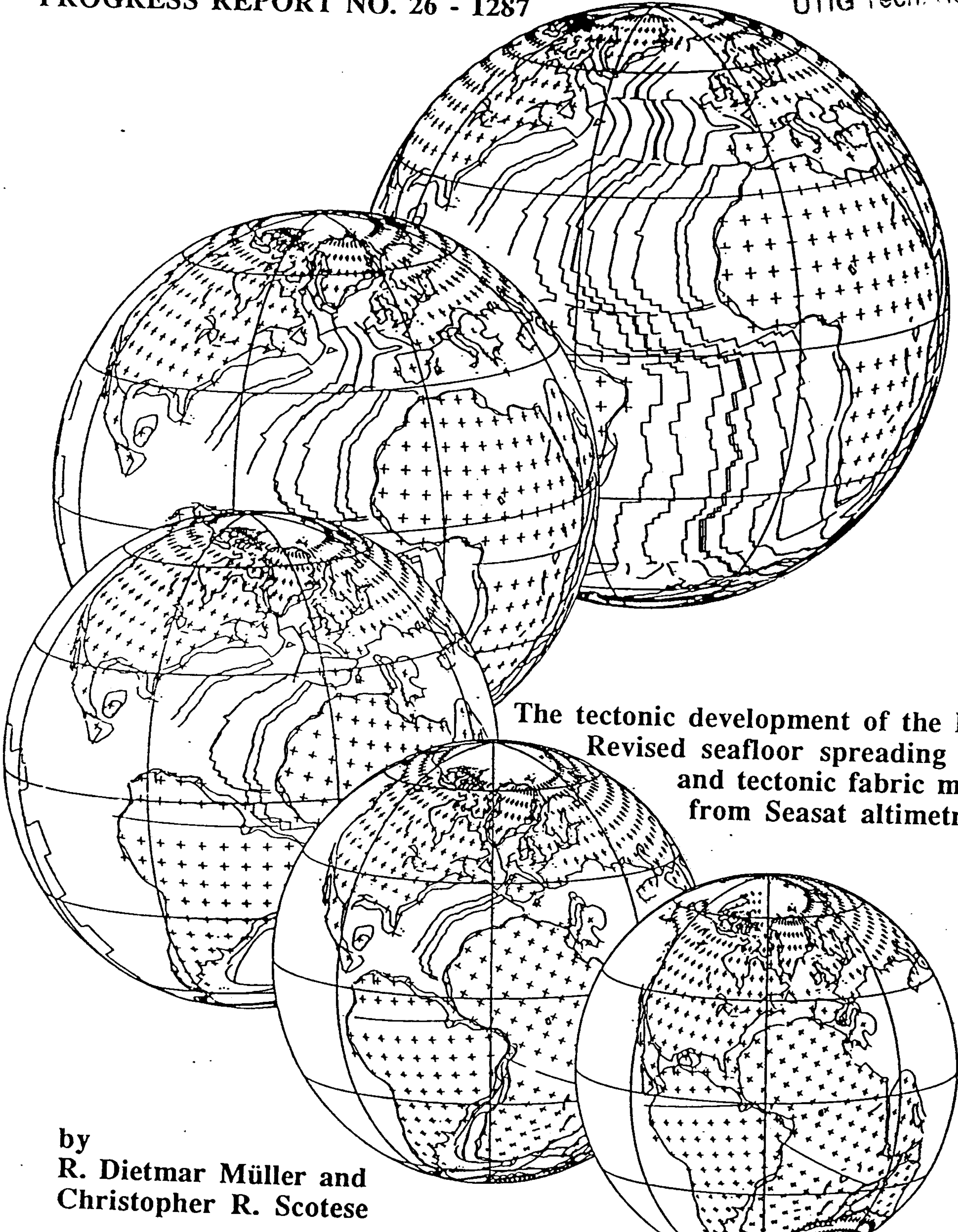

The tectonic development of the North Atlantic: Revised seafloor spreading isochrons and tectonic fabric map from Seasat altimetry

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Abstract

New plate reconstructions for the opening of the North Atlantic were made by combining recent magnetic anomaly data and Seasat altimetry data. A tectonic fabric map of the North Atlantic from interpretation of Seasat data allowed us to trace the Charlie Gibbs Fracture Zone from the North American to the European margin. We use fracture zone lineations as additional constraints in fitting magnetic anomaly pairs by interactively using the advanced 3-D graphics capabilities of an Evans & Sutherland PS 300 computer system. We have applied a hierarchical analysis technique (Ross & Scotese, in press) to obtain a new set of reconstruction poles of relative motion for plates around the North Atlantic. Intraplate movements in the Canadian Arctic, in NE-Greenland, and the North Sea region were included in the model to improve the fit reconstruction and better describe propagating rift tectonics.

Plate reorganizations at Chron 25 and 13 resulted in major changes of the plate boundary between Eurasia and North America in eastern Siberia and between Greenland and Svalbard. For the relative motion between Eurasia and North America in the Bering Sea region we suggest a succession of 4 tectonic phases from the Aptian to present day. Sinistral transpression dominated from chron M0 (118.7 Ma) to chron 25. It was followed by dextral transtension from chron 25 to chron 13. Compression/left lateral transpression prevailed after chron 13. Our plate model predicts a Tertiary tectonic development between Greenland and Svalbard in four phases. We propose extension from chron 30 (68.4 Ma) to 25 (59.2), strike

slip from chron 25 to 24 (56.1) and transpression from chron 24 to 20 (46.2 Ma) followed by transtension after chron 20.

Introduction

Since the first set of quantitative reconstructions for the North Atlantic was published by Pitman & Talwani (1972), a large number of different models for the opening of the North Atlantic have been proposed (see POMP Progress Report No 20). We present a new set of reconstructions which were derived by using Seasat fracture zone lineations as additional constraints for the fit of magnetic lineations between Europe and North America. Our model predicts gradual changes of seafloor spreading direction and rates between North America and Europe, interrupted only by distinct events of regional plate reorganizations. These large scale reorganizations are recognized by abrupt changes of spreading parameters in the North Atlantic.

New data for the boundaries between oceanic and continental crust around the North Atlantic were used to better constrain the predrift-fit. Recently published magnetic anomaly identifications and reinterpretations for the southern North Atlantic (Klitgord & Schouten 1986), the southern Eurasian Basin (Vogt 1986) and the eastern Norwegian Sea (Hagevang et al. 1983) are included in our database. We have determined finite rotation poles for 18 times from 175 Ma to 10.6 Ma (Table 1) and produced maps for 13 times. In addition we have produced 8 maps, which display the tectonic development between Greenland and Svalbard.

Data

Magnetic anomaly data used in this study are from Srivastava (1978), Hagevang (1983), Nunns (1983), Kovacs et al. (1985), Klitgord & Schouten (1986), Srivastava & Tapscott (1986) and Vogt (1986) (Fig. 1). The boundaries between oceanic and continental crust include data from Srivastava (1978), Rice & Shade 1982, Hanisch (1983), Emery & Uchupi (1984), Larsen (1984), Reksnes and Vågnes (1985) and Bott (1987). Tectonic lineations on Svalbard are taken from Ohta (1982). Seasat altimetry data in the form of "along track deflection of the vertical" (Sandwell 1984) were used to generate a tectonic fabric map of the North Atlantic ocean floor (Fig. 2). The processing techniques for the generation of the fabric map is discussed in Gahagan et al. (1987).

Methods

Tectonic fabric map

A tectonic fabric map for the North Atlantic interpreted from Seasat data is shown on Fig. 2. Bold and thin lines delineate negative and positive slopes of the sea surface, respectively, as viewed to northeast. The variations in height of the sea surface correspond closely to variations in the height of the geoid. Topographic features on the ocean floor cause variations in the height of the geoid. Hence linear slopes of the sea surface reflect linear topographic features on the ocean floor, such as fracture zones. Broad positive and negative slopes, shown as hatched areas, are related to volcanic ridges and plateaus on oceanic crust or to the basement structure along continental margins.

Fracture zone geoid lineations north of the Azores triple junction are generally not as distinct and continuous as in the Central Atlantic (POMP Prog. Rep. No 21). This is due to the slow spreading in the North Atlantic. Proximity to the pole of relative motion results in dominating small offset fracture zones with complex morphologies (Colette 1986).

Since small offset fracture zones have small age differences across them, they therefore 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, in particular for the predrift fit. We have interpreted the trend of the Charlie Gibbs Fracture Zone from Seasat lineations (Fig. 4), using additional information about its morphology from bathymetric data .

The Charlie Gibbs Fracture Zone

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 E-W striking troughs that are separated by a median ridge. This morphology, however, becomes more and more 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.

The Seasat signature of the younger part of the Charlie Gibbs Fracture Zone is in good accordance with the bathymetric contours as shown by Olivet et al. (1974). The median wall is delineated by a bold line (upslope) to the south, the northern valley is outlined by a thin line (downslope) to the south, partly followed by a bold lineation to the north. The southern valley is expressed on the tectonic fabric map only west of the active transform. Here a thin line marks the southern wall of the valley.

The Seasat lineations become less distinct for the older part of the fracture zone. Here they either merge into broader areas of gravity anomalies or show a disrupted pattern. The fracture zone trend, however, is well expressed in the strike of its geoid features and can be traced to the continental margins. Our interpreted flowline of the Charlie Gibbs Fracture Zone abuts the Rockall Plateau to the south and merges into the large offset of the Canadian continental margin north of Grand Banks.

Plate reconstructions

Plate reconstructions were made using interactive computer graphics to determine finite poles of rotation which best satisfy the constraints of the data. We started with the rotation poles of Srivastava & Tapscott (1986), first reconstructing Europe with respect to North America by finding the best match for magnetic anomaly pairs and the interpreted flowline of the Charlie Gibbs fracture zone.

We found that several of Srivastava & Tapscott's (1986) poles do not satisfy the constraints as imposed by the Charlie Gibbs Fracture Zone. Following the principles of plate tectonics, two corresponding branches of a fracture zone with a particular age have to be superimposed for a reconstruction at that particular time since they were generated at the same active transform. Most reconstruction poles of Srivastava & Tapscott (1986) do not match the eastern and western branch of the Charlie Gibbs fracture zone.

Specific problems arise at chrons 25, 21 and 13. Magnetic anomalies 25, 21 and 13 north of King's Trough show a considerable overlap when a good overall match is achieved north to that region, as noted by Vink (1982) and Srivastava & Tapscott (1986). In order to explain the misfit, Srivastava & Tapscott invoked a new plate called the Porcupine Plate. The non-fitting magnetic anomalies are now considered to be misinterpretations (Klitgord pers. com.). Hence we disregarded the misfit for our reconstructions.

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 Schouten et al. (in press) for relative motions of Iberia was evaluated with interactive computer graphics. According to Schouten et al. (in press) 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 except for anomaly M0. Hence we kept Iberia rigidly fixed to Africa for reconstructions from Chron 34 to 13.

The new set of plate tectonic reconstructions was then used to define isochrons following the method described in POMP Progress Report No 21. The resulting isochron map is shown on Fig. 3.

All plate reconstructions for the North Atlantic are plotted with magnetic lineations, but without isochrons. The magnetic lineations allow us to evaluate the quality of the fit for every reconstruction time. Areas of overlap between the continental margins are stippled and gaps between continental margins are hatched. The entire Arctic Ocean region was included in Figs. 3-20 to illustrate the predicted tectonic regime between the Eurasian and North American plates in the Bering Sea region. All reconstructions for the North Atlantic are plotted with North America fixed. The reconstructions for Greenland relative to Svalbard are plotted with Greenland held fixed.

Reconstructions for Greenland relative to Svalbard were included in this report because we wanted to outline the implications of our plate model for the tectonic development in that region. In general this area was a strike slip zone in the early Tertiary oriented subparallel to the opening direction between Greenland and Svalbard from Chron 25 to 13. Plate models for seafloor spreading in the Norwegian Greenland Sea predict the transtensional or transpressional nature of strike slip between Greenland and Svalbard at different times. In this report we describe how our model is consistent with on-land geology on NE-Greenland and Svalbard.

Middle Jurassic to Lower Cretaceous (Figs. 5, 6)

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-Teisseyre lineament formed the boundary between Fennoscandia/East Europe and the Ringkøbing Fyn/Pompeckj Block (Pegrum 1983). The latter block was offset from the Rhenish-Bohemian Massif to the south by a second major transform (Ziegler 1982). The North Sea grabens were closed in our fit reconstruction by assuming 50% extension (Jarvis & McKenzie 1980). The major rifting event in the North Sea is interpreted to have occurred between the Bathonian and Berriassian (Badley et al. 1984). Assuming rigidity of the Fennoscandian/East European Craton, rifting in the North Sea 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 & Worsley 1984).

Hatchured areas between the Chukotsk Peninsula and eastern Siberia, the North Slope Block of Alaska as well as west of Ellesmere Island (Fig. 5) outline the area that underwent compression in the Cretaceous/Tertiary. The relative motion between the Eurasian and North American plates in the Bering Sea region was right-lateral transpression along the South Anyuy suture between the Chukotsk Peninsula and eastern Siberia. The South Anyuy suture is interpreted to be the plate boundary between the North American and Eurasian plates in the Bering Sea region(Parfenov & Natal'in in prep.) The suture consists of a highly compressed fold belt (Shilo & Til'man 1981) that records collision from Late Jurassic to Neocomian (Parvenov & 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).

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 in this work. It proposes that the North Slope Block of Alaska 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 & 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 & Jarrard 1987). The Yukon-Koyukuk region presumably consists of trapped Jurassic or older oceanic crust (Churkin & Trexler 1980).

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.). 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 100 km of strike slip between Ellesmere Island and Greenland based on restoration of the two branches of the suture. Closure of the Labrador Sea requires an additional amount of strike slip between Greenland and North America of about 100 km. This problem can be resolved by including rifting within the Canadian Arctic Islands in our model. Hamilton (1983) proposed 100 km of extension for 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 & 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.

For our fit reconstruction in the Iberian region we have used the reconstruction pole from Masson & Miles (1984) for Iberia relative to North America (Fig. 5). Alternatively we have plotted a reconstruction that shows the fit between Iberia and Newfoundland after Srivastava and Tapscott (1986) (Fig. 6), who imply movement of Iberia with Africa from the initial breakup. This fit results in a considerable gap in the Bay of Biscay indicating that a more northward position of Iberia is required to close the Bay of Biscay. Secondly this reconstruction implies a large amount of overlap between Galicia Bank and Flemish Cap. Tankard & Welsink (1987) have estimated the average extension to be 20% for the Grand Banks margin and 45% for the Galicia margin. The asymmetry is interpreted to be due to a westward dipping low angle decollement zone giving rise to a westward decrease of extension (Tankard & Welsink 1987). The amount of overlap between the two margins as implied by Srivastava and Tapscott is too high (Fig. 6). The fit by Masson & Miles (1984), which implies an anticlockwise rotation of Iberia separate from Africa closes the Bay of Biscay and results in a smaller overlap between Grand Banks and Galicia Bank. The relatively large overlap between the western margins of the Bay of Biscay in this reconstruction could be decreased by closing the rift basins south of Great Britain. We therefore feel that the fit after Masson & Miles (1984) is more accurate and have incorporated it into our model.

Chron M0 (118.7 Ma, Aptian, Fig. 7)

Seafloor spreading propagated from the Central Atlantic to the Newfoundland Basin and into the Bay of Biscay prior to Chron M0. This extensional tectonic regime initiated rift basins north of Newfundland from the Rockall Trough to the western margin of Norway (Price & Rattey 1984). The series of basins west of Norway are characterized by broad negative geoid anomalies that are visible on the map of the tectonic fabric of the North Atlantic (Fig. 2). The main rifting of the Rockall Trough occurred during the Cretaceous Quiet Zone (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 & Worsley (1984) interpreted the uplift as part of doming related to subsequent transtensional tectonics between Svalbard and Greenland. The uplift may 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.

No reasonable fit for M0-age magnetic anomalies off Newfoundland and Iberia can be achieved by assuming no motion between Iberia and Africa. The unsatisfactory predrift-fit between Iberia and Newfoundland as well as the poor fit of the M0 anomalies off Newfoundland and the Galicia margin by using the reconstruction poles of Srivastava & Tapscott (1986) leads us to the conclusion that Iberia moved separately during the early opening phase, at least until Chron M0. The fit of magnetic anomalies 34 to 13 between Newfoundland and Iberia were found to match by assuming no motion between Iberia and Africa. Hence we assume that Iberia became attached to Africa during the Cretaceous Quiet Zone.

Chron 34 (84 Ma, Campanian, Figs. 8, 9)

At this time seafloor spreading started in the southern Labrador Sea and west of the Rockall Plateau in the Cretaceous Magnetic Quiet Zone; seafloor spreading in the Rockall Trough stopped prior to Chron 34 (Srivastava & Tapscott 1986). The gap shown between the northern extension of Rockall Plateau and Greenland (Fig. 8) actually reflects oceanic crust formed east of this region during the rift phase that separated the Rockall Plateau from Europe. The northward extension of the tensional regime is thought to have resulted in the formation of ocean crust in the Faroe and Møre Basins (Bott 1984, Smythe et al. 1983). 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 (comp. Figs. 8, 10)). 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 (see also Savostin et al. 1983) . Upper Cretaceous treanspression 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 predicted by our model is in accordance with the formation of pull-apart basins along the Trolle Land Fault System in northeast Greenland (Håkansson & Pedersen 1982).

Chron 30 (67.5 Ma, Maastrichtian, Figs. 10, 11)

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 & Shade 1982) had decreased significantly and oceanic crust began to form in central Baffin Bay (Fig. 10). 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 & Pedersen 1982). On Svalbard, where Upper Cretaceous sediments are absent, the Central Tertiary Basin began to subside in the Lower Paleocene (Steel & 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 (Fig. 26a). In contrast, half spreading rates between North America and Eurasia increased drastically from 10 to 17 mm/yr between Chron 32 and Chron 25 (Fig. 27a) A similar change in spreading rates is predicted by the model of Srivastava & Tapscott (1986) (Fig. 27b). This change in rates induced transtension between Greenland and Norway and slow extension between Greenland and Svalbard with a total rate of approximately 1 mm/yr. The extension from Chron 30 to 25 between Greenland and Svalbard predicted by this model suggests about 90 km of crustal stretching along the Hornsund Fault Zone. This observation is supported by initiation of subsidence of the Central Tertiary Basin on Svalbard in the Lower Paleocene (Steel et al. 1985). The direction of spreading between North America and Eurasia inevitably 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, Figs. 12, 13)

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 changed the tectonic regime between Greenland and Svalbard from extensional to strike slip. Rifting propagated from the Charlie Gibbs Fracture Zone to the Eurasian Basin (Fig. 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 subsidence and formation of pull-apart basins along the Bering margin (Harbert et al. 1987).

A number of volcanic rises and plateaus was formed during this plate reorganization, i.e. the Thulean Rise (Vogt & Avery 1974) and the Greenland Scotland Ridge, volcanics on the Morris Jessup Rise and Yermak Plateau (Vogt et al. 1979) as well as on the Vøring Plateau and Faroer Islands (Talwani & Eldholm 1977). Anomaly 24 is doubled north of Jan Mayen (Hagevang et al. 1982), giving evidence for a ridge jump between Chrons 24 and 23. The stage pole for fitting these anomalies results in an age of 55.6 Ma for the jump.

Chron 24 (56.1 Ma, Ypresian) to Chron 20 (46.2 Ma, Lutetian) (Figs. 14 to 22)

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 Senja Fracture Zone. A change of motion between Eurasia and Greenland (Fig. 28) 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 22 (52.6 Ma.). Magnetic anomalies between Jan Mayen and Eurasia older than Chron 22 can be well fitted by assuming a rigid attachment of Jan Mayen to Greenland during that time. The counterclockwise rotation of Greenland relative to North America after Chron 21 initiated the second phase of the Eurekan Ororogeny 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. Figs. 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 that is dated as of Eocene age (Steel & 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 foldbelt 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 & Tapscott 1986). The amount of overlap (stippled area, Fig. 14) along the plate boundary between Iberia and Eurasia (after Searle & 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) (Figs. 22 to 25)

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 chron 6 is displayed by a stippled area (Fig. 17, 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 A6 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.

Spreading directions and rates in the North Atlantic

Figs. 26 and 27 illustrate spreading directions and half spreading rates for Europe and Greenland relative to North America for our plate model and the model of Srivastava & Tapscott (1986) (Fig. 26). 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 & 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 (Fig. 4). 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 (Fig. 3). The histogram for spreading direction (Fig. 26a) 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 & Tapscott (1986) (Fig. 26b) 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 (Fig. 17) show a 3 stage development in our model as well as in Srivastava & Tapscott's (1986) model. We consider the sharp change in spreading direction between chron 25 and 24 in Srivastava & Tapscott's (1986) model as shown in Fig. 27b 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
120	CAI	CANADIAN ARCTIC ISLANDS
301	EUR	EURASIA
304	IBR	IBERIA
318	RKL	ROCKALL PLATEAU
330	TOB	TORNQUIST BLOCK
331	UKB	UK BLOCK
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 presented 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 & 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 & SCHOUTEN 1986
101	74.3	80.76	-11.76	23.91	714	!NAM-AFR AN 33y KLITGORD & SCHOUTEN 1986
101	80.2	78.30	-18.35	27.06	714	!NAM-AFR AN 33o KLITGORD & SCHOUTEN 1986
101	84.0	76.55	-20.73	29.60	714	!NAM-AFR AN 34 KLITGORD & SCHOUTEN 1986
101	118.7	66.30	-19.90	54.25	714	!NAM-AFR AN M 0 KLITGORD & SCHOUTEN 1986
101	126.5	66.13	-19.00	56.39	714	!NAM-AFR AN M 4 KLITGORD & SCHOUTEN 1986
101	131.7	65.95	-18.50	57.40	714	!NAM-AFR AN M 10N KLITGORD & SCHOUTEN 1986
101	141.9	66.10	-18.40	59.79	714	!NAM-AFR AN M 16 KLITGORD & SCHOUTEN 1986
101	149.9	66.50	-18.10	61.92	714	!NAM-AFR AN M 21 KLITGORD & SCHOUTEN 1986
101	156.6	67.15	-16.00	64.70	714	!NAM-AFR AN M 25 KLITGORD & SCHOUTEN 1986
101	170.0	67.02	-13.17	72.10	714	!NAM-AFR BSMA KLITGORD & SCHOUTEN 1986
101	175.0	66.95	-12.02	75.55	714	!NAM-AFR ECMA KLITGORD & 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 AN 13
102	46.2	62.16	-75.83	-1.95	101	!GRN-NAM AN 20
102	50.3	62.16	-75.83	-3.55	101	!GRN-NAM AN 21
102	52.6	60.68	-85.99	-3.96	101	!GRN-NAM AN 22
102	54.7	59.12	-92.86	-4.30	101	!GRN-NAM AN 23
102	56.1	58.08	-96.49	-4.62	101	!GRN-NAM AN 24
102	59.2	61.97	-103.27	-5.35	101	!GRN-NAM AN 25

```
102  67.5  68.10 -111.14  -7.53 101 !GRN-NAM AN 30  INTERPOLATED
102  71.7  69.16 -112.33  -8.33 101 !GRN-NAM AN 32
102  74.3  69.89 -111.52  -9.04 101 !GRN-NAM AN 33y INTERPOLATED
102  80.2  71.09 -109.92 -10.63 101 !GRN-NAM AN 33o
102  84.0  71.80 -109.05 -11.68 101 !GRN-NAM AN 34
102  95.0  70.95 -109.95 -13.11 101 !GRN-NAM FIT

103   0.0   0.00    0.00   0.00 101 !NSL-NAM PRESENT DAY
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

106   0.0   0.00    0.00   0.00 102 !ELS-GRN PRESENT DAY
106  35.9   0.00    0.00   0.00 102 !ELS-GRN AN 13
106  95.0  67.25  178.50   2.40 102 !ELS-GRN FIT

107   0.0   0.00    0.00   0.00 101 !BIS-GRN PRESENT DAY
107  35.9   0.00    0.00   0.00 101 !BIS-NAM AN 13
107  95.0 -69.79  101.72   5.98 101 !BIS-NAM FIT

119   0.0   0.00    0.00   0.00 102 !BRE-GRN PRESENT DAY
119  68.4   0.00    0.00   0.00 102 !BRE-GRN AN 30
119  68.4  51.69  128.04  11.79 301 !BRE-EUR AN 30

120   0.0   0.00    0.00   0.00 101 !CAI-NAM PRESENT DAY
120  35.9   0.00    0.00   0.00 101 !CAI-NAM AN 13
120  95.0  57.15 -137.00  -1.07 101 !CAI-NAM FIT

301   0.0   0.00    0.00   0.00 101 !EUR-NAM PRESENT DAY
301  10.6  65.38  133.58  -2.44 101 !EUR-NAM AN 5
301  20.5  67.27  135.49  -4.73 101 !EUR-NAM AN 6
301  35.9  69.16  137.13  -7.93 101 !EUR-NAM AN 13
301  46.2  68.33  139.75 -10.10 101 !EUR-NAM AN 20
301  50.3  67.79  140.59 -11.04 101 !EUR-NAM AN 21
301  52.6  67.50  141.27 -11.85 101 !EUR-NAM AN 22
301  54.7  66.02  142.33 -12.45 101 !EUR-NAM AN 23
301  56.1  65.08  142.91 -12.87 101 !EUR-NAM AN 24
301  59.2  63.25  144.00 -13.75 101 !EUR-NAM AN 25
301  67.5  69.87  146.12 -17.39 101 !EUR-NAM AN 30
301  71.7  71.23  146.96 -18.32 101 !EUR-NAM AN 32
301  74.3  72.21  147.60 -19.04 101 !EUR-NAM AN 33y
301  80.2  74.20  149.07 -20.51 101 !EUR-NAM AN 33o
301  84.0  75.34  150.12 -21.55 101 !EUR-NAM AN 34
301  95.0  75.38  147.80 -23.23 101 !EUR-NAM FIT LABRADOR SEA
```

301 105.0 75.30 149.50 -24.75 101 !EUR-NAM FIT ROCKALL PLATEAU
301 145.0 75.30 149.50 -24.75 101 !EUR-NAM STOP MAIN FIFTING PHASE NORTH SEA
301 170.0 75.30 152.00 -25.34 101 !EUR-NAM START MAIN RIFTING PHASE NORTH SEA

304 0.0 0.0 0.0 0.0 101 !IBR-NAM PRESENT DAY
304 10.6 65.38 133.58 -2.44 101 !IBR-NAM AN 5
304 20.5 67.27 135.49 -4.73 101 !IBR-NAM AN 6
304 35.9 51.07 144.08 -7.13 101 !IBR-NAM AN 13
304 50.3 72.35 130.90 -11.09 101 !IBR-NAM AN 21
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
304 130.0 73.72 -0.92 -44.44 101 !IBR-NAM FIT AFTER MASSON & MILES (1984)

330 0.0 0.00 0.00 0.00 331 !TOB-UKB PRESENT DAY
330 145.0 0.00 0.00 0.00 331 !TOB-UKB STOP MAIN FIFTING PHASE NORTH SEA
330 170.0 24.19 36.20 0.59 331 !TOB-UKB START MAIN RIFTING PHASE NORTH SEA

331 0.0 0.00 0.00 0.00 301 !UKB-EUR PRESENT DAY
331 145.0 0.00 0.00 0.00 301 !UKB-EUR STOP MAIN FIFTING PHASE NORTH SEA
331 145.0 75.30 149.50 -24.75 101 !UKB-NAM START MAIN RIFTING PHASE NORTH SEA

907 0. 0.00 0.00 0.00 301 !JMN-EUR PRESENT DAY
907 35.9 64.61 -11.90 -10.20 301 !JMN-EUR AN13
907 46.2 64.90 -12.30 -31.57 301 !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

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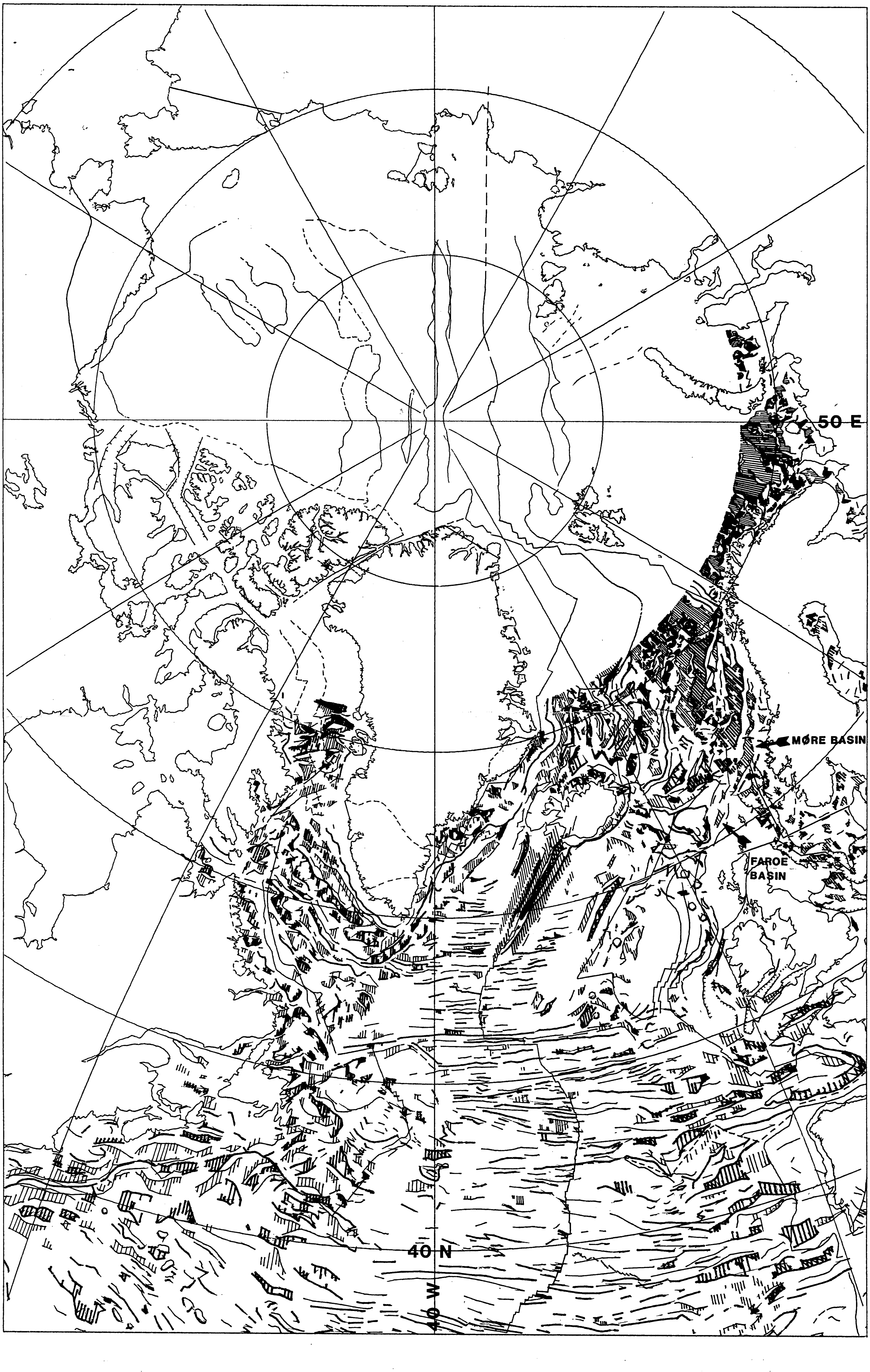


Fig. 2: Tectonic fabric map from satellite altimetry data in the North Atlantic

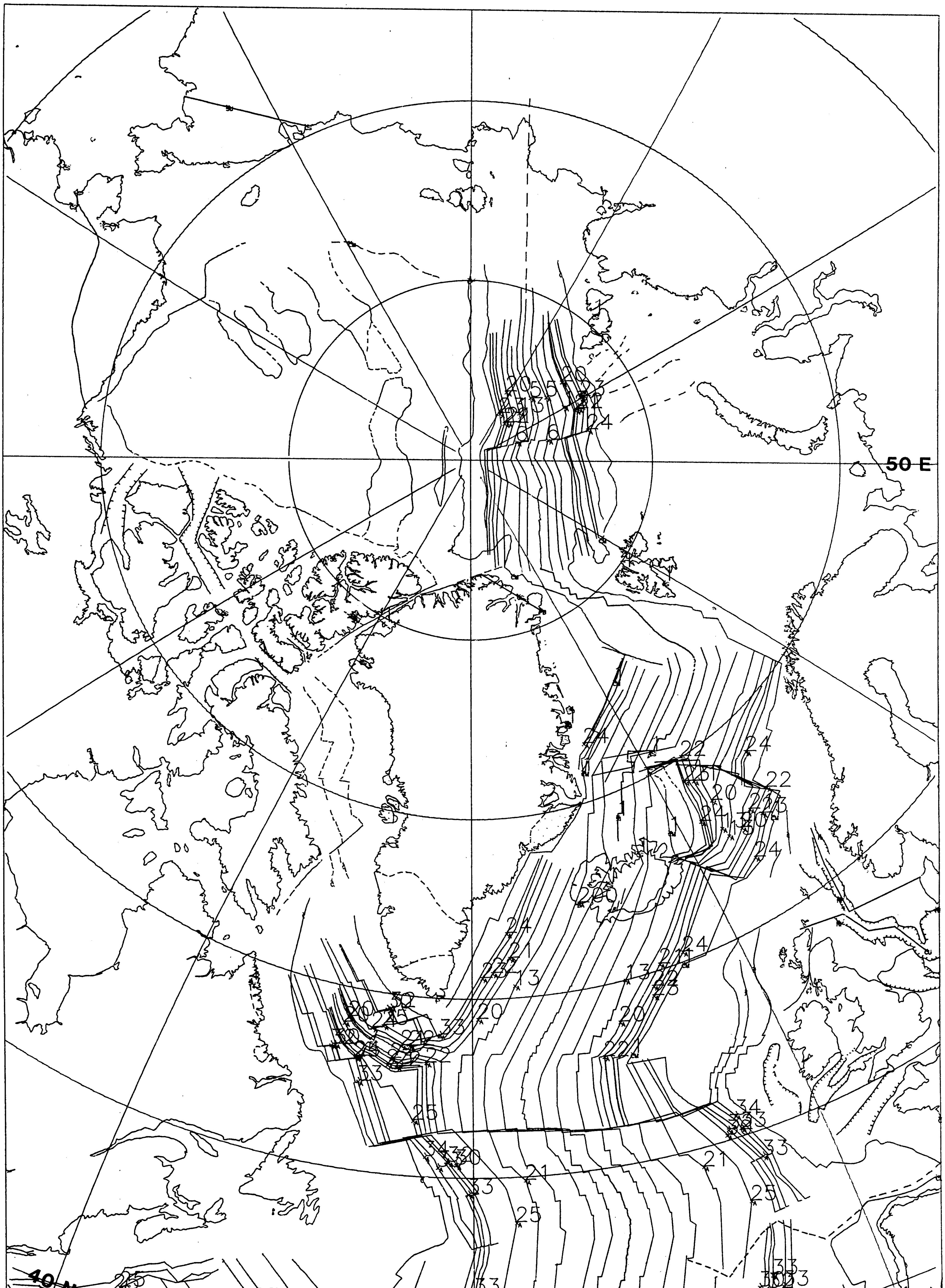


Fig. 3: Isochrons of the North Atlantic ocean floor

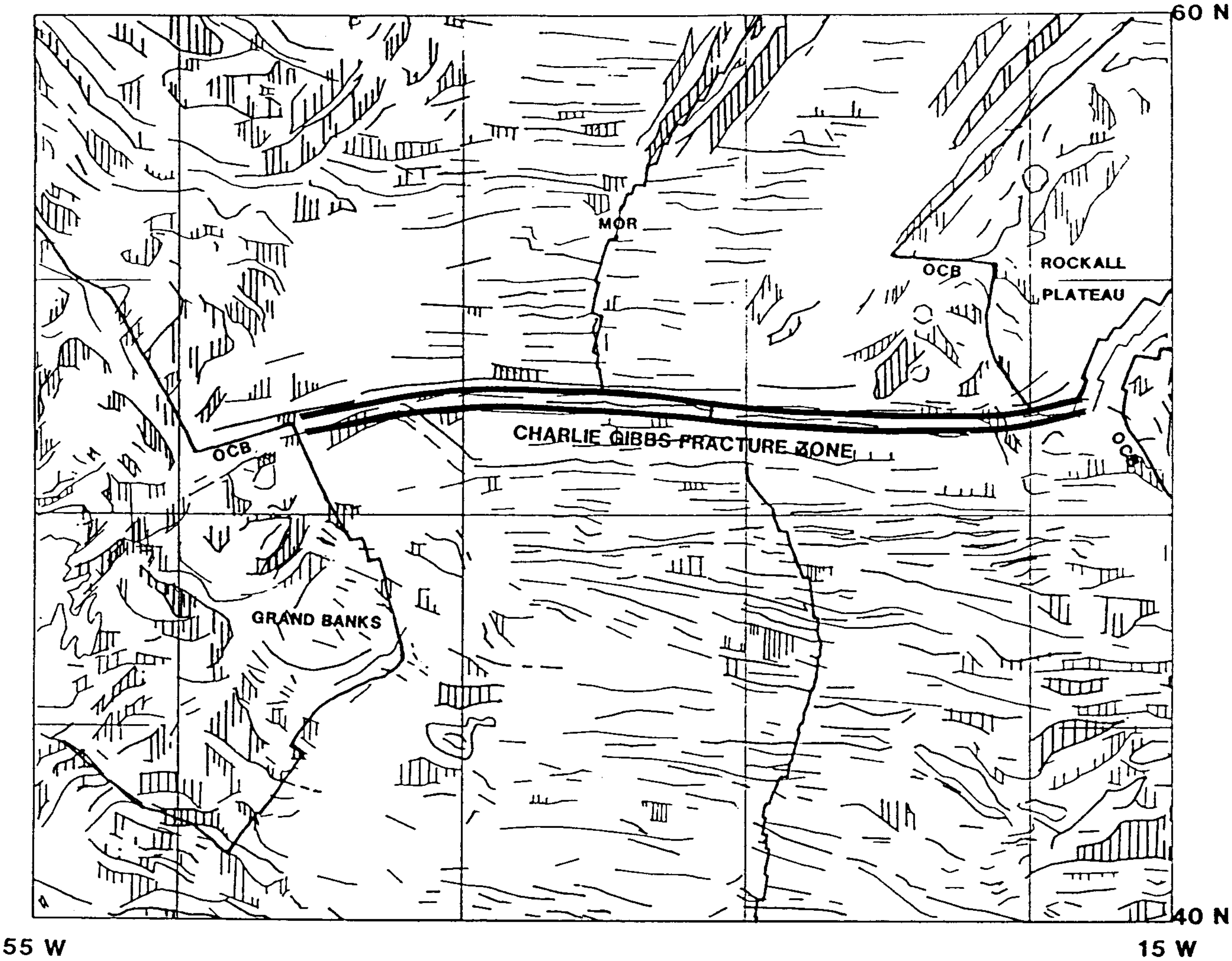


Fig. 4: Tectonic fabric in the southern North Atlantic.

Bold lines are interpreted location

of the Charlie Gibbs Fracture Zone.

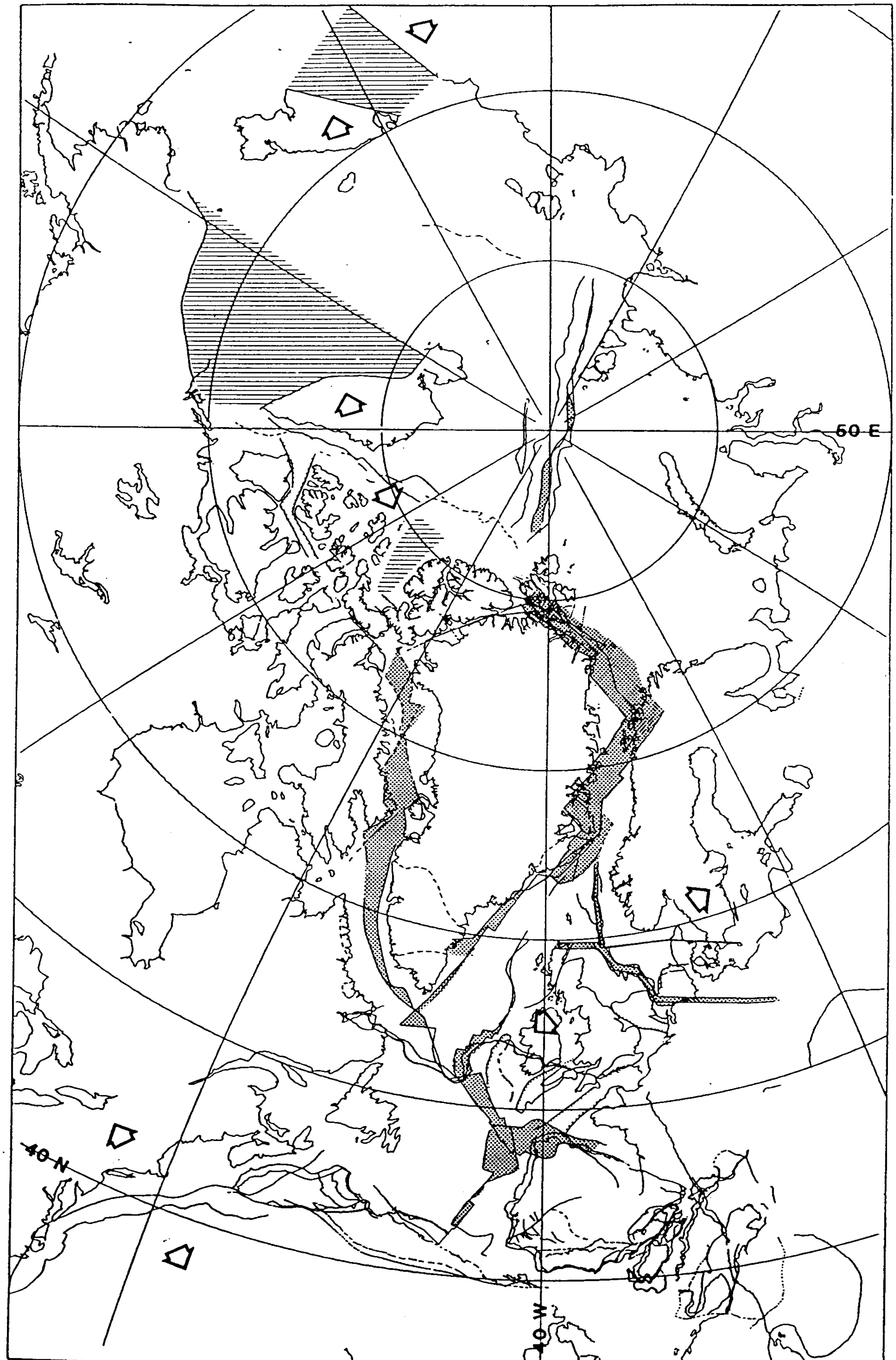


Fig. 5: Fit reconstruction (175 Ma)

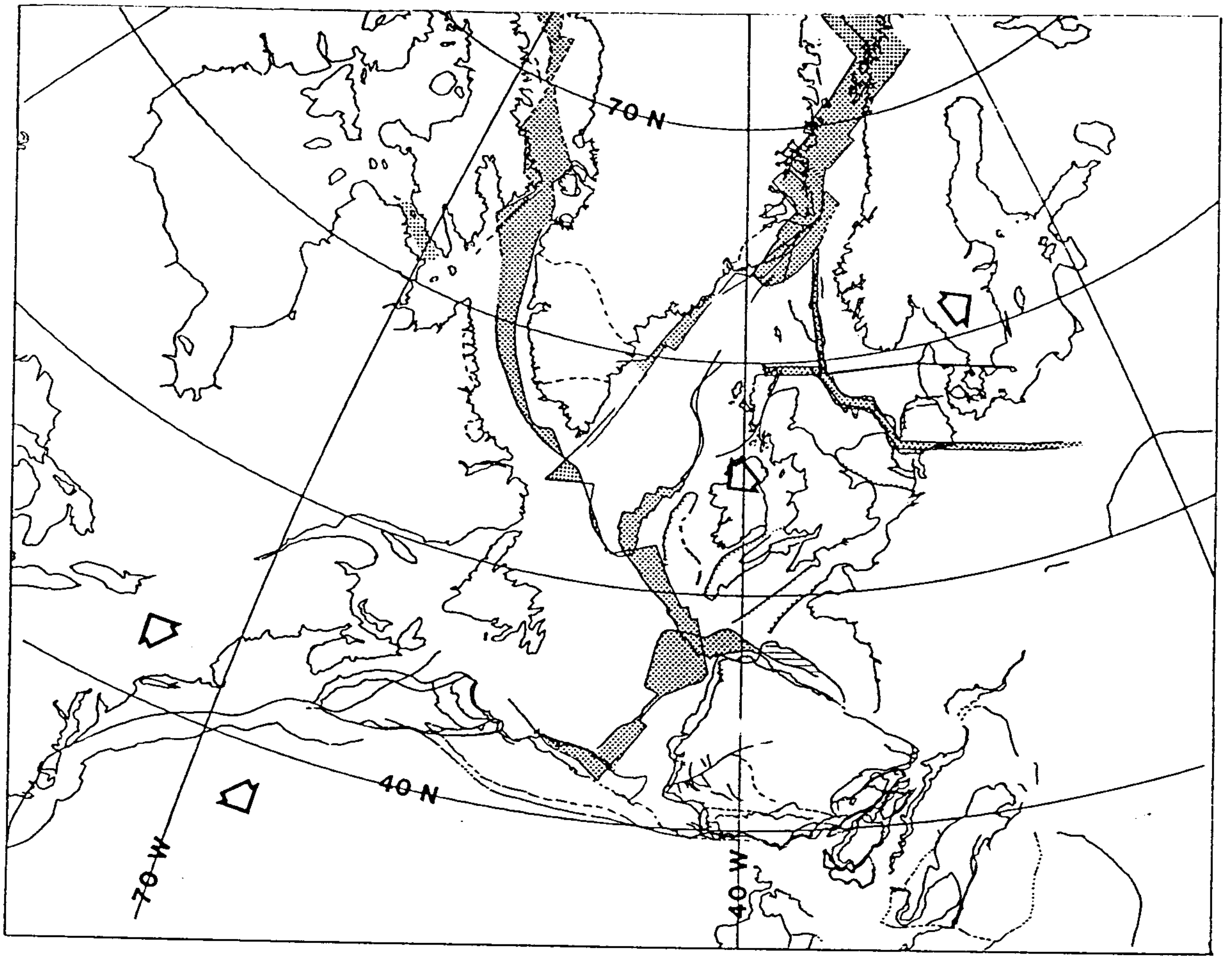
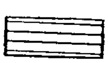


Fig. 6: Fit reconstruction (175 Ma):

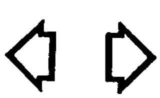
Fit of Iberia relative to North America after Srivastava & Tapscott (1986).

Fig. 6a: Legend

overlaps of oceanic/continental crust boundaries of plate boundaries



gaps between oceanic/continental boundaries or plate boundaries



direction of relative motion between two plates

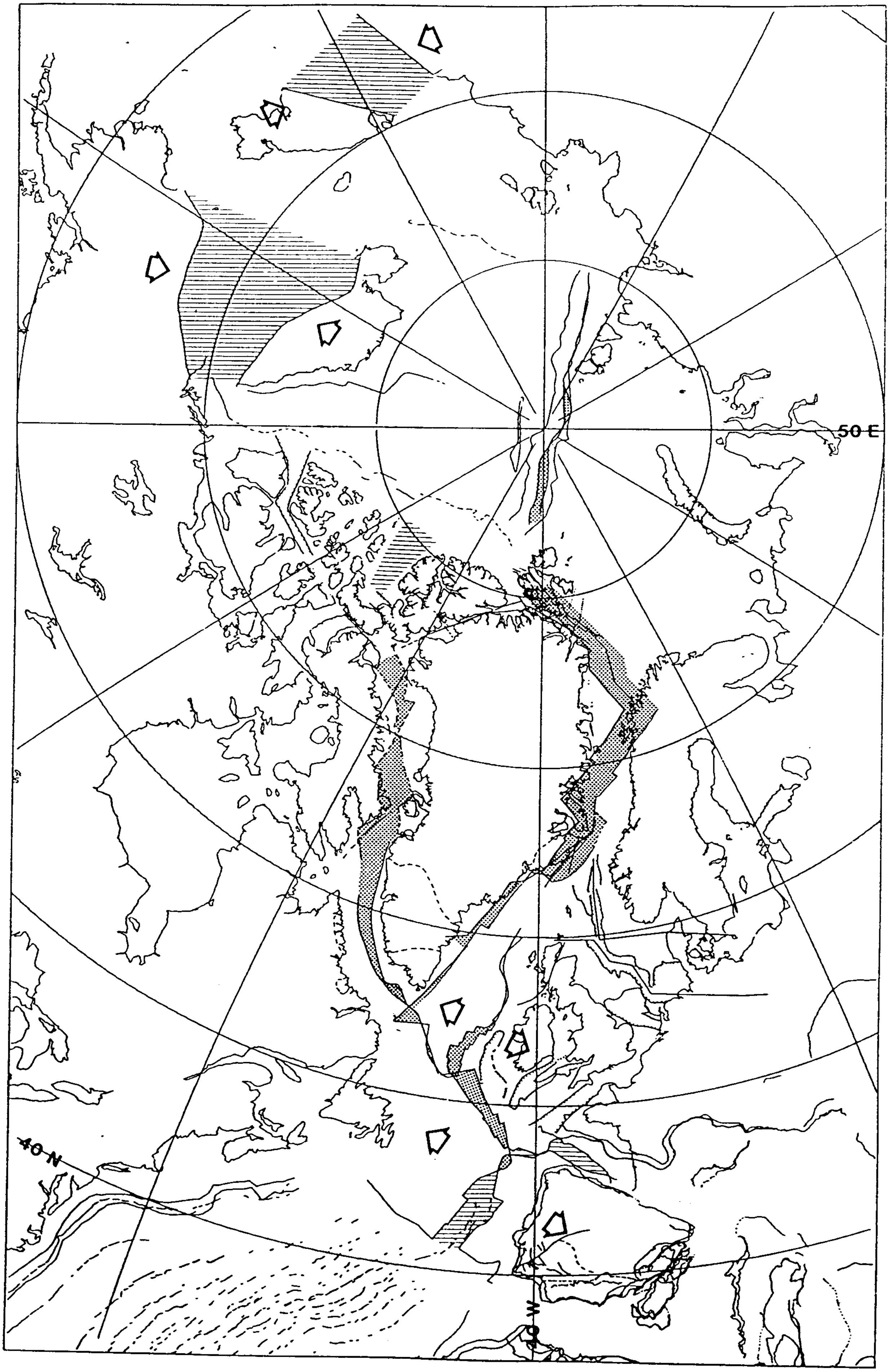


Fig. 7: Chron M0 (118.7 Ma, Aptian)

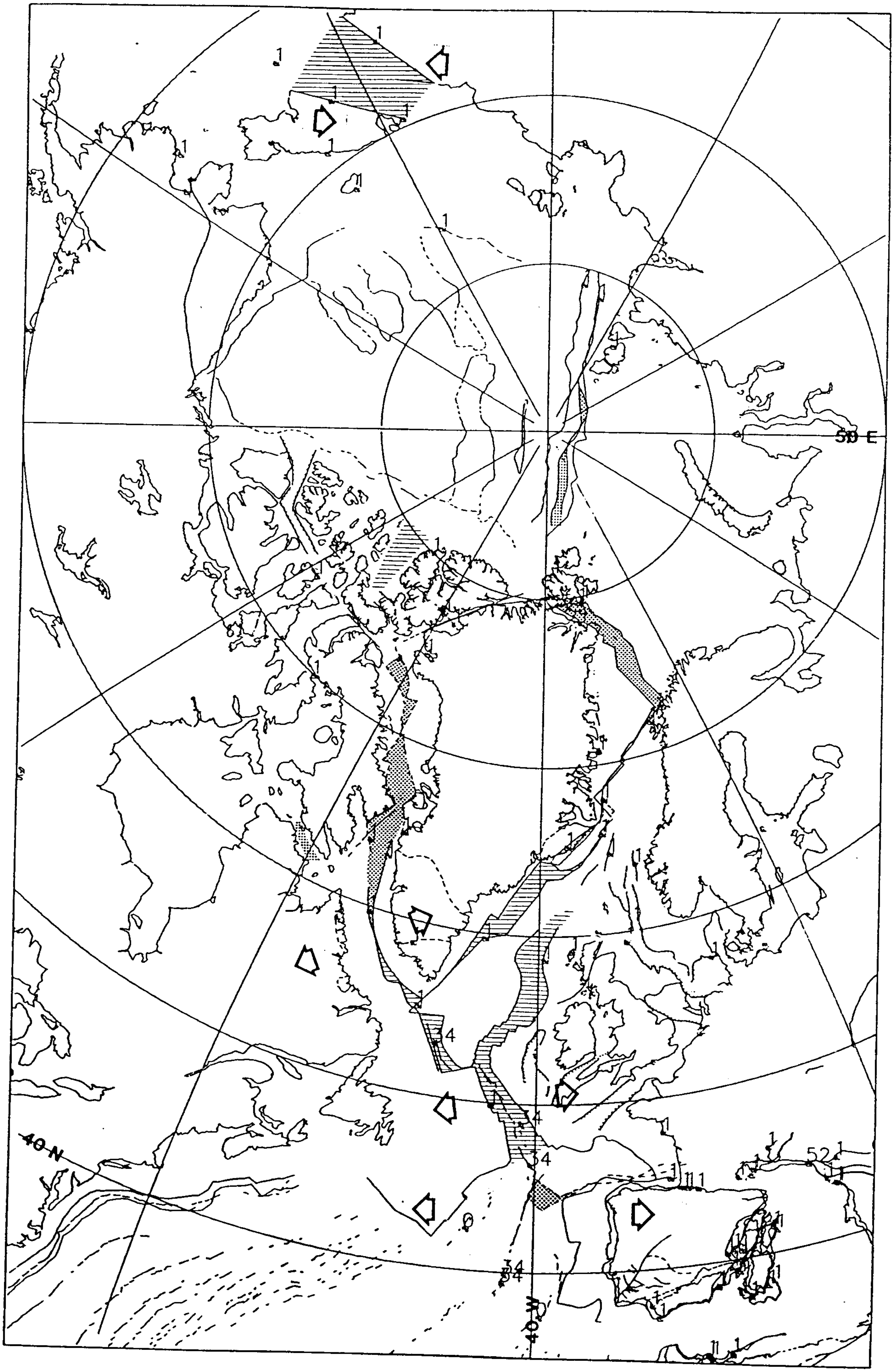


Fig. 8: Chron 34 (84 Ma, Campanian)

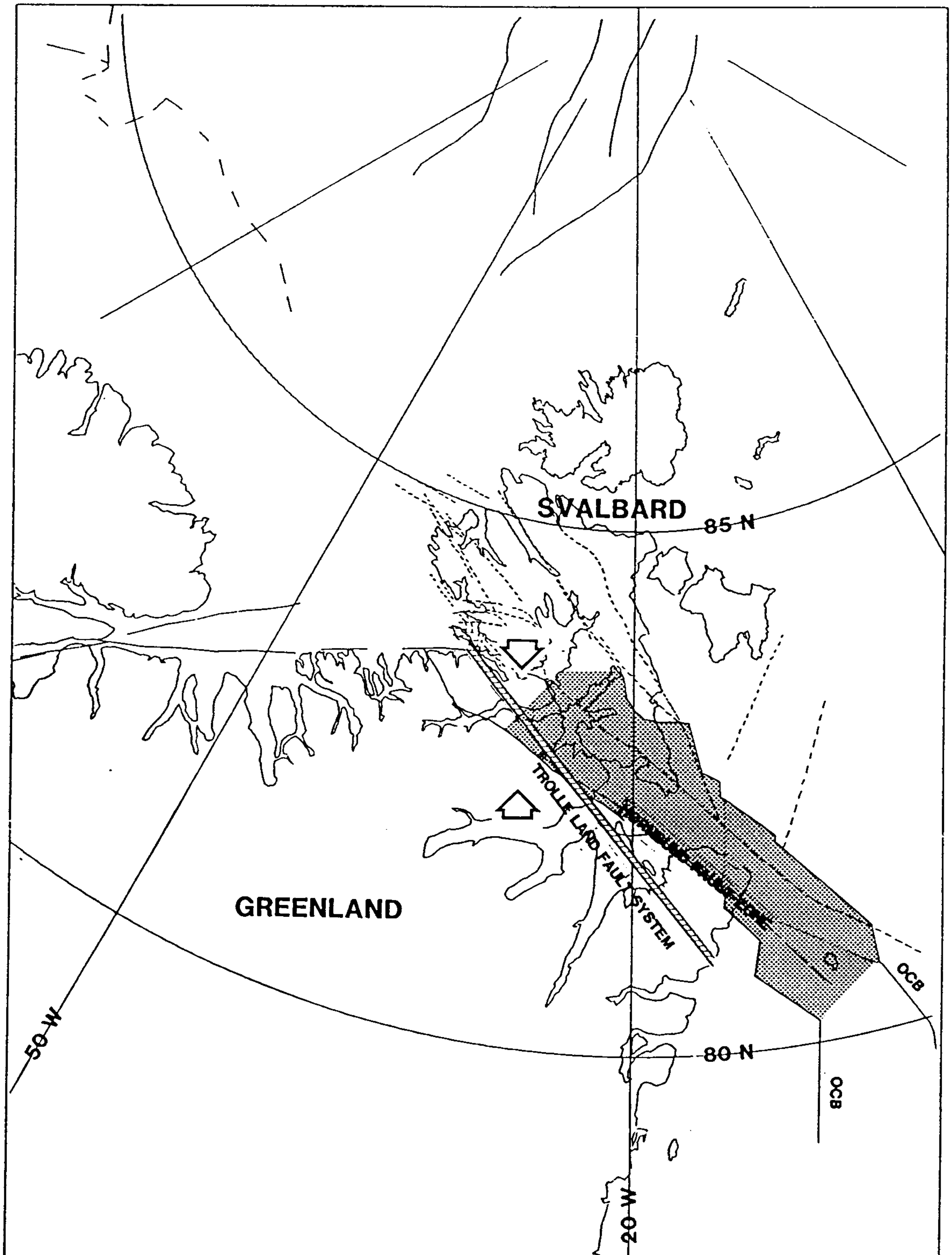


Fig. 9: Chron 34 (84 Ma, Campanian)

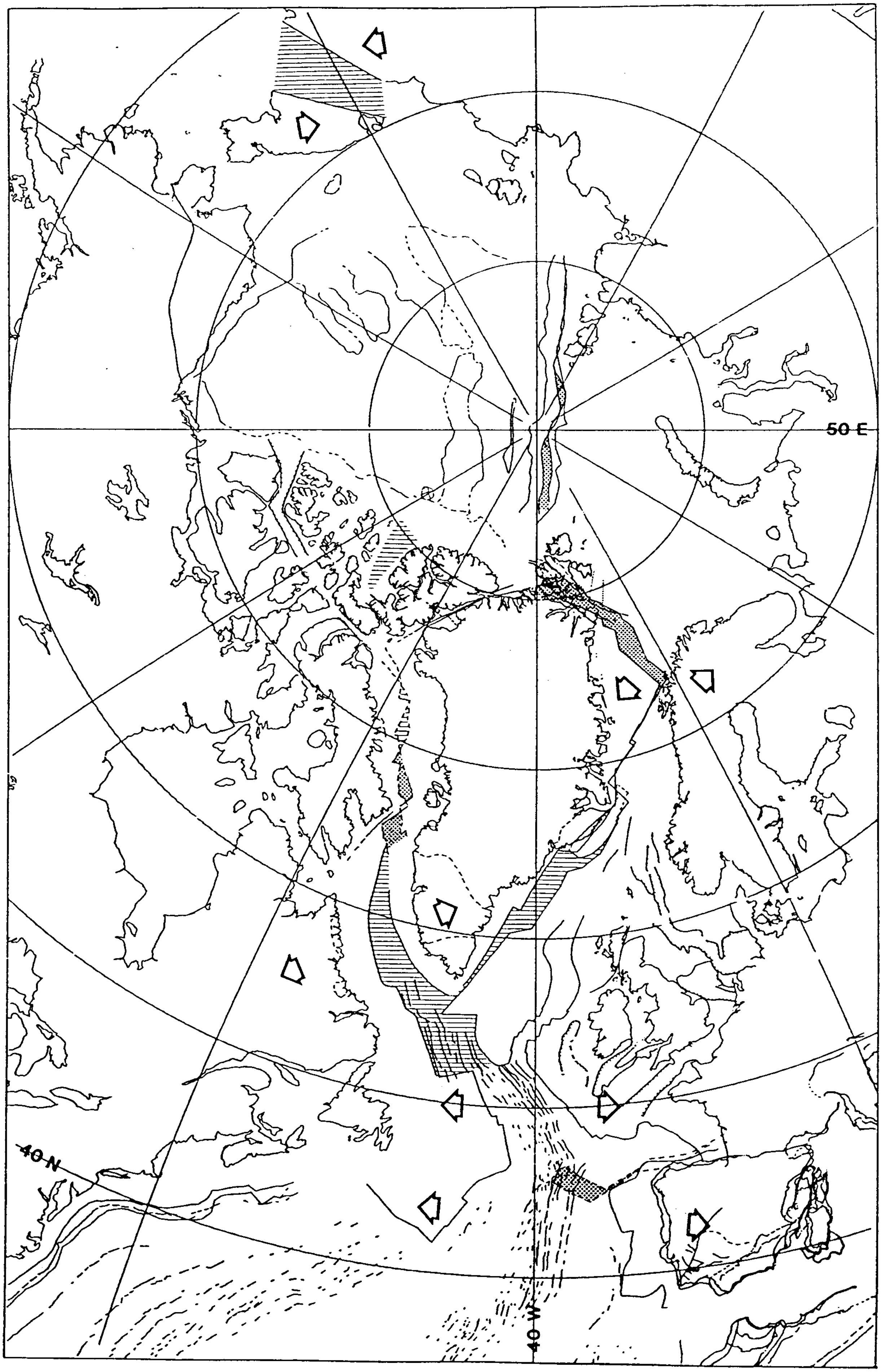


Fig. 10: Chron 30 (68.4 Ma, Maastrichtian)

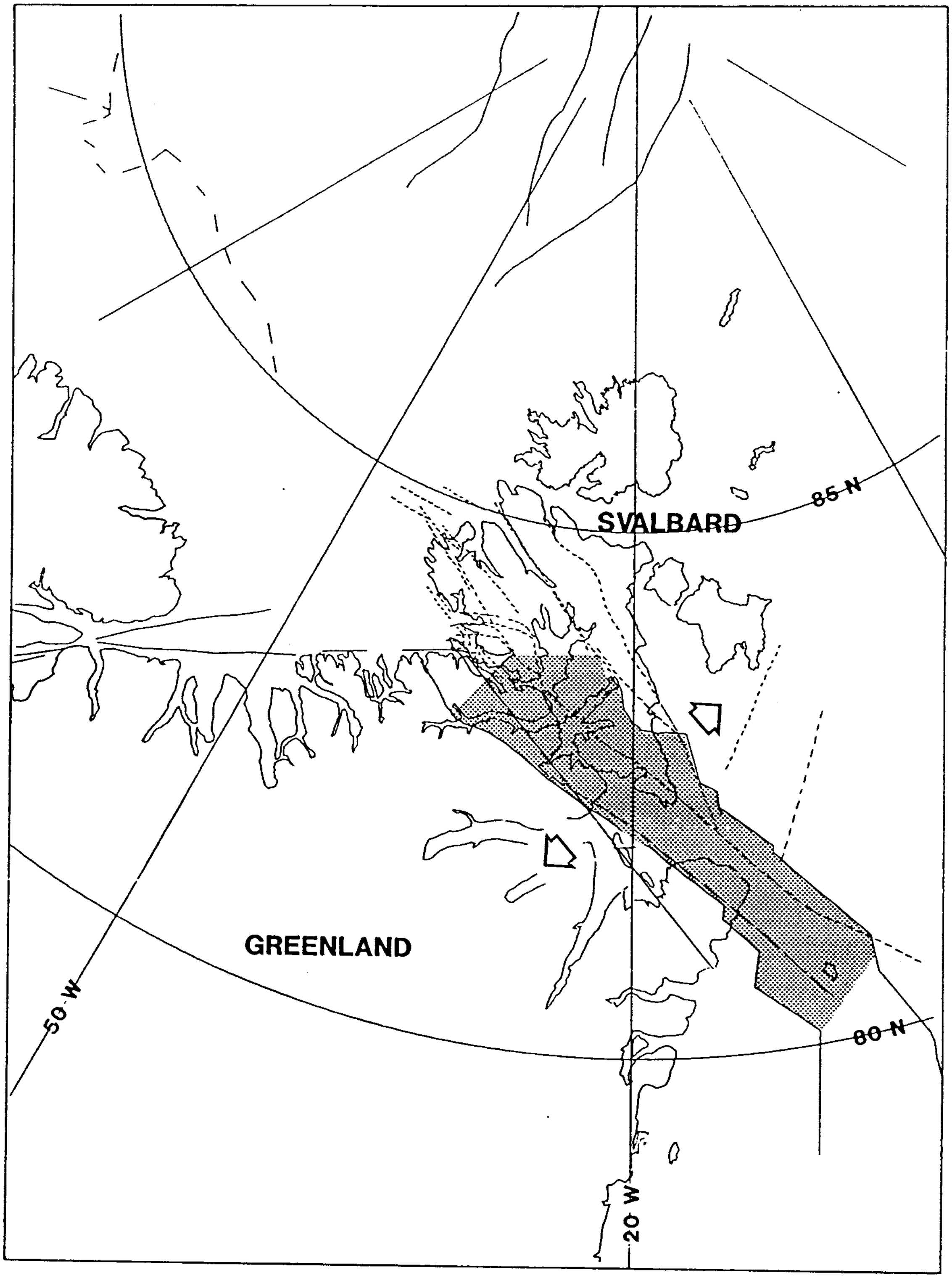


Fig. 11: Chron 30 (68.4 Ma, Maastrichtian)

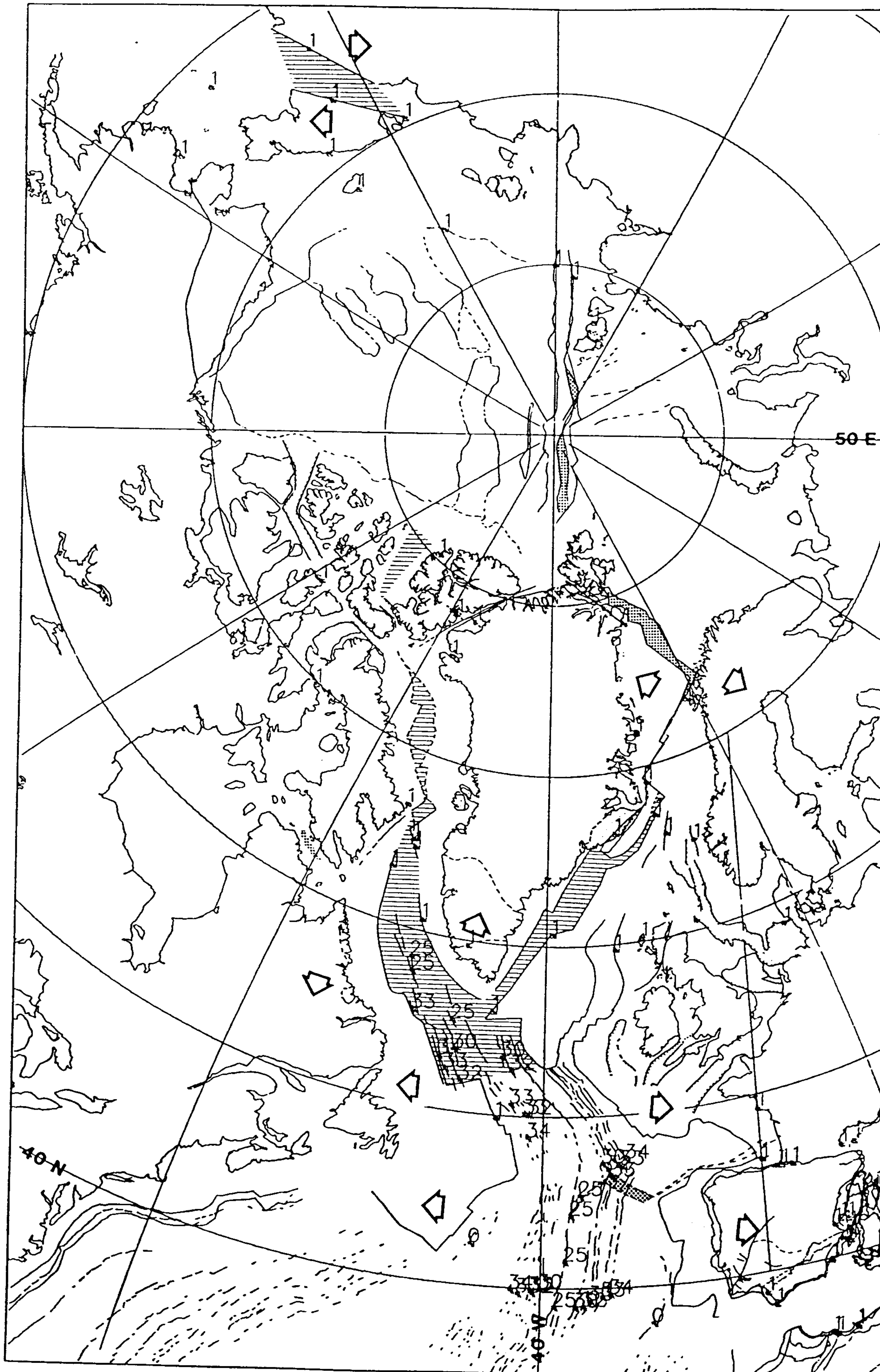


Fig. 12: Chron 25 (59.2 Ma, Thanetian)

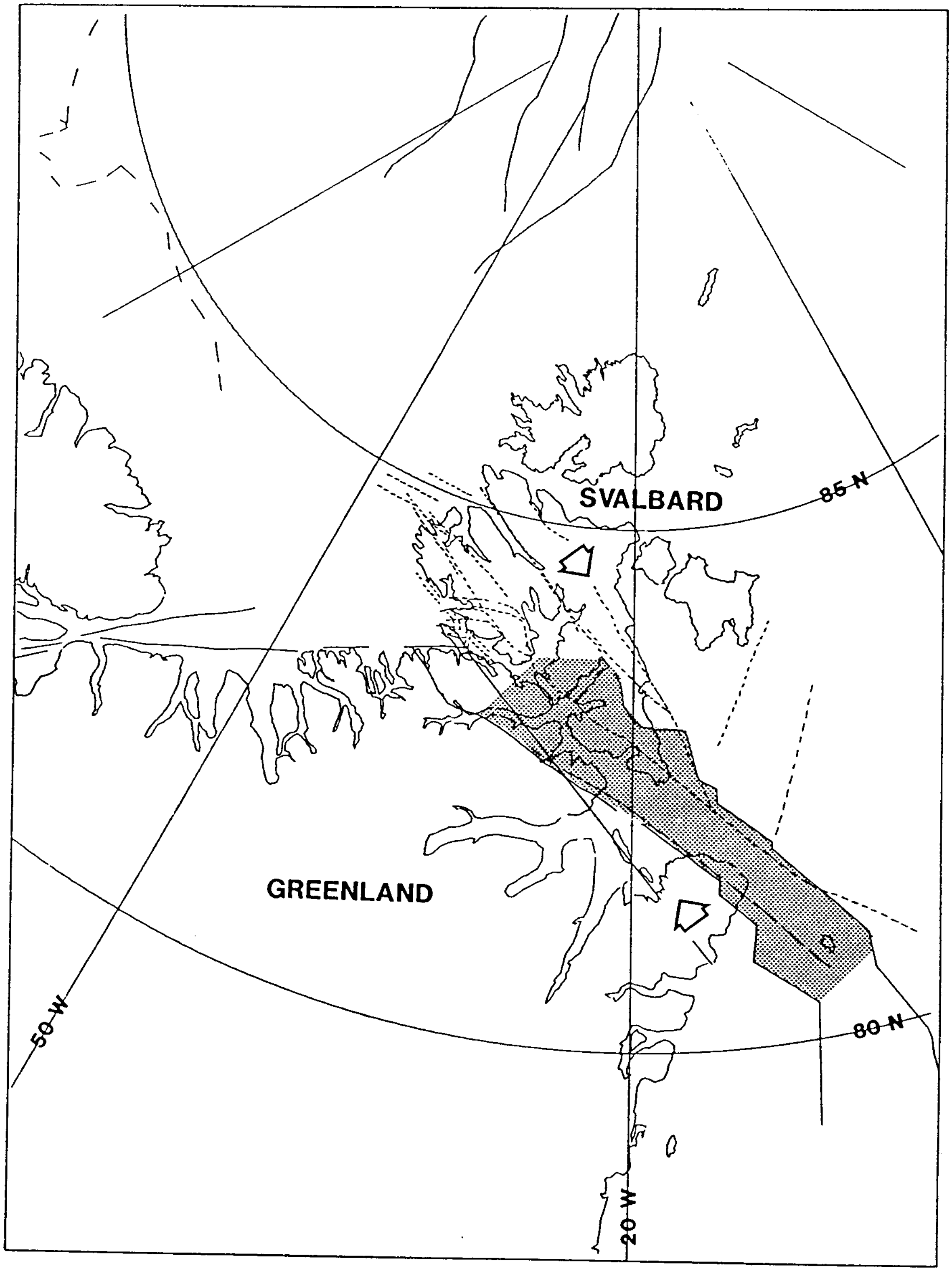


Fig. 13: Chron 25 (59.2 Ma, Thanetian)

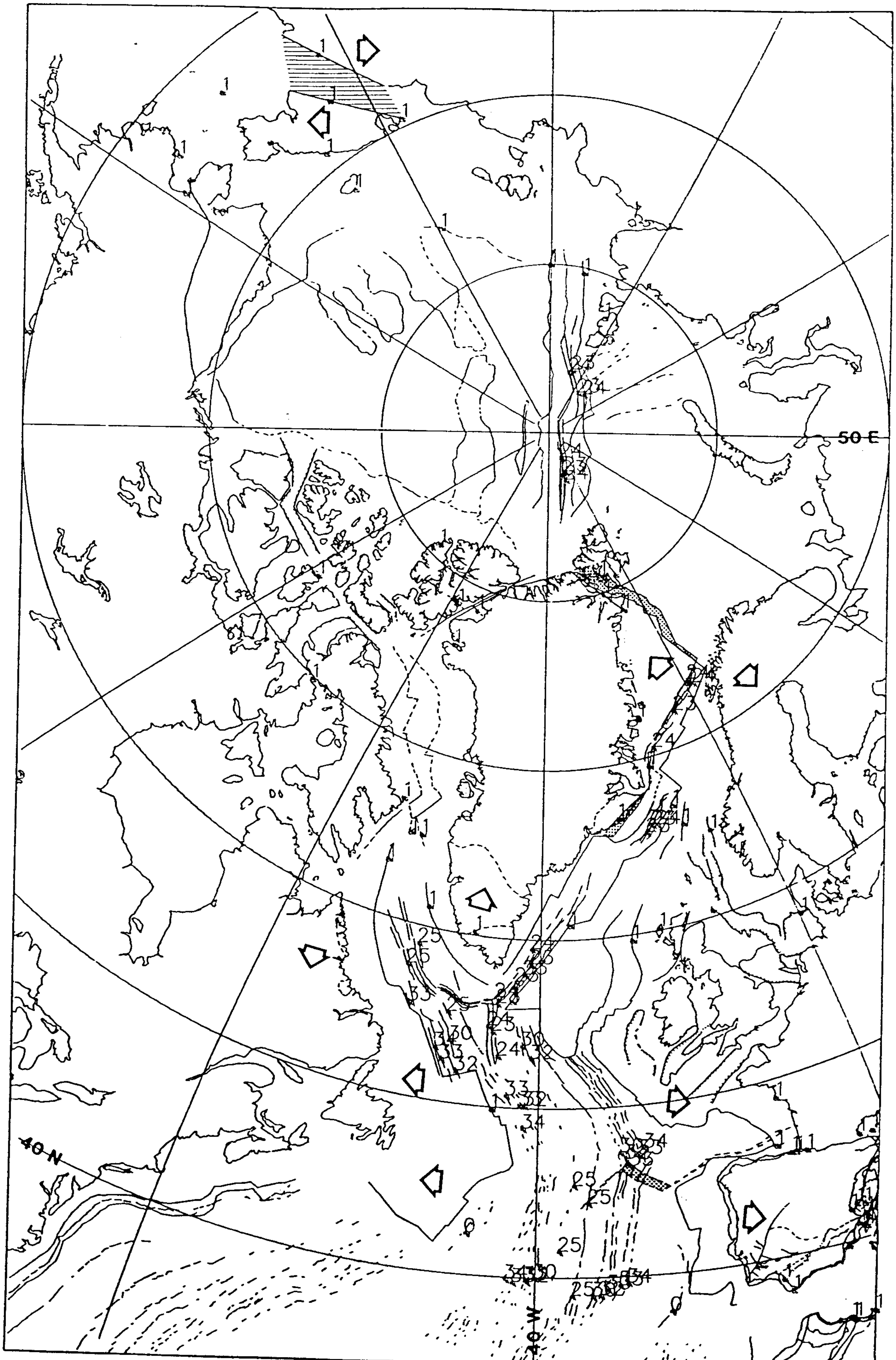


Fig. 14: Chron 24 (56.1 Ma, Ypresian)

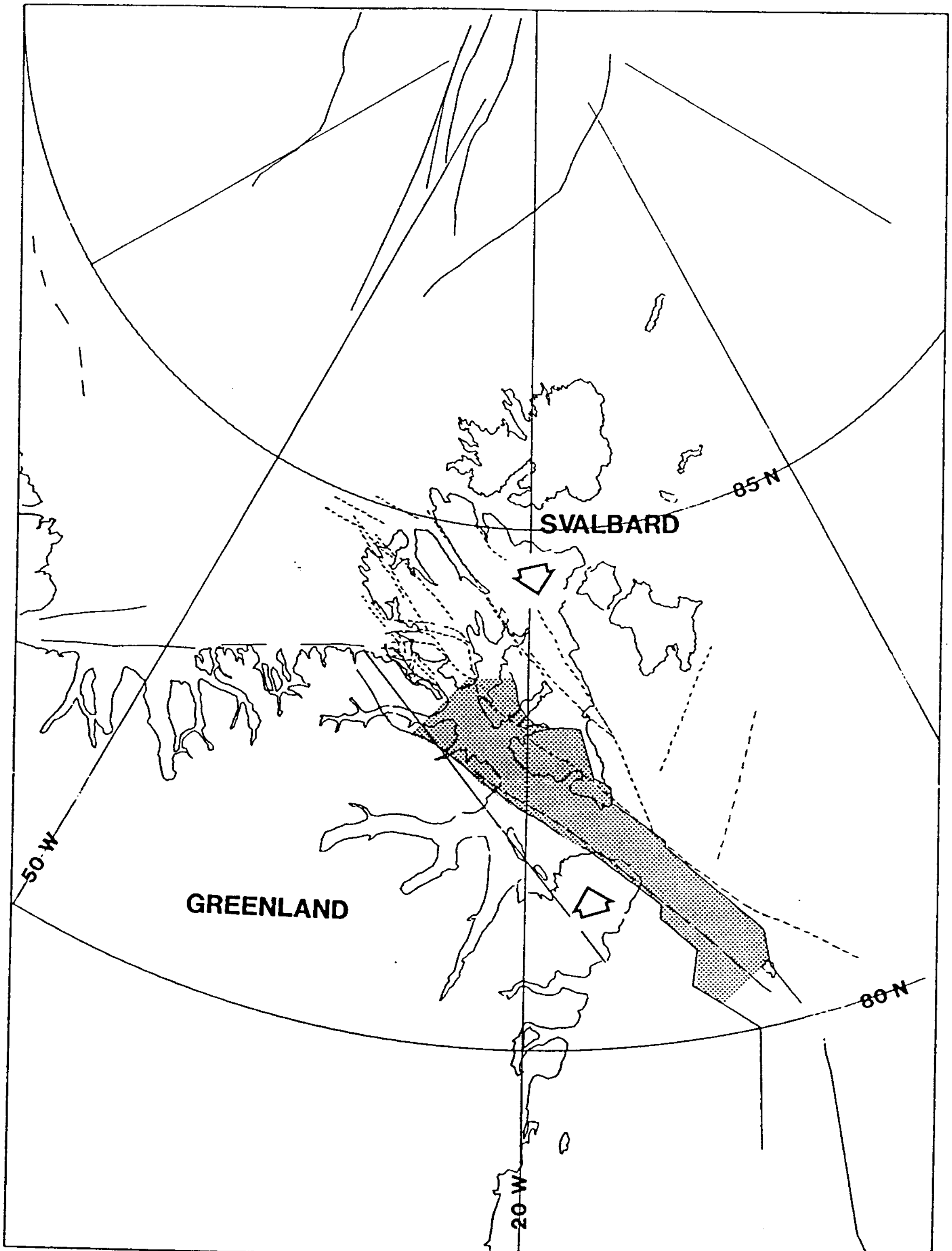


Fig. 15: Chron 24 (56.1 Ma, Ypresian)

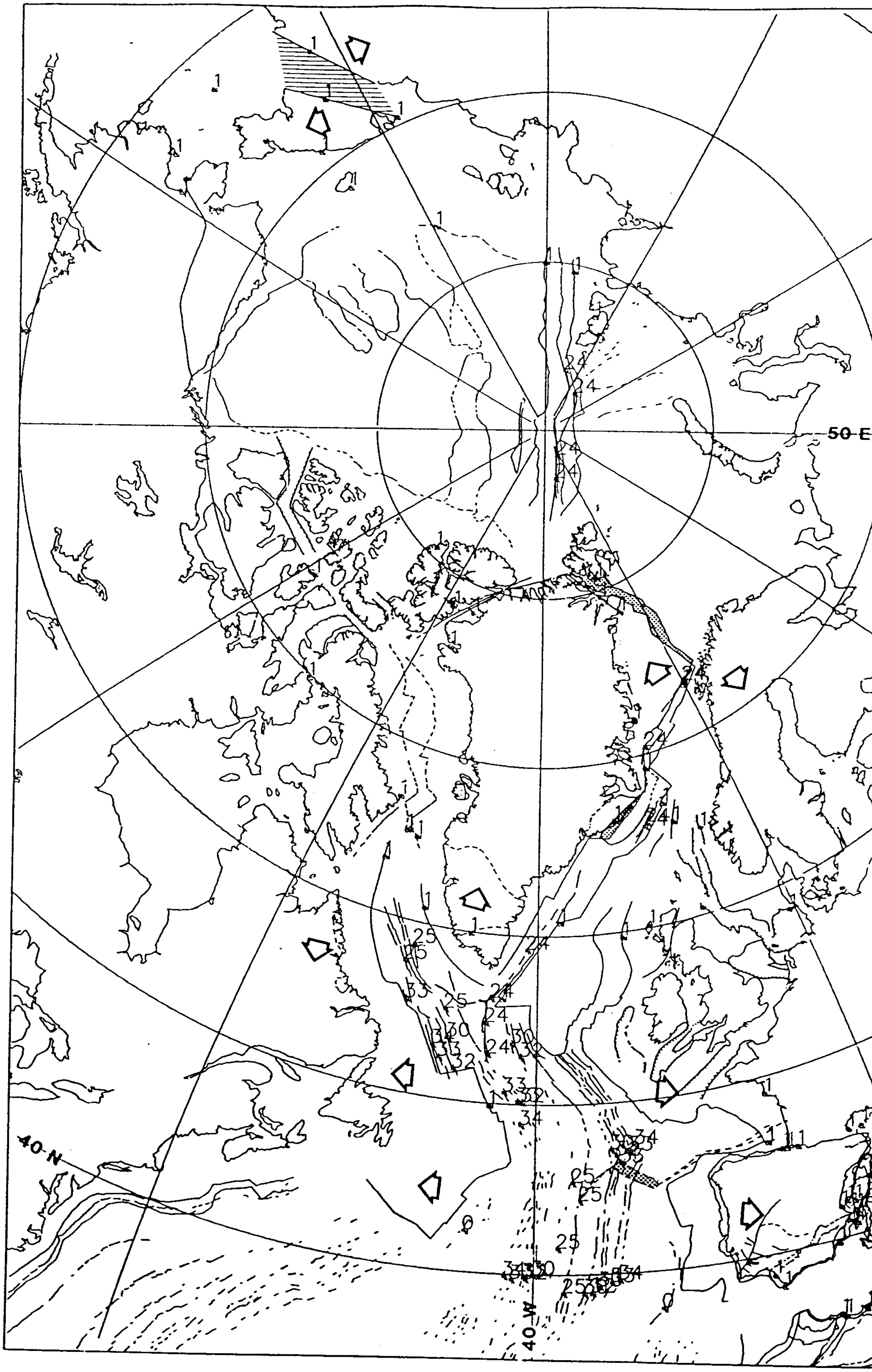


Fig. 16: Chron 23 (54.7 Ma, Ypresian)

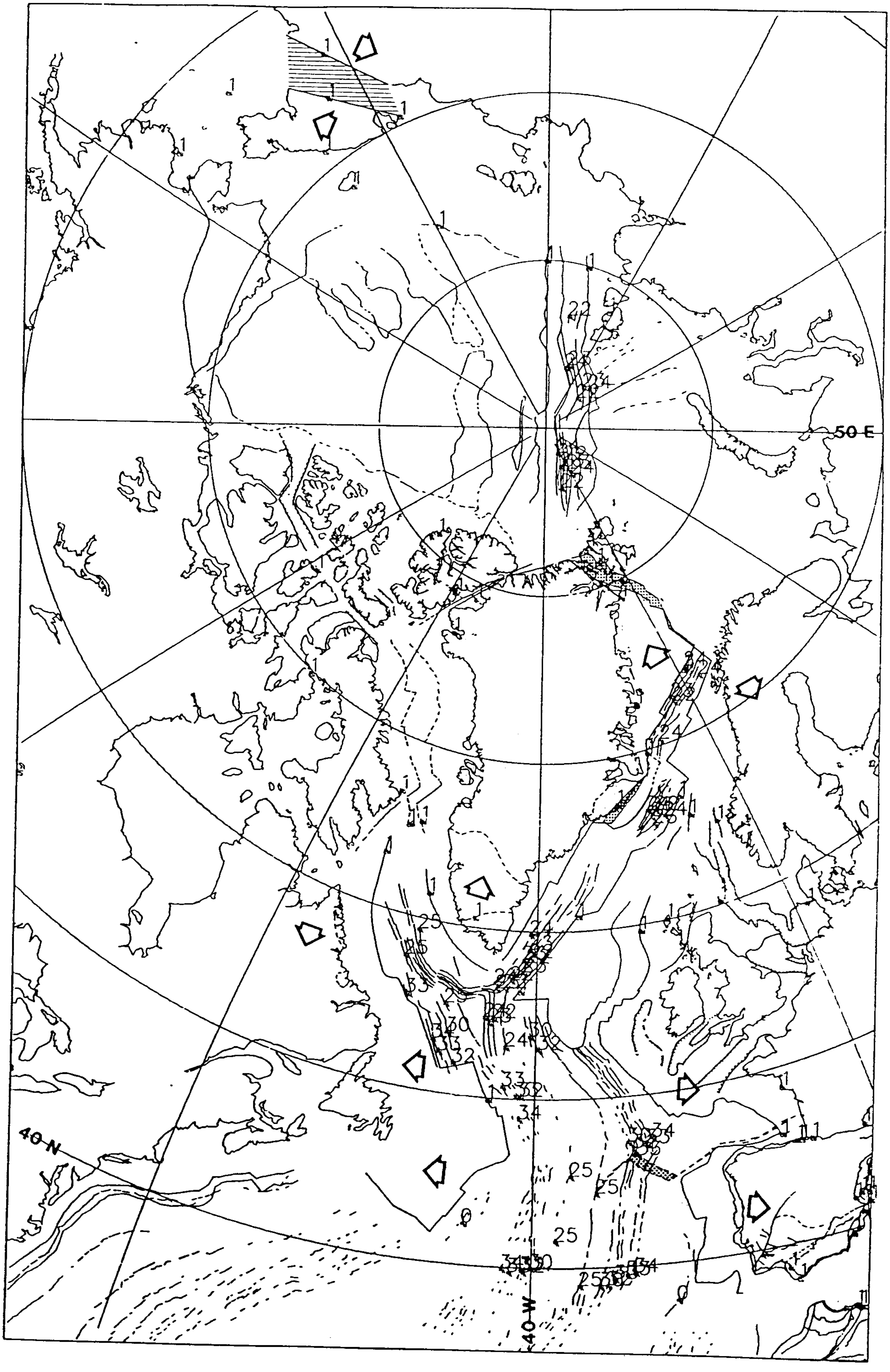


Fig. 17: (Chron 22 (52.6 Ma, Ypresian)

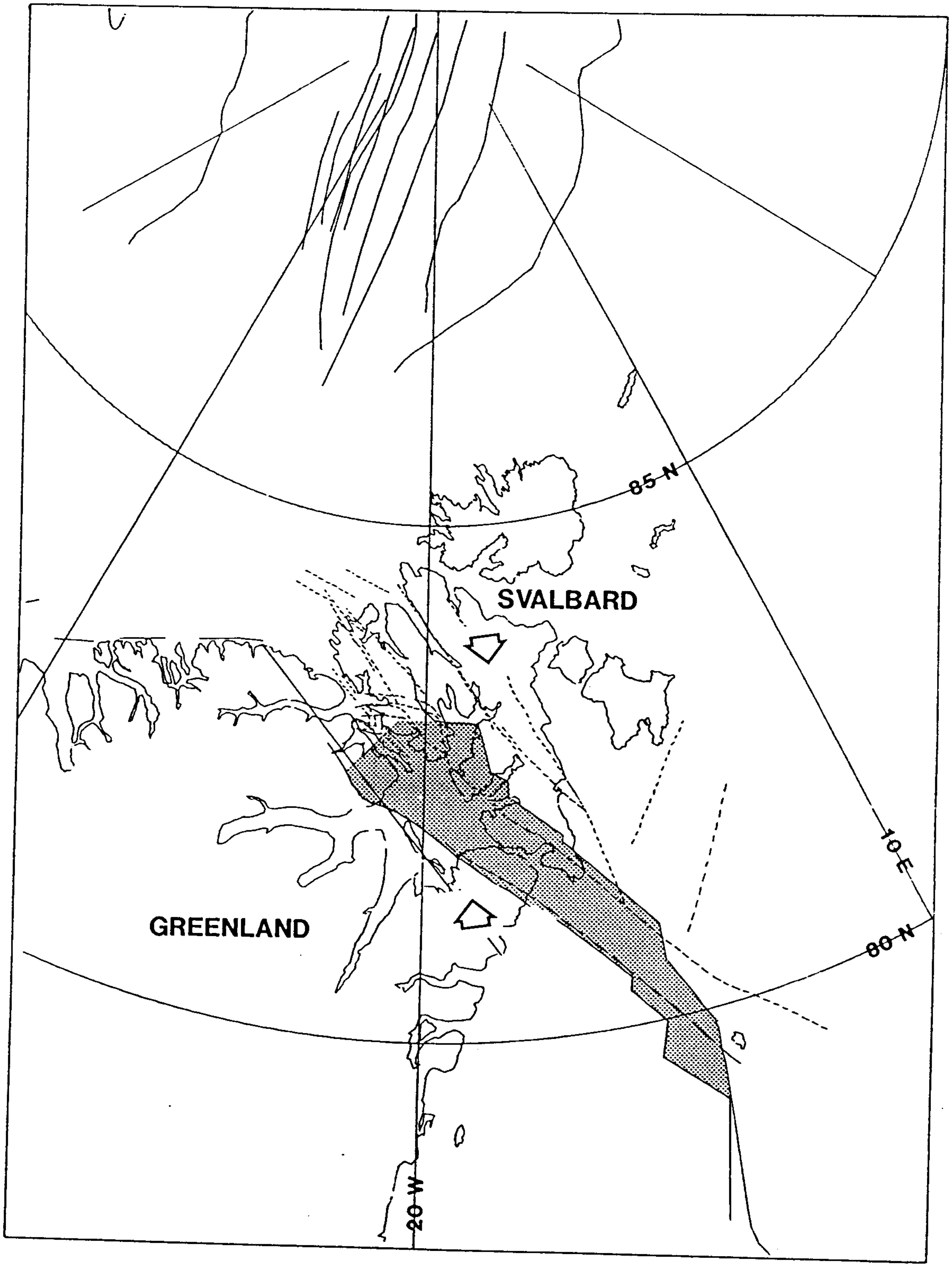


Fig. 18: Chron 22 (52.6 Ma, Ypresian)

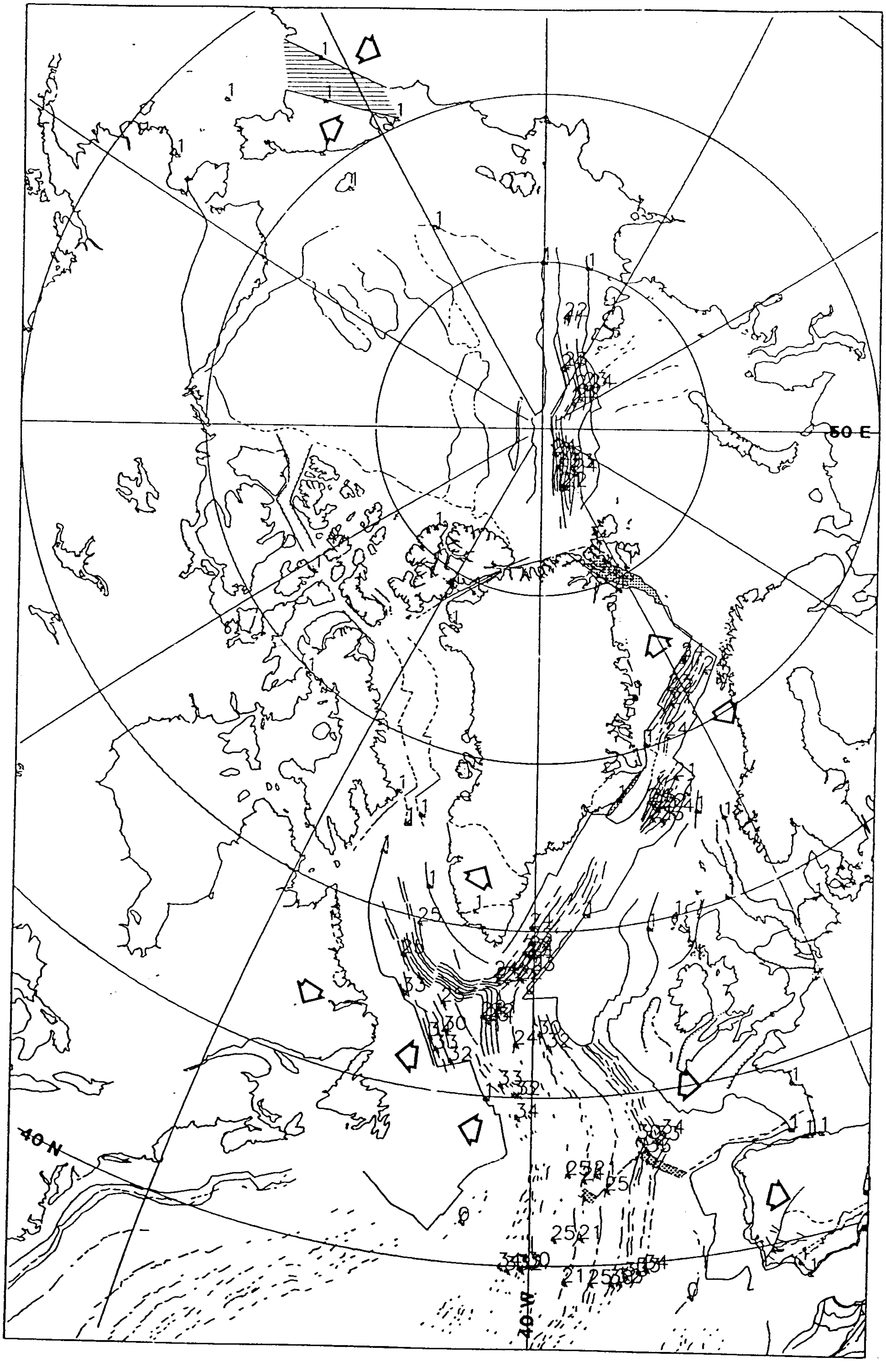


Fig. 19: Chron 21 (50.3 Ma, Lutetian)

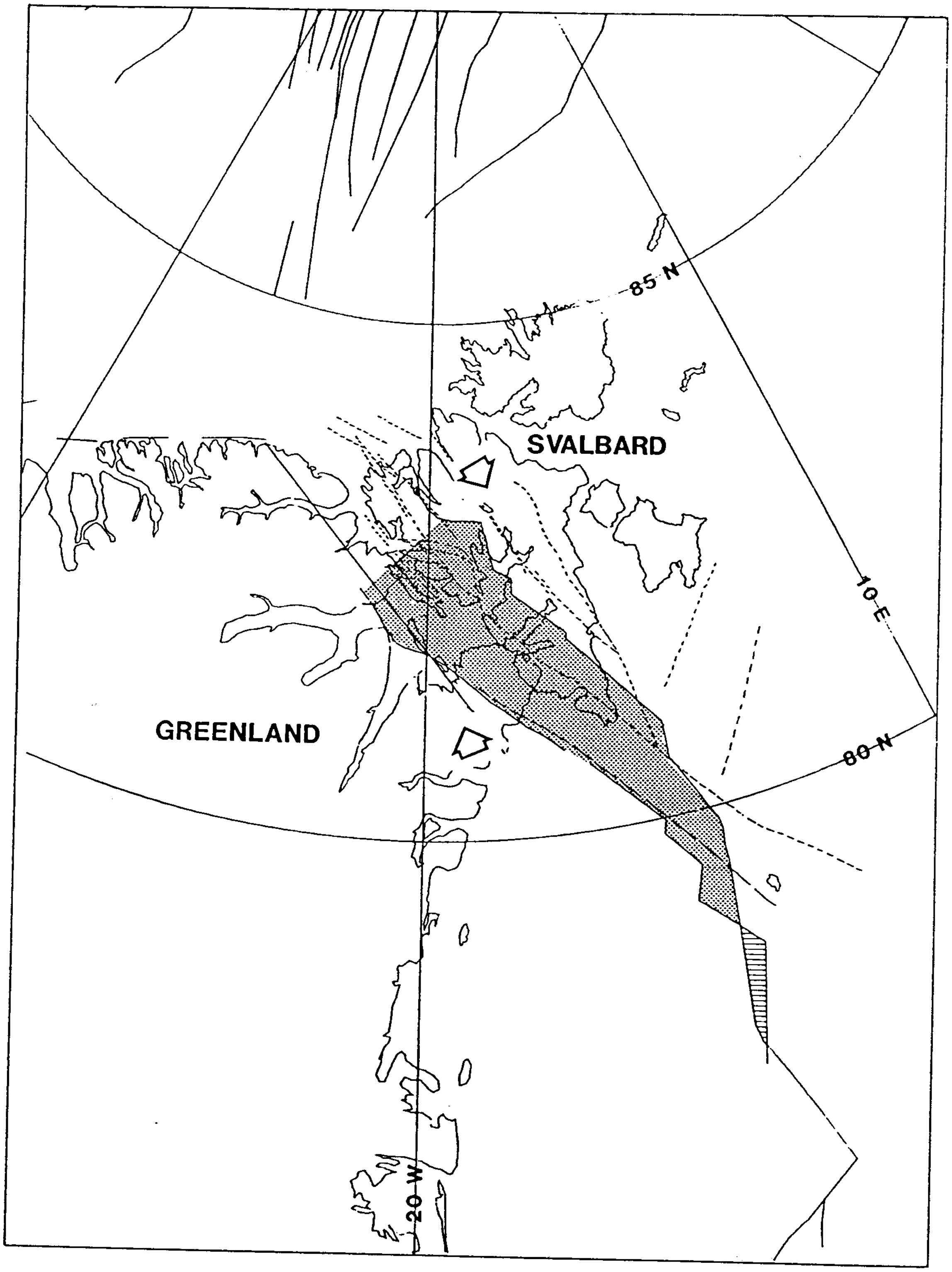


Fig. 20: Chron 21 (50.3 Ma, Lutetian)

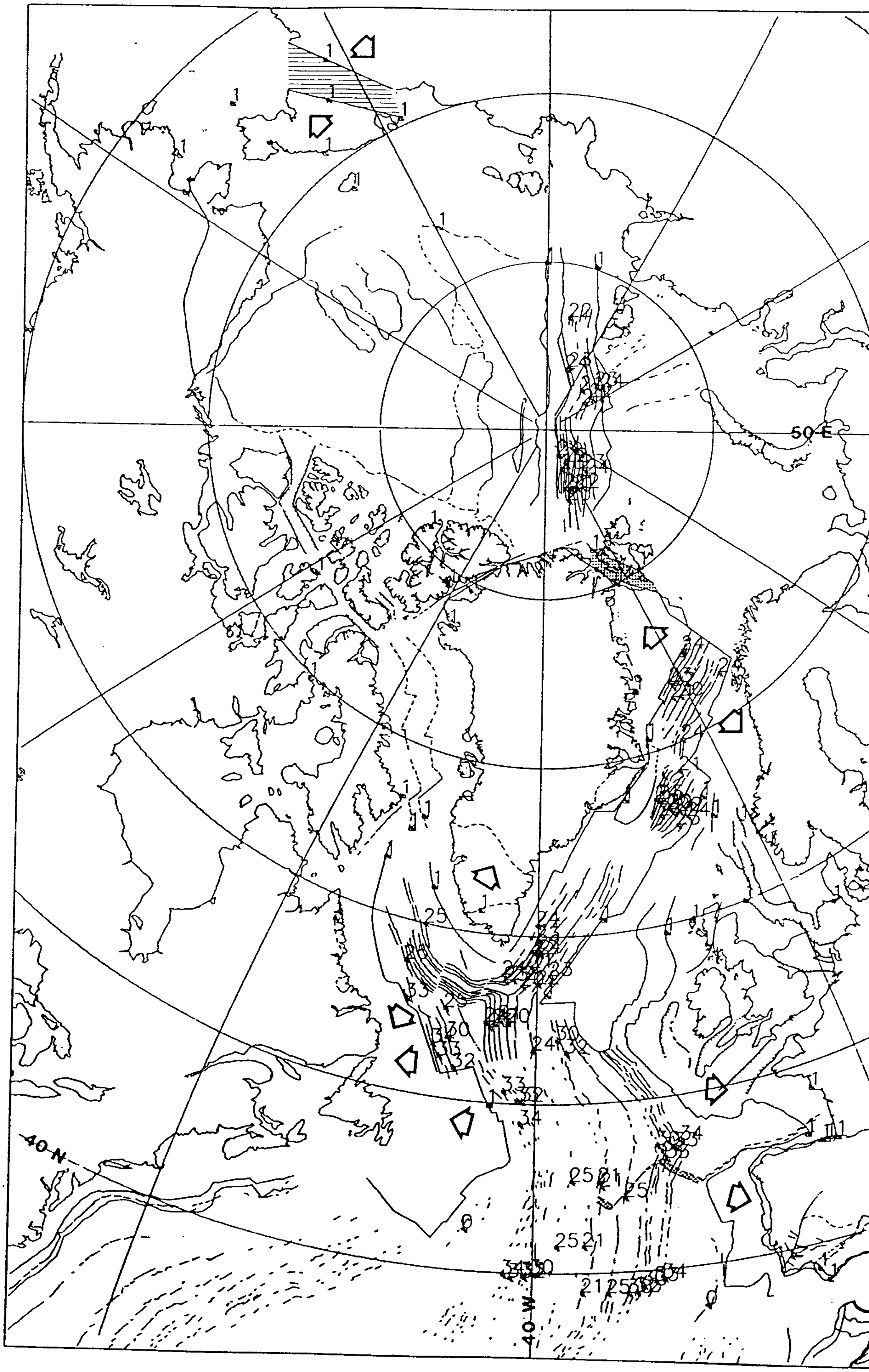


Fig. 21: Chron 20 (46.2 Ma, Lutetian)

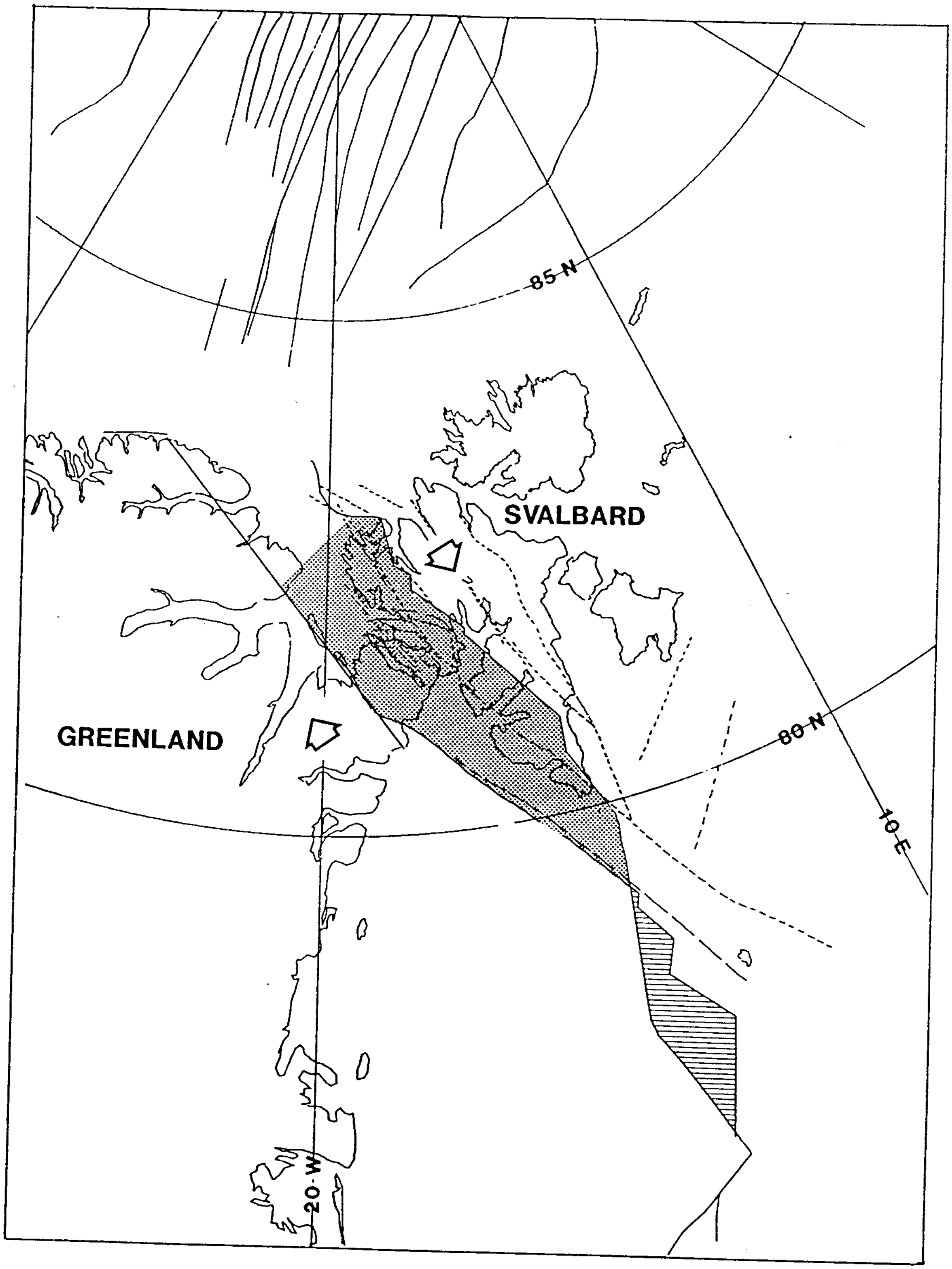


Fig. 22: Chron 20 (46.2 Ma, Lutetian)

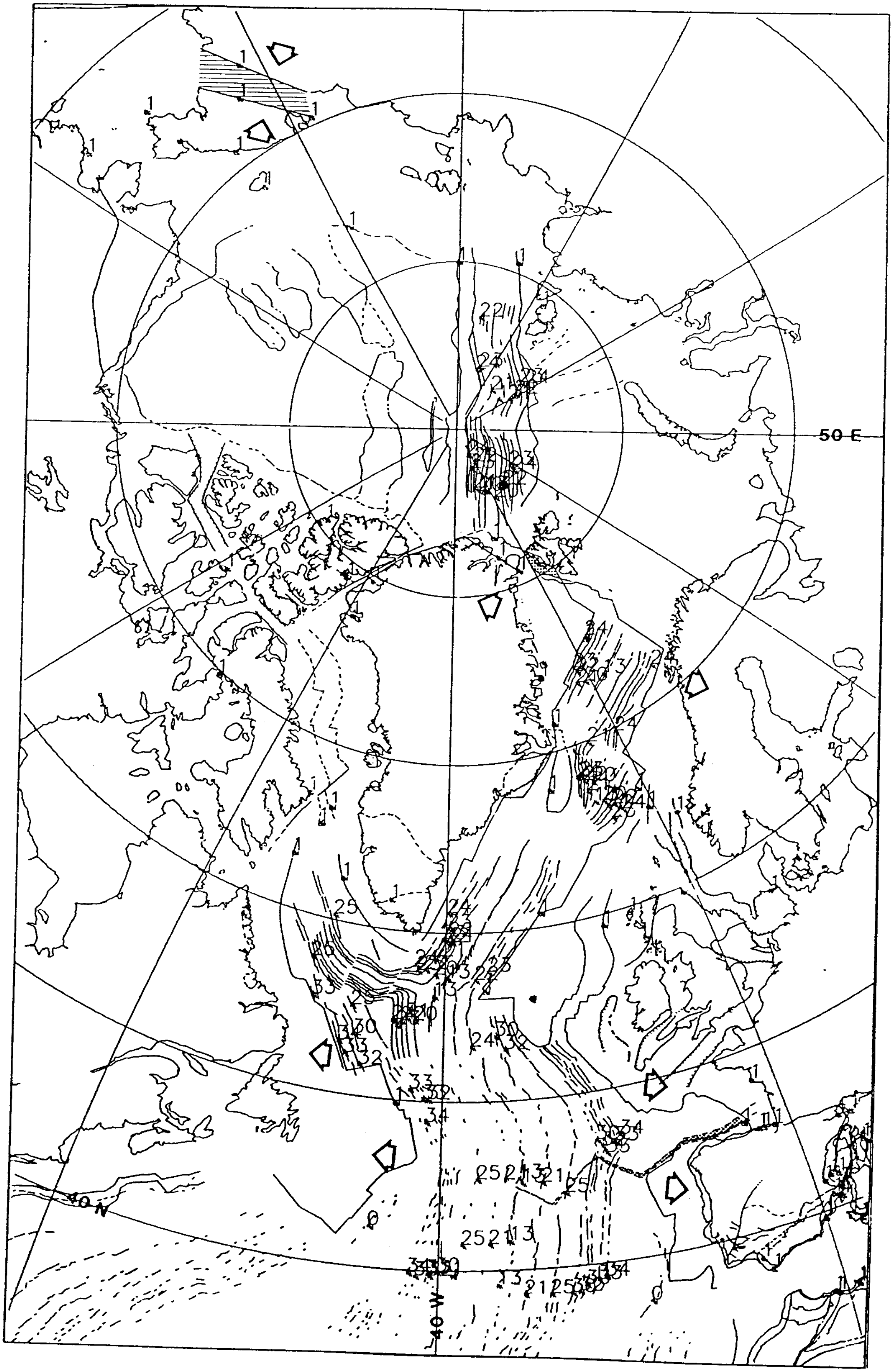


Fig. 23: Chron 13 (35.9 Ma, Rupelian)

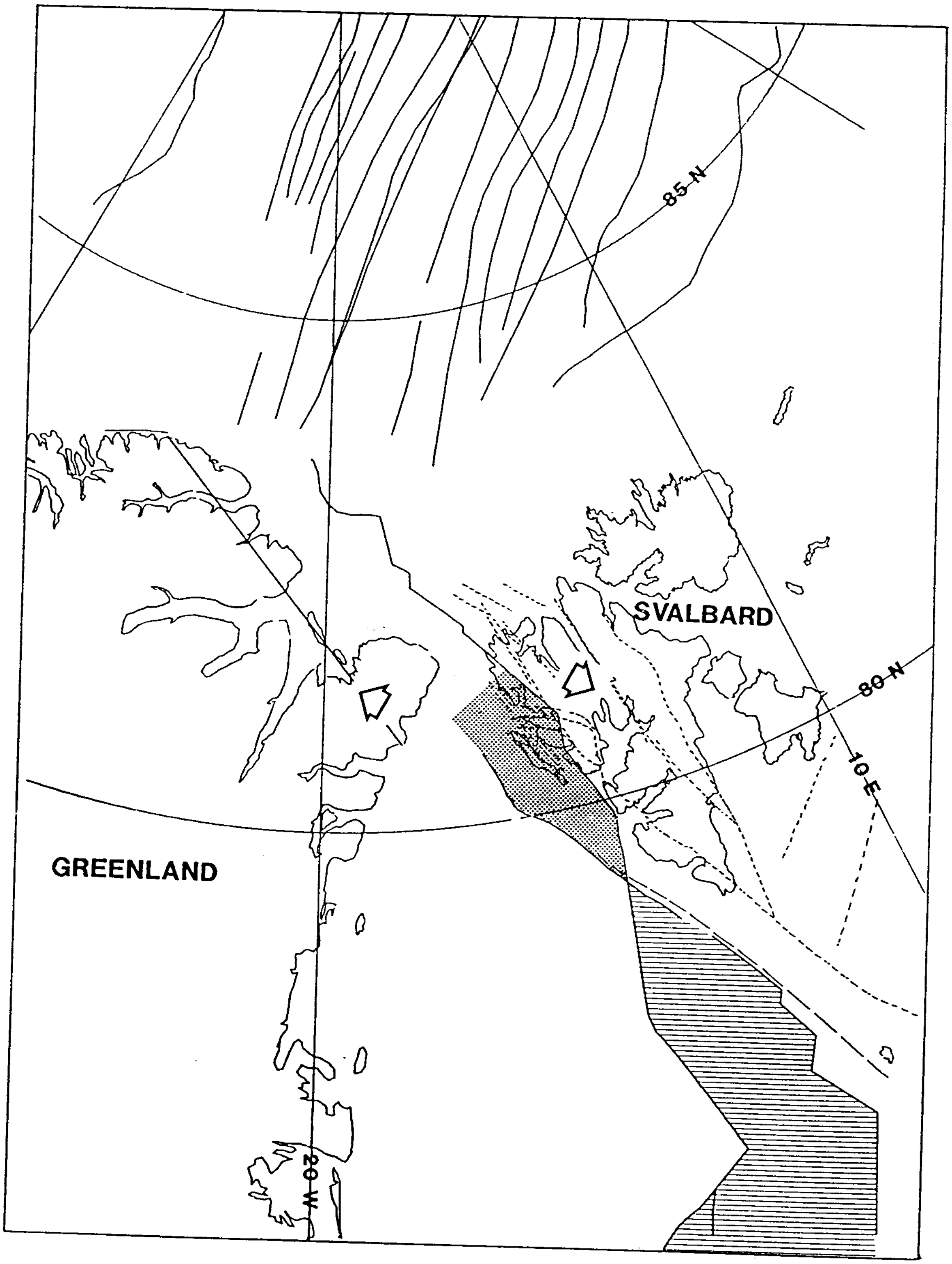


Fig. 24: Chron 13 (35.9 Ma, Rupelian)

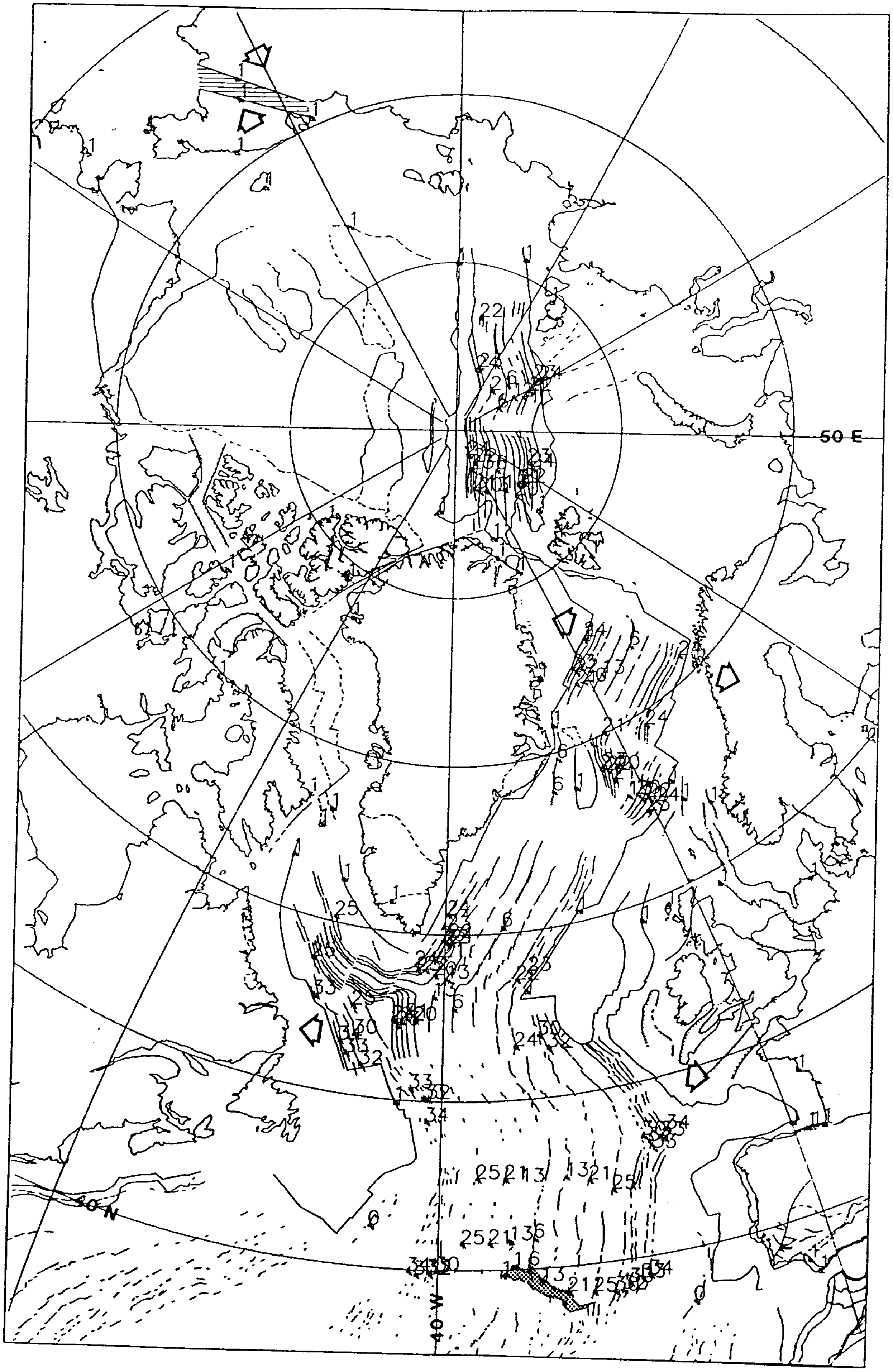


Fig. 25: Chron 6 (20.5 Ma, Burdigalian)

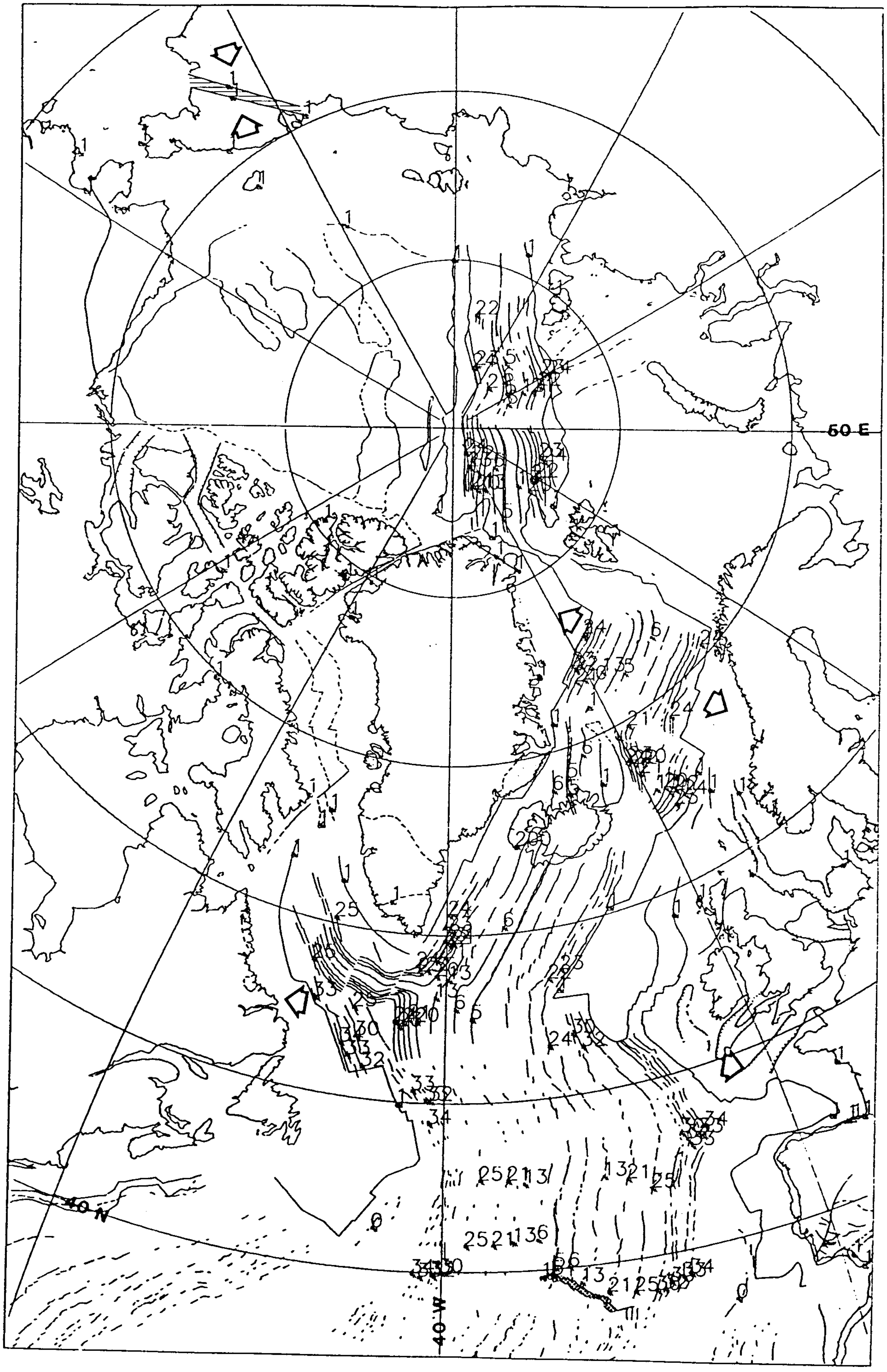


Fig. 26: Chron 5 (10.6 Ma, Tortonian)

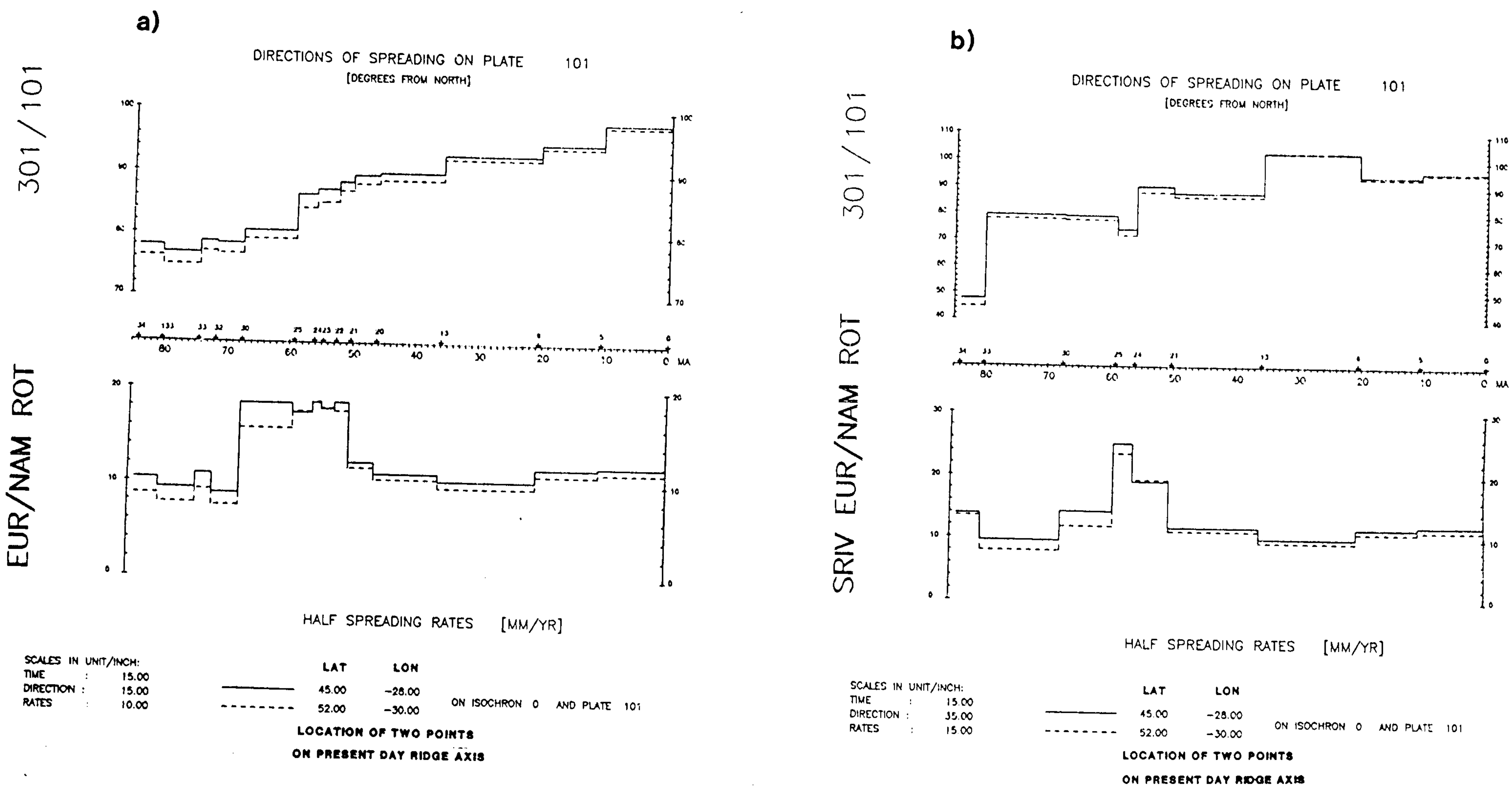


Fig. 27: Spreading directions and rates for Eurasia relative to North America

a: this paper

b: Srivastava & Tapscott (1986)

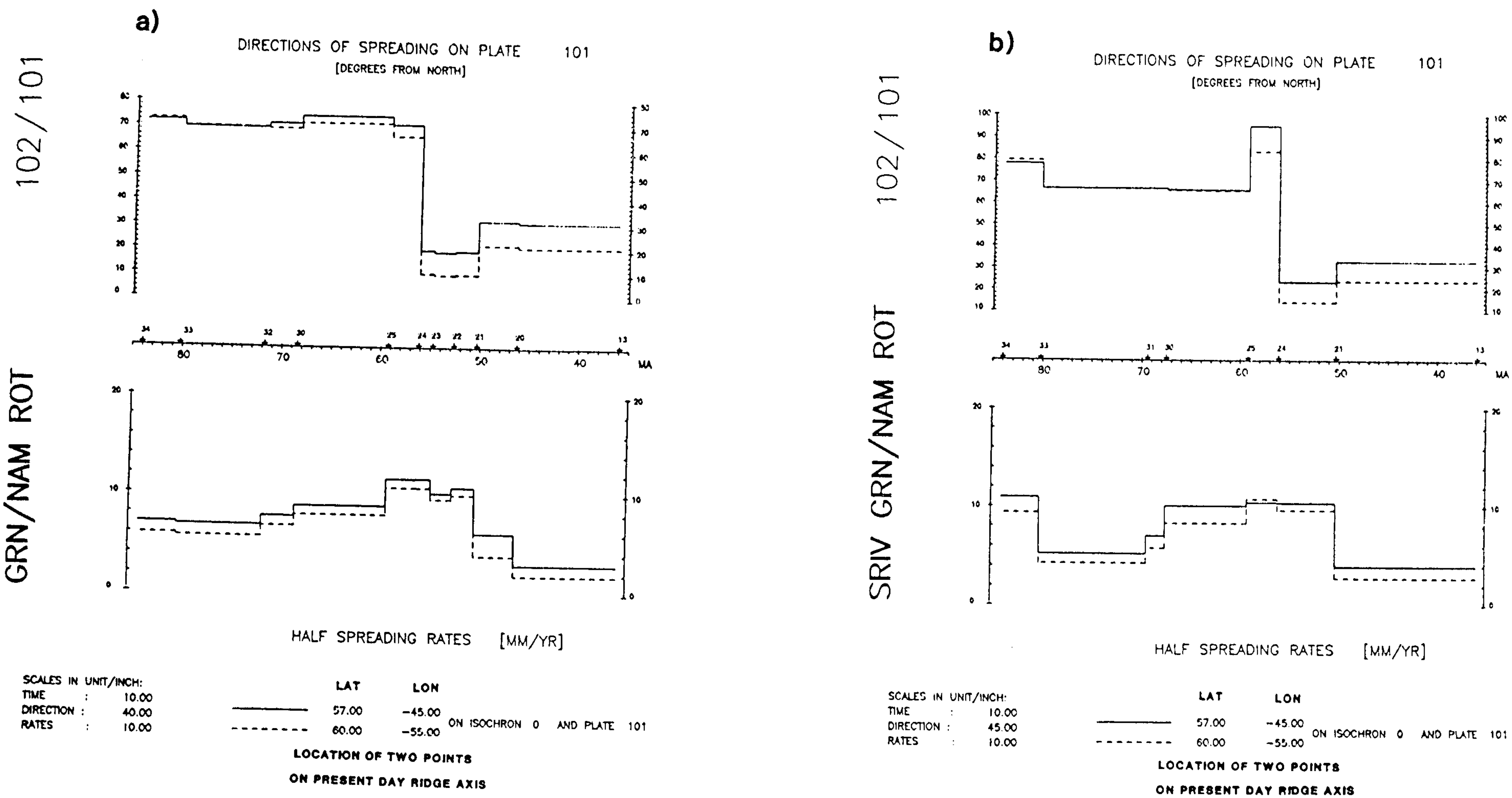


Fig. 28: Spreading directions and rates for Greenland relative to North America

a: this paper

b: Srivastava & Tapscott (1986)