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Contents

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Bathymetry of the Norwegian-Greenland Sea*

By GISLE GRØNLIE[1] AND MANIK TALWANI[2]

Abstract

We present a new bathymetric chart of the Norwegian-Greenland Sea contoured in uncorrected fathoms (sound velocity 800 fms = 1 s) in Mercator projection.

A large amount of geophysical data has been collected in the Norwegian-Greenland Sea during the last decade. The usefulness of the data has been enhanced by the use of satellite navigation on all cruises.

The bathymetry of the Norwegian-Greenland Sea reflects to a large extent the tectonic evolution of the area from the time of separation of Greenland from Norway in Early Eocene time to the present.

Introduction

During the past 15 years several bathymetric charts of the Norwegian-Greenland Sea have been published (Eggvin 1963; Johnson and Eckhoff 1966; Johnson and Heezen 1967). These maps were based on celestial navigation and relatively few soundings. We felt the need for a revised map existed which would take into consideration concepts of plate tectonics and utilize the large collection of new data with precise satellite navigation obtained since 1966.

Data base

The primary basis for the map is bathymetric data collected on board Lamont-Doherty Geological Observatory's research ship VEMA during its cruises in the Norwegian-Greenland Sea during the summers of 1966, 1969, 1970, 1972, and 1973 (V27, 28, 29, 30). In addition we have used recent data collected by the following oceanographic institutions:

Centre National pour L'Exploitation des Oceans (JEAN CHARCOT cruises 13, 14, 15, 16, 39, 40, 55, 56, 60, 62, 64)

US Naval Oceanographic Office (LYNCH cruises 12, 21, 32, and SPAR cruise 1966 (Loran C navigation))

* Lamont-Doherty Geological Observatory Contribution No. 2817

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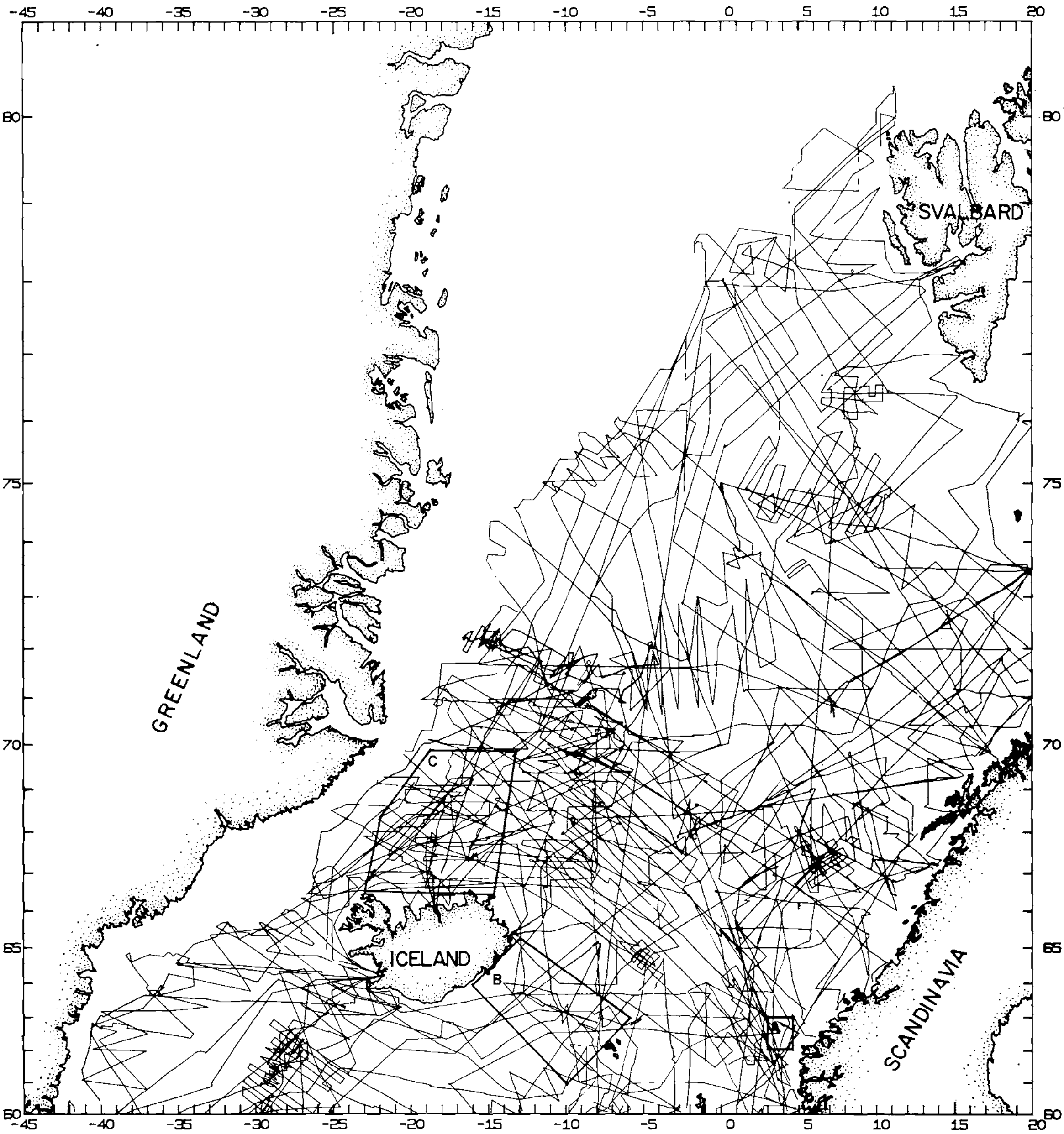

Fig. 1. *Map showing tracks with satellite navigation.*
A, B and C are areas where Deutsches Hydrographisches Institut has conducted detailed surveys.
A : Dietrich, G., 1969 (METEOR). B : Fleischer et al., (METEOR, 1968, 1970).
C: PLANET, 1971, unpublished.

Naval Research Laboratories (HAYES 1975)
Shirshov Institute of Oceanology (AKEDEMIK KHURCHATOV)
JOIDES (GLOMAR CHALLENGER, leg 38, 1974).

All these data (except SPAR, which used Loran C) were collected using satellite navigation, and the track lines are shown in Fig. 1 and on a separate figure on the bathymetric chart at the back of this volume.

Plotted sheets were also made available from US Naval Oceanographic Office, Deutsches Hydrographisches Institut (including the latest cruises of R/V's PLANET and METEOR), Det Kongelige Danske Søkort Arkiv and from Sjømaelingar Islands.

The map covers the area from 60°N to 79°N between Greenland and Norway and is presented in Mercator projection at a scale of approximately 1:4,000,000 measured at latitude 63°N. The same map is also being published as part of a geophysical atlas at a scale of approximately 1:1,330,000 at latitude 63°N (Grønlie and Talwani 1978).

The map is contoured at an interval of 100 fathoms based on a reflection time depth with an assumed velocity of sound, 1 fm = 1.8288 m. The depth correction to be made for the variation in velocity of sound is, according to Matthews (1939) tables, less than 40 fathoms in the deepest areas of the map, but in most areas less than 10 fathoms. Corrections for the change in sound velocity with temperature are given as Table 1 and Fig. 2.

The contours were originally drawn at a scale of approximately 1:1,000,000. The contours were then digitized and stored in a computer. The advantage with this system is that maps later can be easily plotted by the computer in different projections and/or at different scales.

Severe ice conditions north of 75°N prevented ships from approaching the western part of the Greenland Sea and the map is therefore less accurate in this area. A similar map using mostly the same data base in polar-stereographic projection has recently been published by Perry et al. (1977).

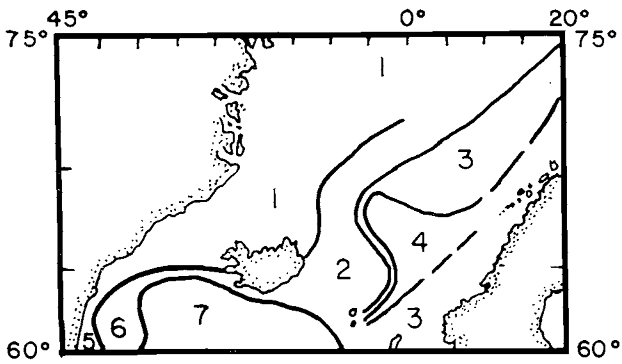

Fig.2. *Velocity correction regions in the Norwegian-Greenland Seas, after Matthews, 1939. See Table 1.*

Table 1

Table of values to add to the nominal depth to correct for variable velocity of sound in sea water (from Matthews, 1939)

	Regions						
Depth in Fathoms	*1*	*2*	*3*	*4*	*5*	*6*	*7*
100	–2	0	1	0	2	1	2
200	–3	–1	1	1	3	2	2
300	–3	–1	2	1	3	2	4
400	–4	–2	2	2	4	3	5
500	–4	–2	2	3	4	4	6
600	–4	–2	2	3	5	5	7
700	–4	–2	3	4	5	6	9
800	–3	–2	3	6	7	8	10
900	–2	–1	3	7	8	10	11
1000	–1	–1	4	9	10	11	14
1100	–1	0	6	11	12	14	15
1200	0	2	6	14	15	15	18
1300	2	3	8	16	16	18	20
1400	4	4	9	19	19	21	23
1500	6	6	11	21	23	23	26
1600	8	8	12	24	26	26	30
1700	—	—	—	28	30	30	33
1800	—	—	—	32	34	35	37
1900	—	—	—	36	36	39	41
2000	—	—	—	40	41	44	45

Nomenclature

There is some confusion about names of geographical features in the Norwegian Greenland Sea. We have used Iceland-Jan Mayen Ridge rather than Kolbeinsey Ridge, and Knipovich Ridge rather than Atka Ridge. We also prefer the names Lofoten and Norway Basins for the basins north and south of the Vøring Plateau.

We present in Table 2 a list of geographical names used in the Norwegian-Greenland Sea, together with comments on the origin.

Table 2

Origin of names used in the bathymetric map

Geographic name	*Suggested by*	*Named after*
Boreas Basin	Johnson & Eckhoff (1966)	The Greek God of the North Wind
Extinct axis	Talwani & Eldholm (1977)	
Hovgaard fracture zone	Johnson & Eckhoff (1966)	Hovgaard island off east coast of Greenland
Knipovich ridge		Nicolai M. Knipovich, 1862-1939, Russian zoologist
Mohns ridge		Henrik Mohn, 1835–1916, Norwegian meteorologist
Senja fracture zone	Talwani & Eldholm (1972)	Island off the coast of Norway
Spar fracture zone	Johnson & Heezen (1967)	The ship Spar
Vøring plateau	Nansen (1904)	The ship Vøringen

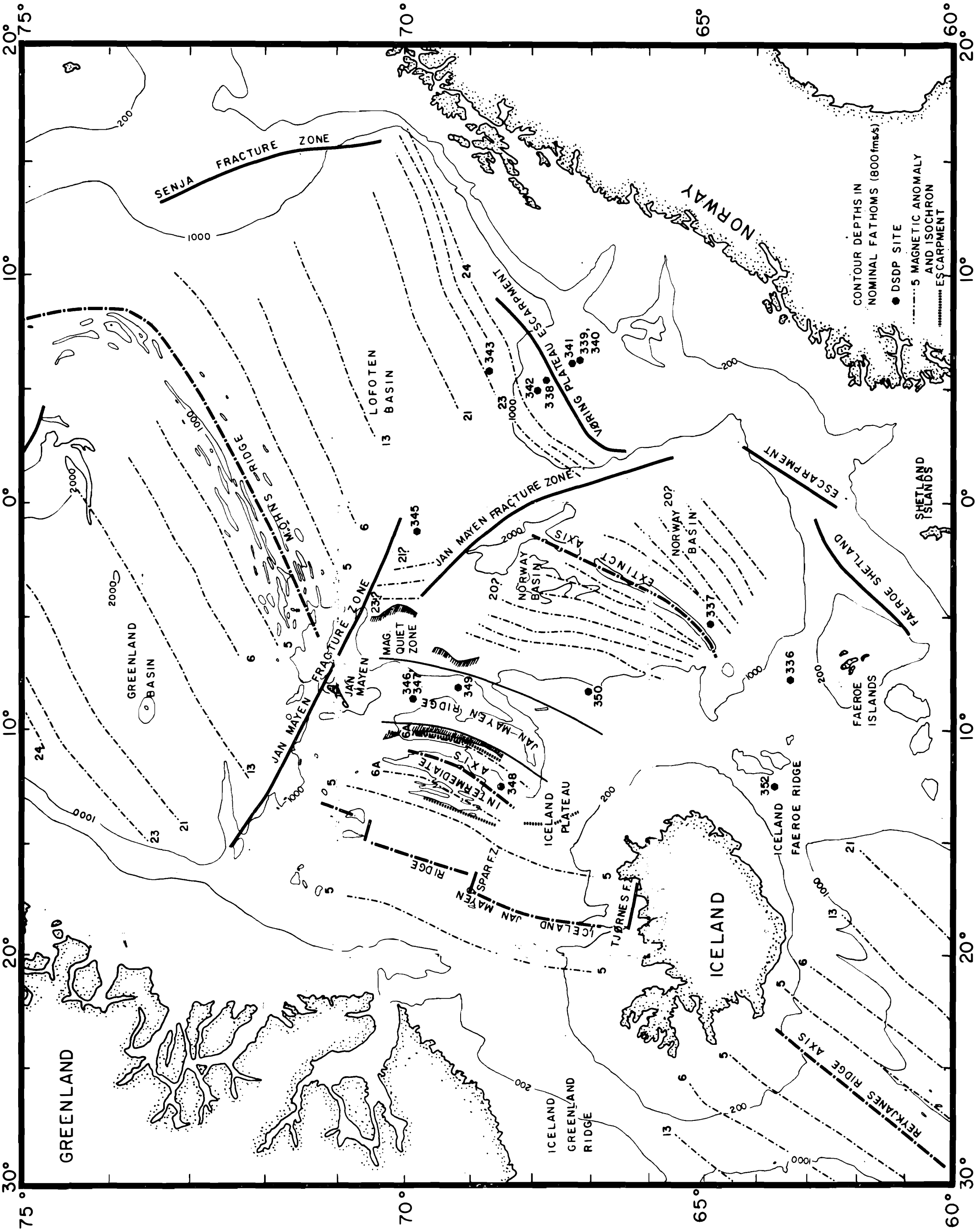

Fig.3. *Magnetic lineations in the Norwegian-Greenland Sea (Talwani and Eldholm 1977; Grønlie et al. this volume).*

Tectonic evolution of the Norwegian-Greenland Sea

The concept of ocean floor spreading and plate tectonics was developed in the 1960's, and refined in the 1970's. Magnetic anomalies were used to identify and date oceanic crust which was being created at mid-ocean ridges in the world's oceans and destroyed in deep trenches close to continents. The symmetric magnetic anomaly pattern across the mid-oceanic axes were identified by numbers, and magnetic time scales relating anomaly numbers to time were developed. Fig. 3 shows the magnetic anomaly lineations in the Norwegian-Greenland Sea with corresponding anomaly numbers, as identified by Talwani and Eldholm (1977) and Grønlie et al. (this volume).

The evolution of the Norwegian-Greenland Sea has recently been discussed by several authors including Johnson and Heezen (1967), Johnson et al. (1971, 1972), and most recently by Talwani and Eldholm (1977) and Talwani and Udintsev (1976). The following tectonic summary is mostly based on Talwani and Eldholm (1977).

The break-up between Norway and Greenland took place (Fig. 4) along what are now marginal escarpments (Vøring Plateau and Faeroe-Shetland escarpments in the east and Greenland escarpment in the west) about 57 MyBP, according to the revised geomagnetic time scale by LaBrecque and others (1977). Sea floor spreading on the Mohns Ridge has taken place about the same axis of spreading since the time of opening while spreading in the areas north of the Greenland Fracture Zone and south of the Jan Mayen Fracture Zone has been more complex.

The area south of the Jan Mayen Fracture Zone is thought to have had at least two extinct spreading centers before the establishment of presently spreading Iceland-Jan Mayen Ridge which has been active since about the time of magnetic anomaly 5 (10 My). From the time of opening to some time between 36 My (anomaly 13) and 26 My (anomaly 7) the extinct axis in the Norway Basin was active. After this the axis shifted west of the Jan Mayen Ridge possibly in two steps, the northern part first, close to 36 My ago creating the western segment of the Jan Mayen Fracture Zone, followed by the southern part around 26 My (Grønlie et al. this volume) at which time spreading began at an intermediate axis which was active from 23 to 17 MyBP (anomaly 6A to 5D). During the shift of axis, a fragment of Greenland was broken off, creating the Jan Mayen Ridge. At 10 My (anomaly 5) another westward shift in the spreading occurred when the present spreading axis was created.

North of the Greenland Fracture Zone ocean floor spreading from the Knipovich Ridge has only taken place since about anomaly 13 time (36 My). No major opening existed prior to that, and the motion between Greenland and Svalbard was primarily one of shear along the Greenland and Senja Fracture Zones.

In contouring the map, we have made use of these ideas regarding the evolution of the Norwegian-Greenland Sea.

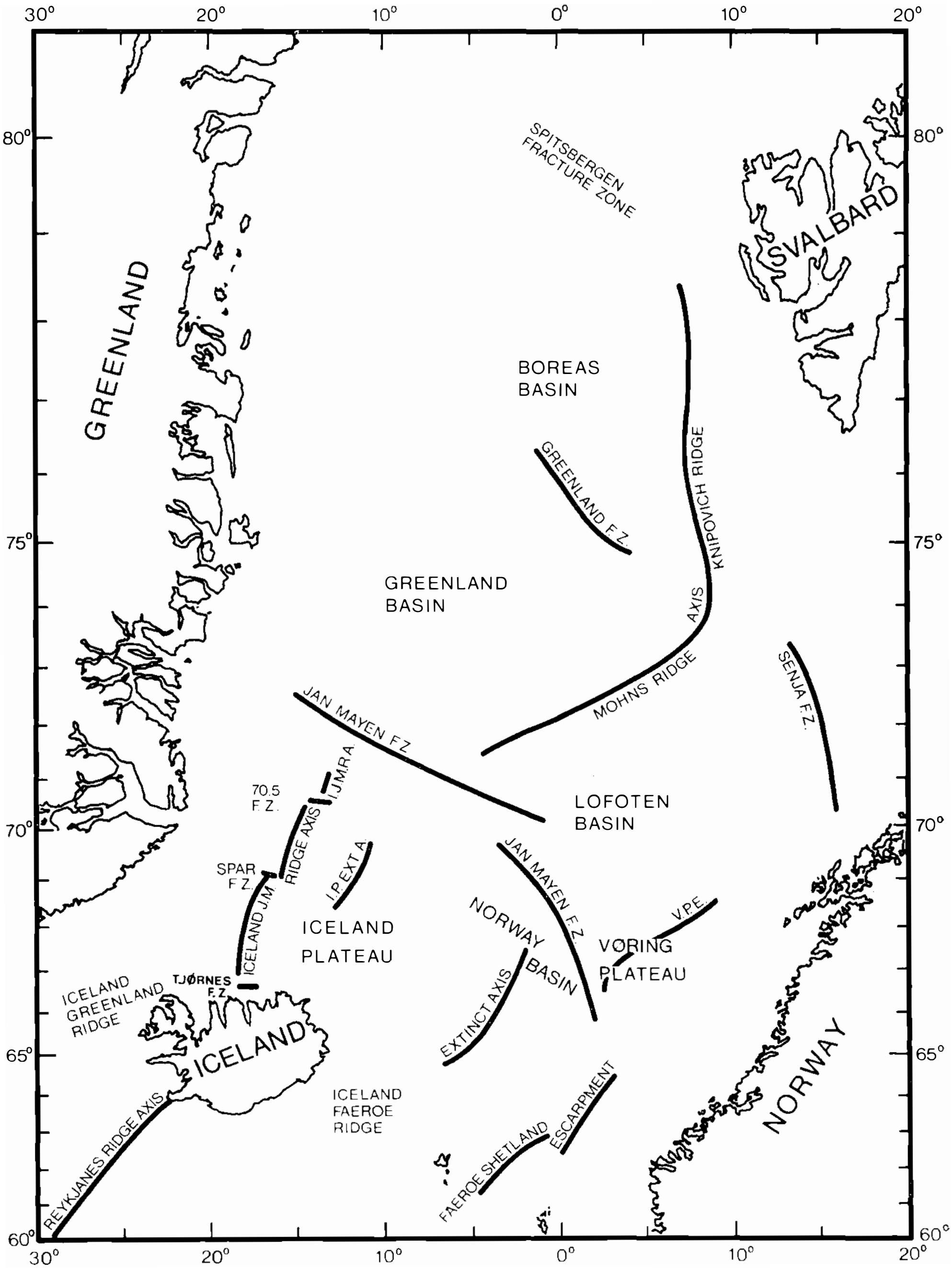

Fig. 4. *Major physiographic features of the Norwegian-Greenland Sea.*

Ridges

REYKJANES RIDGE

The Reykjanes Ridge north of 60°N is a rather wide, shallow spreading ridge that lacks an axial valley (Ulrich 1960; Talwani et al. 1971; Ruddiman 1972) although some isolated profiles very close to Iceland show some evidence of a rift valley. The ridge axis is flanked on both sides by parallel valleys and ridges which become gradually deeper away from the axis. The ridge crest is nearly devoid of sediments (Talwani et al. 1971). There is a general increase on sediment thickness toward the ridge flanks.

The Reykjanes Ridge continues into Iceland at the Reykjanes Peninsula. The transform fault that connects it to the spreading zone in Iceland is not very precisely defined. The azimuth of the Reykjanes Ridge is 35° between Iceland and 60°N.

EXTINCT AXIS IN THE NORWAY BASIN

The history of sea floor spreading has been very complex in the area lying north of Iceland and south of the Jan Mayen Fracture Zone (Talwani and Eldholm 1977). The major part of sea floor spreading probably began at a now extinct axis in the Norway Basin, although an even older spreading axis was probably once active close to Norway. The extinct axis was active from about 55 My (anomaly 23) to between 36 to 26 My (anomaly 13 and 7) and is today seen as a deep valley (more than 2100 fms) with an almost horizontal floor due to sediment infill (Fig. 5). The valley has an azimuth of c. 50° in the southern part which gradually changes into a more northerly trend (Az = 25°) in the central Norway Basin. In the southern part we find an east -west continuation of the central valley (1400 fms deep) which trends into the northern flank of the Iceland-Faeroe Ridge. Although ridges flank both sides of the valley (Fig. 5), it is the valley and not the ridges that constitutes the most important morphological feature. The bathymetric profile does not resemble those over Reykjanes Ridge and Mohns Ridge, in which the ridge is well developed and the valley is either absent or less prominent.

INTERMEDIATE SPREADING AXIS WEST OF JAN MAYEN RIDGE (ICELAND PLATEAU)

Johnson et al. (1972) first suggested the presence of an intermediate spreading area west of Jan Mayen Ridge, and Talwani and Eldholm (1977) and Grønlie et al. (this volume) later identified an intermediate spreading axis which was active from 26 My (c. anomaly 7) to shortly prior to 10 My (anomaly 5). We see no bathymetric evidence for this extinct spreading axis in the area between latitudes 68–70.50°N and longitudes 10–13°W (Fig. 6). The area containing the spreading anomalies associated with this spreading axis is bounded by two escarpments. The depth is rather uniform at about 1000 fms, in contrast to about 1200 fms just west of the continental Jan Mayen Ridge and 800 fms, or

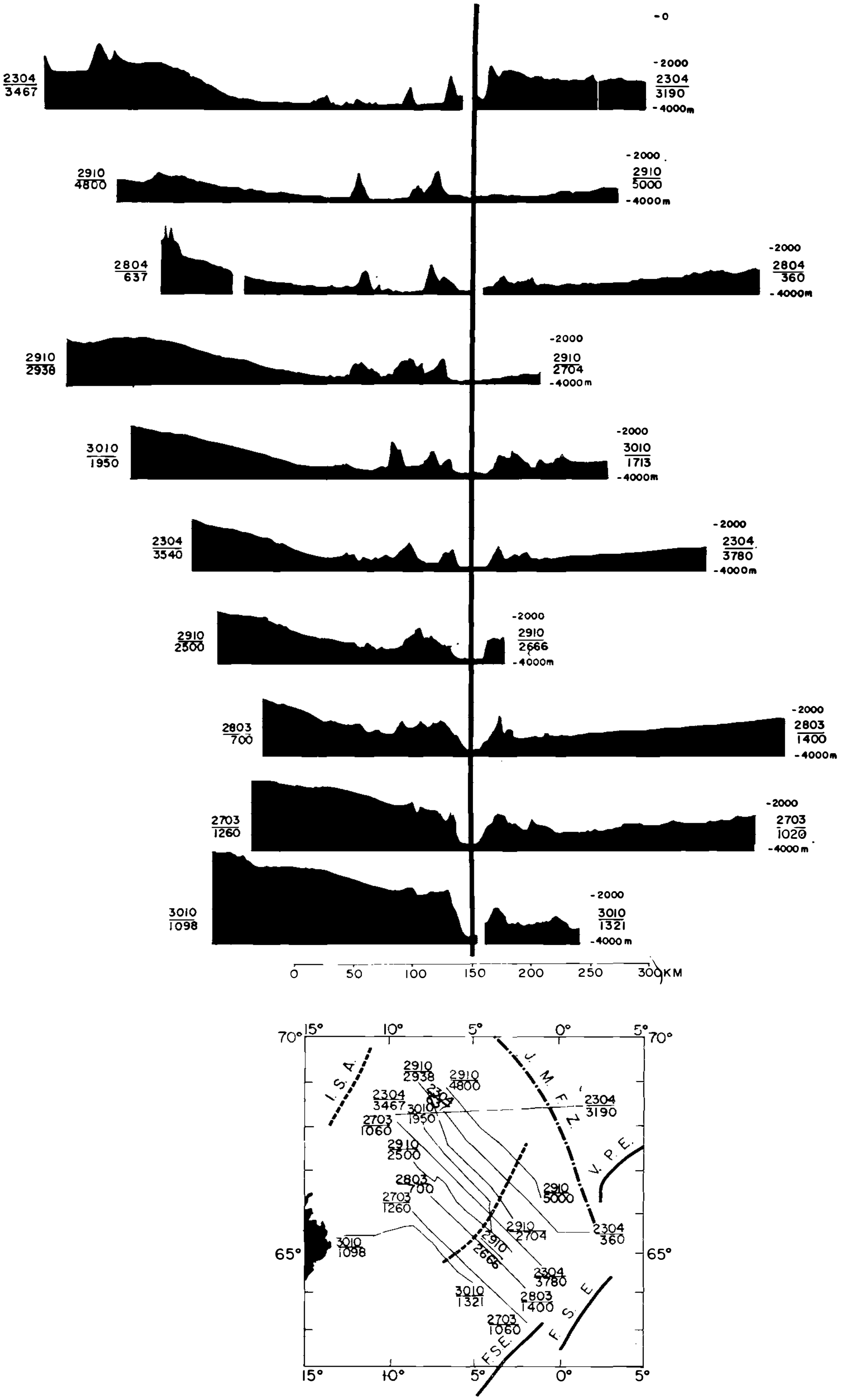

Fig. 5. *Bathymetric profiles across the extinct spreading axis in the Norway Basin. The following nomenclature is used to identify track segments. A point at 1098 nautical miles along the track of Vema Cruise 30 leg 10 is designated by 3010/1098.*

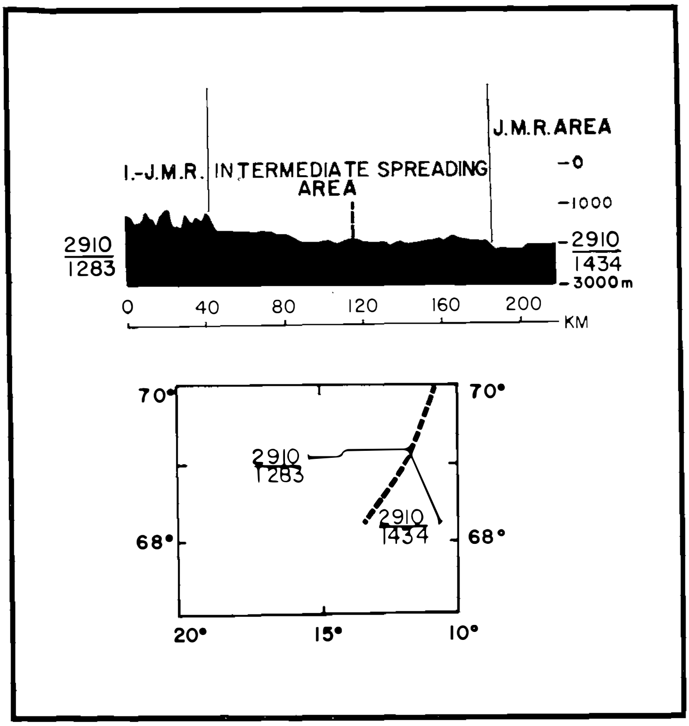

Fig. 6 *Bathymetric profile across the Iceland Plateau, showing that the intermediate spreading area is older and at a deeper level than the Iceland—Jan Mayen Ridge area to the west.*

shallower, further to the west (Grønlie et al. this volume). The entire area west of the Jan Mayen Ridge is anomalously shallow according to the depth-age relationship of Sclater et al. (1971). This anomalous shallowness also applies to the Iceland – Jan Mayen Ridge which is younger and higher than the area around the Intermediate Axis.

ICELAND-JAN MAYEN RIDGE
(C. 67°–70.5°N)

This ridge is the presently active sea floor spreading ridge between Iceland and the Jan Mayen Fracture Zone (Fig. 7). No axial valley is developed between Iceland and the Spar Fracture Zone and the crest of the axis is less than 500 fms deep. North of the Spar Fracture Zone the axis is still very shallow, but a small axial valley about 100 fms deep is evident.

MOHNS RIDGE (71°–74°N)

The ridge between 71°N and 74°N, called Mohns Ridge (Fig. 8), strikes east–northeast (azimuth c. 60°) and is probably the spreading ridge in the Norwegian-Greenland Sea that has had a history of near-continuous spreading from the time of opening until the present without any major jumps and off-

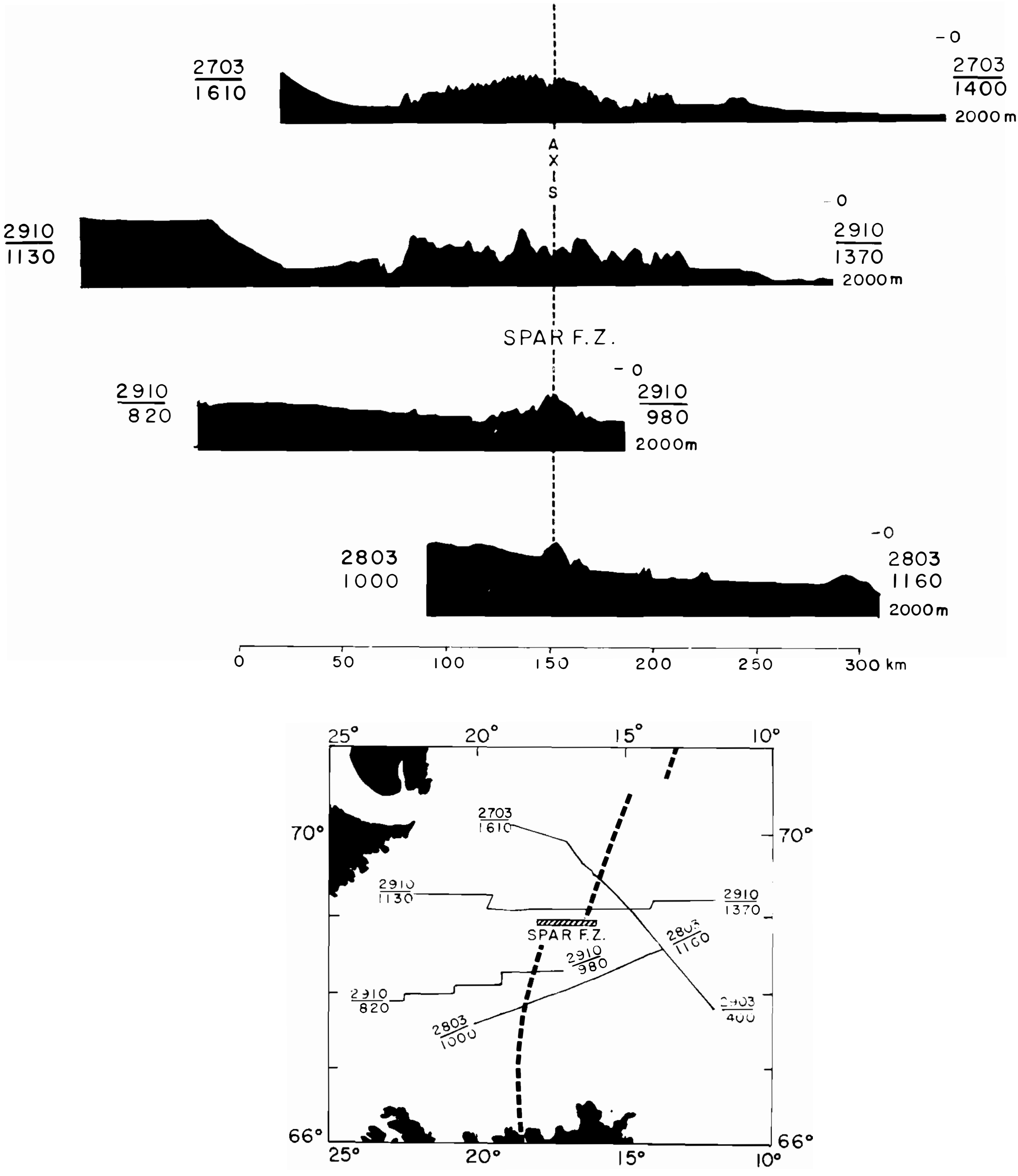

Fig. 7. *Bathymetric profiles across the presently spreading Iceland—Jan Mayen Ridge. Notice the lack of axial valley south of the Spar Fracture Zone.*

sets in the spreading axis (Talwani and Eldholm 1977). The axial valley of the Mohns ridge is continuous from a point close to the Jan Mayen Fracture Zone to its junction with the Knipovich Ridge, and the depth of the valley is 1600–1700 fms. It is not offset by any major transform fault. The ridge appears asymmetric in shape because of the different sedimentary environments that exist on the Greenland and Barents-Norwegian side of the ridge. The connection with the Knipovich Ridge to the north seems to be gradual and smooth. The axial valley bends into a more northerly azimuth at near 73°N and at 74°N the trend is approximately north–south. Neither the Greenland nor the Senja Fracture Zones have been active since 36 My (anomaly 13 time) and they are therefore not developed close to the ridge axis.

KNIPOVICH RIDGE (74°–78.5°N)

The axial valley on Mohns Ridge seems to continue without interruption into the rather deep, north–south trending axial valley of the Knipovich Ridge (Fig. 9). The valley is always deeper than 1700 fms and in places it is deeper than 1900 fms. The valley is bounded by shallow ridges, which are in some places less than 900 fms in depth. The east side of the Knipovich Ridge is buried in sediments which have been deposited from the Barents Shelf and the continental shelf off Svalbard. The west side of the Knipovich Ridge is, on the other hand, a topographic rise not untypical of other Mid-ocean ridges and contains north–south trending valleys and ridges. The ridge bathymetry can be identified as far west as c. 5°E. The Knipovich Ridge seems to end at c. 78.5°N where a series of northwest striking en echelon features, probably indicative of a complex transform fault, connect it with the Nansen Ridge in the Arctic Basin.

Fracture Zones

TJØRNES FRACTURE ZONE

A small depression is revealed by the echo-sounder when crossing this fracture zone which lies just north of Iceland (Fig. 3). The map does not show the fracture zone in part because of the large contour interval and in part because sediments nearly fill up the depression associated with the fracture zone. Negative free air gravity anomalies (Talwani and Grønlie 1976) are present in the fracture zone which extends eastwards into Iceland (Palmason 1974).

SPAR FRACTURE ZONE (69°N, 16–18°W)

Spar Fracture Zone is a 40–50 km right lateral offset of the spreading axis along an east–west transform fault (azimuth c. 90°) (Fig. 3). The fracture zone itself is characterized by an escarpment on the north side. Two elongated "holes" 1100 and 1300 fms deep, are present south of the escarpment.

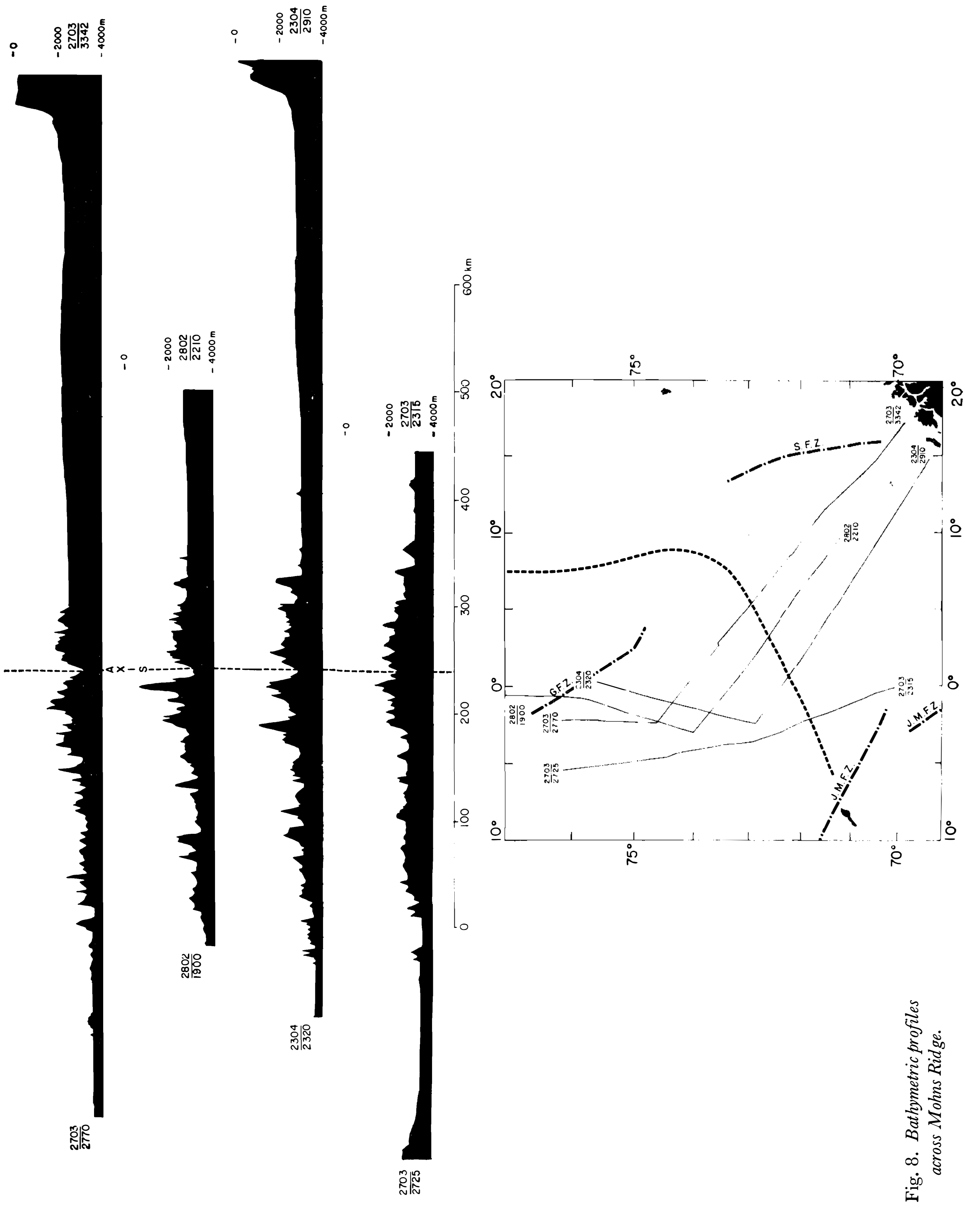

Fig. 8. *Bathymetric profiles across Mohns Ridge.*

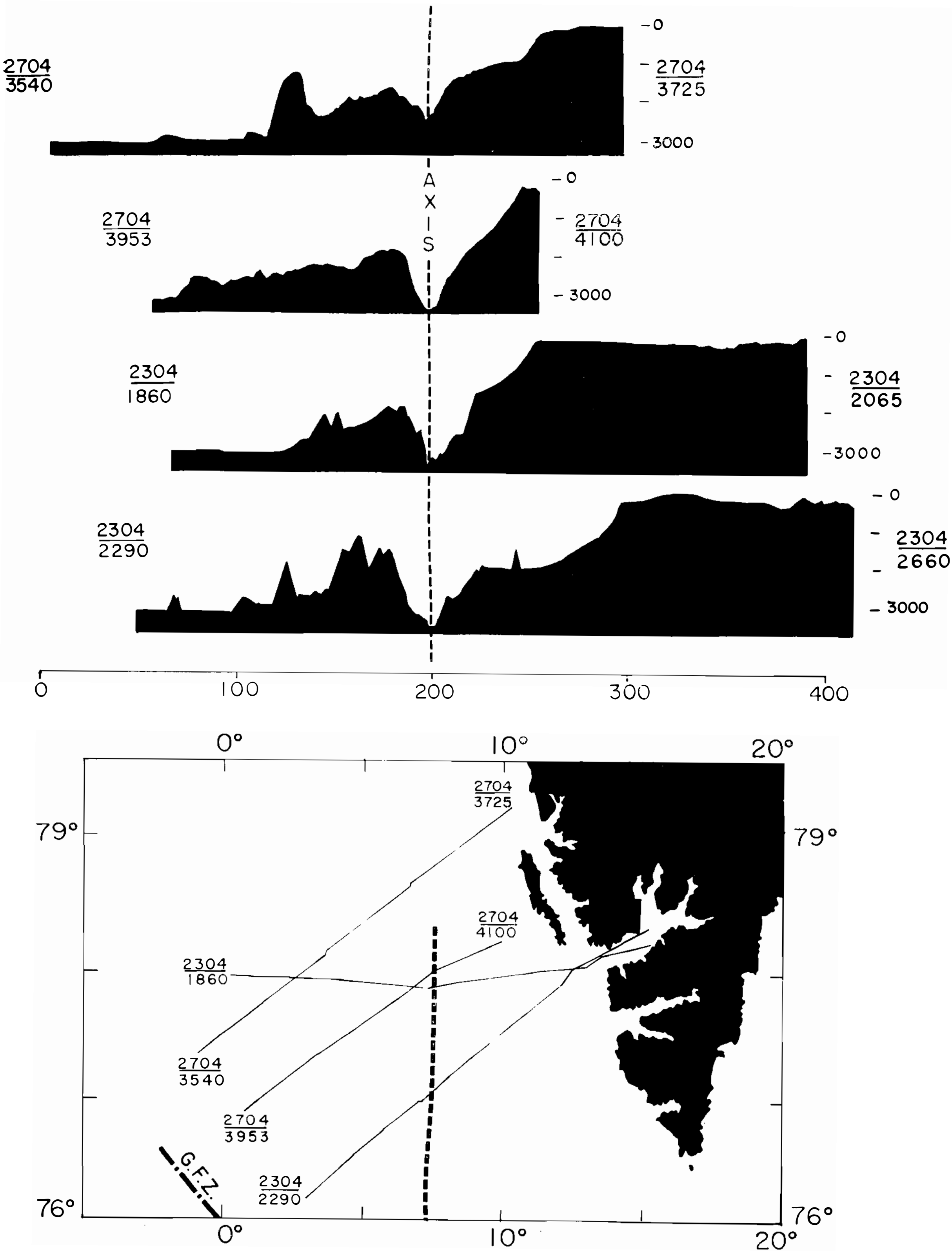

Fig. 9. *Bathymetric profiles across the Knipovich Ridge. Notice the deep axial valley.*

THE 70.5°N FRACTURE ZONE (70.5°N, 13–14°W)

The Iceland–Jan Mayen Ridge seems to be offset right laterally approximately 30 km by the 70.5°N fracture zone (Fig. 3). Magnetic anomaly 5 (Talwani and Eldholm, 1977) is not offset, however, and it is estimated that the fracture zone was created by a shift of the axis not earlier than 4 My ago. The fracture zone contains two deeps, 1100 and 1300 fms, respectively.

JAN MAYEN FRACTURE ZONE

Jan Mayen Fracture Zone consists of two segments, the western segment which probably came into existence later than 36 My (anomaly 13 time) when the axis of sea floor spreading shifted from the Norway Basin to west of Jan Mayen Ridge. The eastern segment is older than 36 My. Both segments are characterized by a zone of rugged and irregular topography about 100 km wide.

The *western* segment has an azimuth of 117° (Fig. 10). The northern side of the rugged fracture zone consists of a remarkably linear escarpment which extends from 14°W to about 2°W. This wall–like feature is only broken once, at the point where it crosses the axis of the Iceland–Jan Mayen Ridge near 72°N, 12°W. This intersection is identified by a "hole" more than 2000 fms deep. The island of Jan Mayen, located on the southern margin of the fracture zone, was probably built by the same processes which created the wide zone of seamounts and raised topography that characterize the area immediately south of the escarpment.

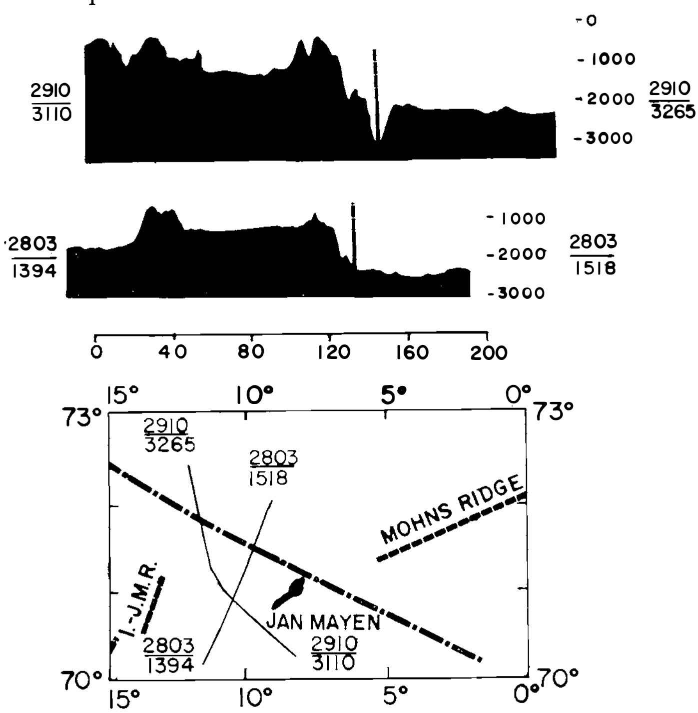

Fig. 10. *Bathymetric profiles across the western Jan Mayen Fracture Zone (Western segment).*

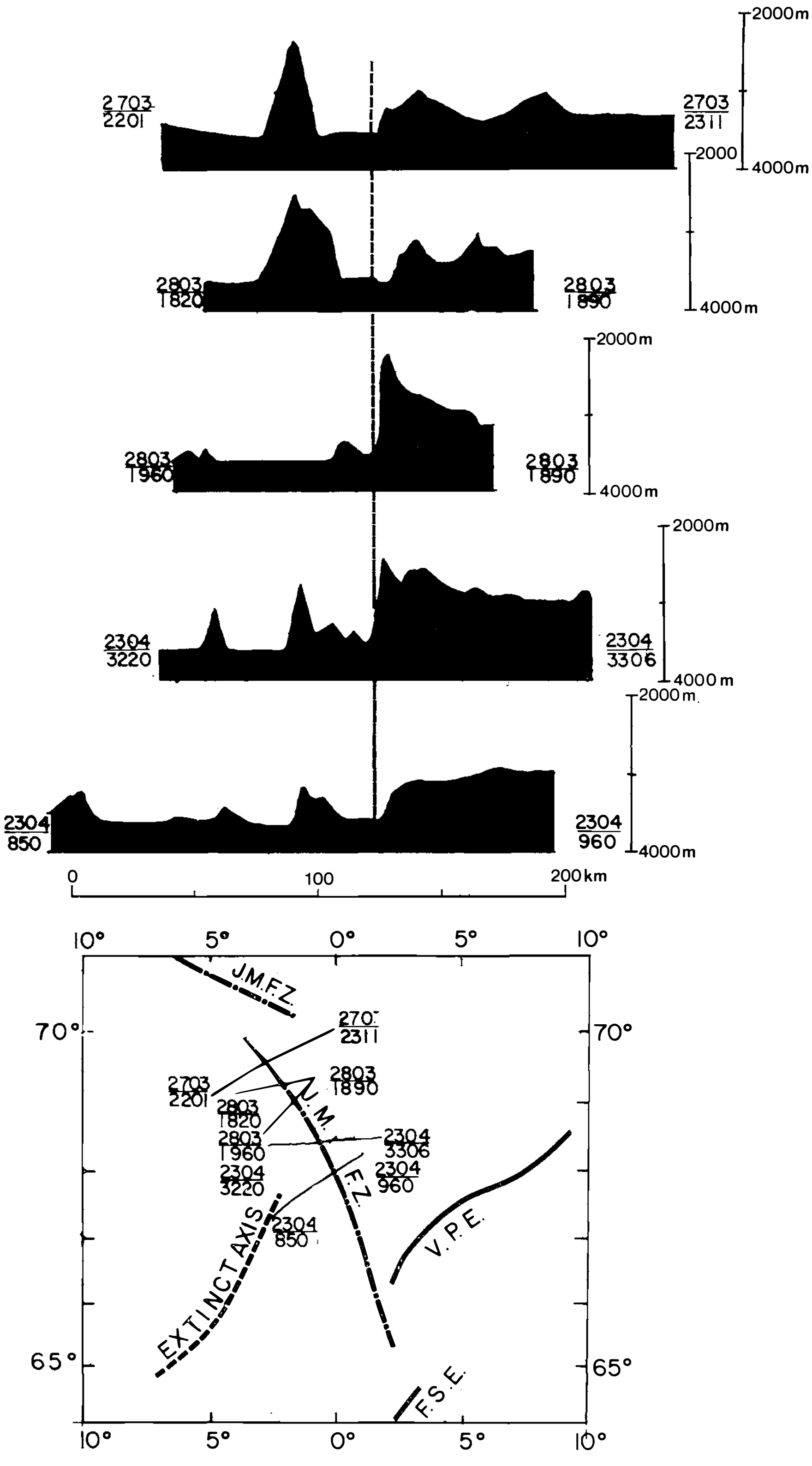

Fig. 11. *Bathymetric profiles across the Jan Mayen Fracture Zone (Eastern segment).*

The *eastern* segment of the Jan Mayen Fracture Zone (Fig. 11) is characterized by the same rugged topographic zone, but the azimuth is 150° in the east as opposed to 130° to the west. The topographic features are also slightly gentler and not as regular as they are along the western segments. Two, (possibly three), parallel and roughly continuous ridges together with two parallel valleys seem to make up the western segment of the fracture zone. The southern (middle) ridge can be traced as far west as 5°W; thus there is an overlap of about 100 km between the eastern and western segment of the fracture zones. The southern end of Jan Mayen Fracture Zone coincides with the south-western margin of the Vøring Plateau. It is not clear how far south the fracture zone extends because the relief is buried under sediment cover. It certainly extends to 67.5°N and 1°E, and possibly as far south as 66°N.

GREENLAND FRACTURE ZONE (75°–77°N, 2.5°E–3°W)

The Greenland Fracture Zone is a very prominent continuous feature which runs from 75°N to 77°N and from about 2°E to 3°W and has an azimuth of 148° (Fig. 12). The ridge has a very steep southwest side and a more gently sloping northeast side. A difference in sea floor elevation is observed on either side probably associated with difference in the age of the oceanic crust on either side of the fracture zone (Talwani and Eldholm 1977). The difference in depth on either side may also be in part due to differences in the sediment load. According to Talwani and Eldholm (1977) the Greenland Fracture Zone has not been active since 36 MyBP (anomaly 13) when the shearing of Greenland with respect to Svalbard ended and the opening of the Greenland Sea began. We notice that the trends of the eastern part of Jan Mayen Fracture Zone and the Greenland Fracture Zone are similar, which lends support to the thesis that both were active during the same time interval.

HOVGAARD FRACTURE ZONE

The Hovgaard Fracture Zone is characterized by a ridge with an azimuth of 140°. The ridge extends south–east to 3°E. It has been difficult to trace its north–west continuation because of an almost continuous cover of sea ice. The Hovgaard Fracture Zone has almost the same strike as the Greenland and Jan Mayen (eastern segment) Fracture Zones, and a similar origin for all these fracture zones is likely.

Basins of the Norwegian-Greenland Sea

NORWAY BASIN

The Norway Basin is bounded in the south by the Iceland–Faeroe Ridge, to the north by the eastern segment of the Jan Mayen Fracture Zone, to the east by the Vøring Plateau and the continental rise of Norway, and to the west by the rise to the Jan Mayen Ridge.

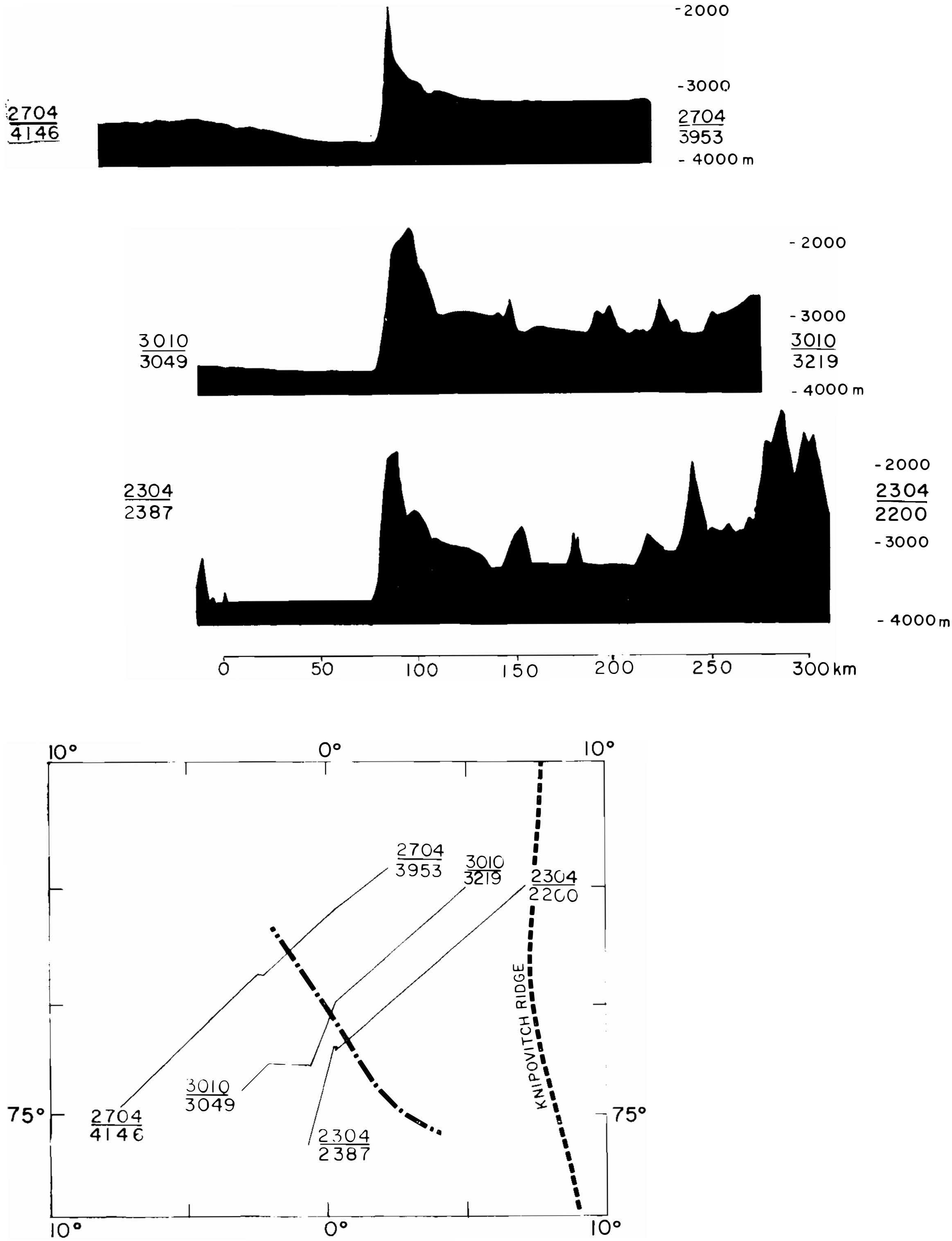

Fig. 12. *Bathymetric profiles across the Greenland Fracture Zone. Notice the step in elevation between the two sides of the fracture zone.*

The central portion of the basin is 1800–2000 fms deep and is dominated by the extinct spreading axis and the topography associated with this. A number of seamounts are present in the basin, especially on its north-west flank.

LOFOTEN BASIN

The Lofoten Basin lies north of the Vøring Plateau and the eastern segment of the Jan Mayen Fracture Zone. It is bounded on the east by the continental rise of Norway, on the northwest by Mohns Ridge, and on the northeast by the continental rise of the Barents shelf. The depth of the central basin is around 1700 fms, but a gradual shallowing is seen to the northeast because of thick accumulation of sediments at the foot of the Barents Shelf. A few seamounts are present on the central basin floor, usually rising less than 300 fms from the sea floor.

GREENLAND BASIN

The Greenland Basin is situated north of the western segment of Jan Mayen Fracture Zone between the continental rise off Greenland and the Mohns Ridge, and is bordered to the north by the Greenland Fracture Zone. The central basin is 1900–2000 fms deep. A few seamounts are found in the north-east corner close to Greenland Fracture Zone. In the south-western part the *Vesteris bank* (69.5°N, 9.5°W) rises from the 1700 fms deep seafloor to less than 100 fms.

BOREAS BASIN

The Boreas Basin is located between the Greenland Fracture Zone and the Hovgaard Fracture Zone. The western and eastern limits are the Greenland continental rise and the Knipovich Ridge respectively. The entire basin is at water-depth of 1600–1700 fms, slightly shallower than the Greenland Basin. A few seamounts are present along the eastern border of the basin.

Other Features

The *Iceland–Faeroe Ridge* is a broad, shallow ridge which runs between the Faeroes and Iceland. The ridge is flat at the top with a width of about 100 km. Typical ridge depth is about 300 fms although it is slightly less than 200 fms in a few places. The contours in this area are based on the detailed map by Fleischer et al. (1974).

The *Iceland–Greenland Ridge* runs between Iceland and the Greenland shelf and is similar in nature to the Iceland–Faeroe Ridge although the sediment thickness is somewhat greater. The ridge depth is around 300 fms at its deepest parts.

The *Jan Mayen Ridge* runs south–southwest from the Jan Mayen Island, and is thought to be continental in origin. The ridge depth is less than 500 fms as far south as 68.5°N. The ridge appears to be interrupted by a major northeast depression at c. 68°N. Morphologically the ridge forms the western boundary of Norway Basin. However, Talwani and Eldholm (1977) have suggested that the structural (continental) Jan Mayen Ridge continues to the south-west and that the elevated area immediately west of the southern part of Norway Basin lies in oceanic crust. Drilling results (Talwani and Udintsev 1976) appear to substantiate this idea.

The *Vøring Plateau* is situated off the continental shelf of Norway between latitudes 65.5°N and 68.5°N. The depth of the plateau is around 700–800 fms. The south-western part of the plateau joins the zone of rough topography which is associated with the Jan Mayen Fracture Zone. A buried escarpment, the Vøring Plateau escarpment (Talwani and Eldholm 1972), divides the plateau into an oceanic outer part and a sediment filled continental inner part. The initial rifting of Norway and Greenland probably took place along this escarpment.

Sediment fan off the Barents Sea Shelf. A cone shaped sedimentary fan is deposited in the Lofoten Basin at the foot of the Bjørnøyrenna, and more than 9 km of sediments (Houtz and Windisch 1977) have been deposited. This delta-shaped fan extends as far south as 70°N and as far north as 74°N.

AREAS OF ANOMALOUS ELEVATION

The depth-age relationship that Sclater et al. (1971) derived for most of the world's oceans does not strictly apply to the Norwegian–Greenland Seas. Cochran and Talwani (1977; 1978) have shown that the area close to Iceland has residual depth anomalies ($5 \times 5°$ averages) of more than 2500 m. The depth anomalies trend almost perpendicular to the ridge crest and decrease to nearly 500 m in the northern parts of the Lofoten and Greenland Basins.

Concluding Remarks

1. Increased bathymetric data obtained with satellite navigation and improved understanding of ocean floor spreading processes have made it possible to construct a new bathymetric chart of the Norwegian–Greenland Sea which we believe to be a considerable improvement over previously published maps.
2. The ice conditions made it difficult to collect data close to Greenland and in the north-western part of the Greenland Sea. Consequently, the map is less accurate in these areas. The track chart shows the extent of data coverage.
3. The map clearly defines the spreading ridges and fracture zones in the Norwegian–Greenland Sea. In particular the bathymetric evidence for the extinct axis in the Norway Basin is quite striking. The geologic evolution of the Norwegian–Greenland Seas is reflected in the morphology of the sea floor.

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Jan Mayen Ridge and Iceland Plateau: origin and evolution*

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Abstract

Jan Mayen Ridge is believed to be a continental fragment derived from the east Greenland continental margin; this is indicated by the sediment thickness, seismic velocities, magnetic and gravity data. The ridge broke off from the continent at anomaly 6B time, when a new oceanic spreading axis was initiated. This axis was active from anomaly 6B time (22.7 MyBP) to anomaly 5D (17.3 MyBP) time but now lies in the Iceland Plateau as an extinct axis. Another ridge jump occurred and spreading began on the Iceland—Jan Mayen axis just prior to anomaly 5 (10 MyBP) time.

There are two segments of the Jan Mayen Fracture Zone and the northern was formed when a small spreading ridge segment at the southern end of Mohns ridge jumped westward and was active from anomaly 13 time to anomaly 7 time. This jump preceded the jump of the ridge axis from the Norway Basin to the Iceland Plateau just after anomaly 7 time.

Regional setting and history

The tectonic evolution and history of the Norwegian–Greenland Sea have been discussed extensively in the literature. Johnson and Heezen (1967) were the first to suggest that the Norwegian–Greenland Sea had been created by sea floor spreading and later authors have all assumed an evolution in terms of a plate tectonic framework. Talwani and Eldholm (1977) have recently presented a reconstruction of the evolution, and their study has largely been verified by the drillings of the Deep Sea Drilling Project (DSDP) (Talwani, Udintsev et al. 1976). The most difficult area to reconstruct in terms of ocean floor spreading has been the area north of Iceland and the Iceland-Faeroe Ridge and south of the Jan Mayen Fracture Zone (Fig. 1). The area includes the oceanic Norway Basin, the Jan Mayen Ridge which is believed to be a continental fragment (Johnson and Heezen 1976), the Iceland Plateau and the presently spreading Iceland–Jan Mayen Ridge.

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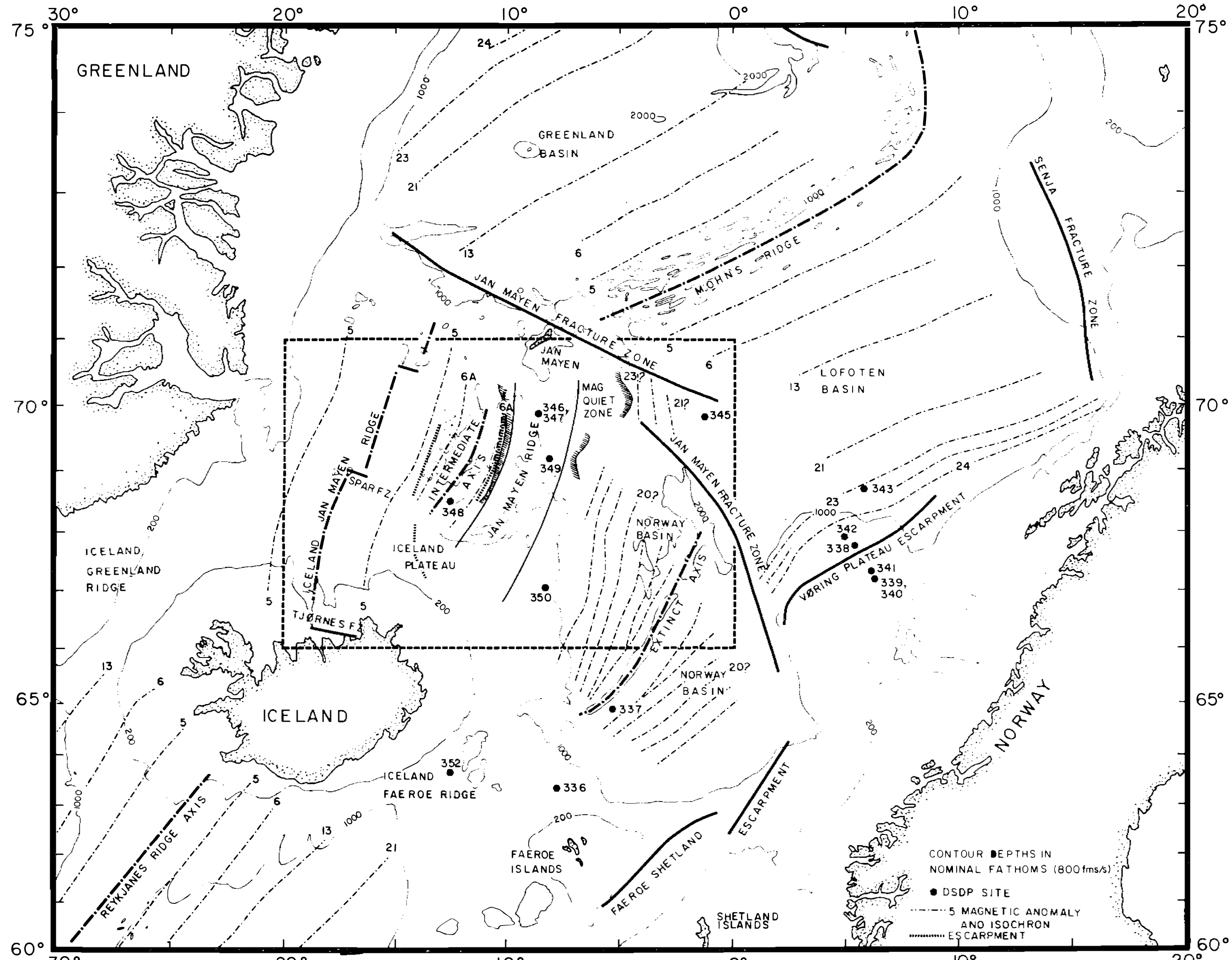

Fig. 1 *Map showing studied area (stipled) in relation to surrounding areas. Important tectonic features, magnetic lineations and bathymetry (200, 1000, 2000 fms) are shown. Inside the studied area we show location of magnetic quiet zones, assumed boundary of the continental Jan Mayen Ridge, topographic escarpments. Positions of DSDP drill sites are also shown.*

Sea floor spreading occurred in the Norway Basin along the extinct axis until approximately anomaly 7 time (Talwani and Eldholm 1977). At about this time the spreading axis jumped westward to the Iceland Plateau. During this process the Jan Mayen Ridge separated from Greenland. Sea floor spreading prevailed on the Iceland Plateau until about anomaly 5 time when another westward jump occurred and spreading began along the now active Iceland–Jan Mayen Ridge.

We present in this study a detailed analysis of the formation and geological history of the Jan Mayen Ridge and Iceland Plateau area and show its relation to surrounding geological events.

We have divided the area into eight different regions (Fig. 2). These eight regions will be shown on all the maps that we present, and will help clarify the text. Area 1 contains the main block of the Jan Mayen Ridge; area 2 is also believed to be continental, but is at a greater depth than area 1. Area 3, morphologically a part of the Jan Mayen Ridge, is thought to be oceanic in origin by Talwani and Eldholm (1977). Areas 4 and 5 are oceanic and were created by sea floor spreading. The Iceland–Jan Mayen spreading ridge, area 5, has been active from a time just prior to anomaly 5 time to the present, while the spreading axis lay on the Iceland Plateau, area 4, before that. Area 6 is the shelf off Iceland; area 7 is the zone of rough topography close to the Jan Mayen Fracture Zone, and area 8 contains the eastern slope of the topographic Jan Mayen Ridge. Although the term Iceland Plateau has generally been used to describe a larger area, we use it in the same manner as Talwani and Eldholm (1977) who used it to describe the area where the intermediate spreading axis was active between the Jan Mayen Ridge and the Iceland–Jan Mayen Ridge.

Bathymetric regions

The bathymetric map (Fig. 3) is part of a bathymetric map of the Norwegian–Greenland Sea (Grønlie and Talwani 1978). The map is constructed using soundings from Lamont–Doherty Geological Observatory (L–DGO), US Naval Oceanographic Offices, Deutsche Hydrographisches Institut (DHI), Centre National pour l'Exploitation des Oceans (CNEXO), Naval Research Laboratories and Shirshov Institute of Oceanology at a contour interval of 100 uncorrected fathoms (sound velocity 800 fms/s). Cruise tracks are shown as dotted lines. Satellite navigation was employed on all of these cruises.

The continental Jan Mayen Ridge has earlier (Johnson and Heezen 1967) been regarded as comprising the areas we number 1, 2, and 3. This was done principally on the basis of morphology. Talwani and Eldholm (1977) argued on basis of geophysical evidence that the southeast flank of the morphological Jan Mayen Ridge (3) was oceanic in origin and the results from DSDP site 350 support this concept.

The northern block (1) including Jan Mayen Island, consists of a single major ridge which can be followed southward without any interruption to 68.2°N, 9.5°W and then with perhaps a minor interruption to 68°N, 11°W.

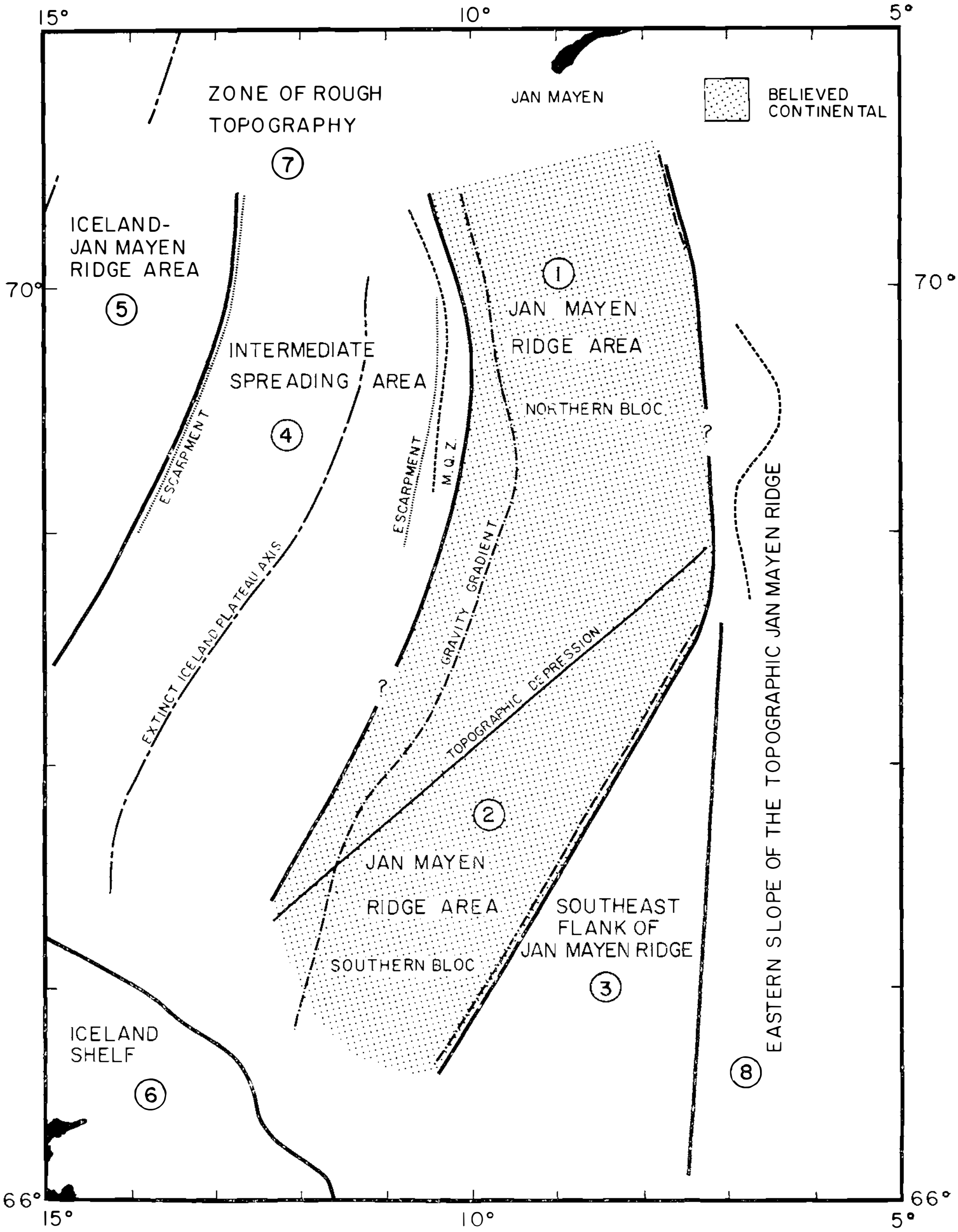

Fig. 2. *Map showing the different morphological and geological areas of the investigated area. The area which we believe is continental is dotted. The boundaries and large numbers in circles (1–8) are used on the maps shown in Figs. 3, 6, 7, and 9 for identification purposes. Also shown on the map are the two escarpments (narrow stripes), the magnetic quiet zone, and the gravity gradient (dashed-dotted lines) described in the text.*

A bend in the ridge is seen at 69.5°N. This northern block is separated by a major southwest–northeast topographic depression from the southern block (2), which appears to consists of several topographic ridges (mapped in detail by Talwani and Eldholm (1977)) that are seen as far south as 67.5°N (Fig. 4).

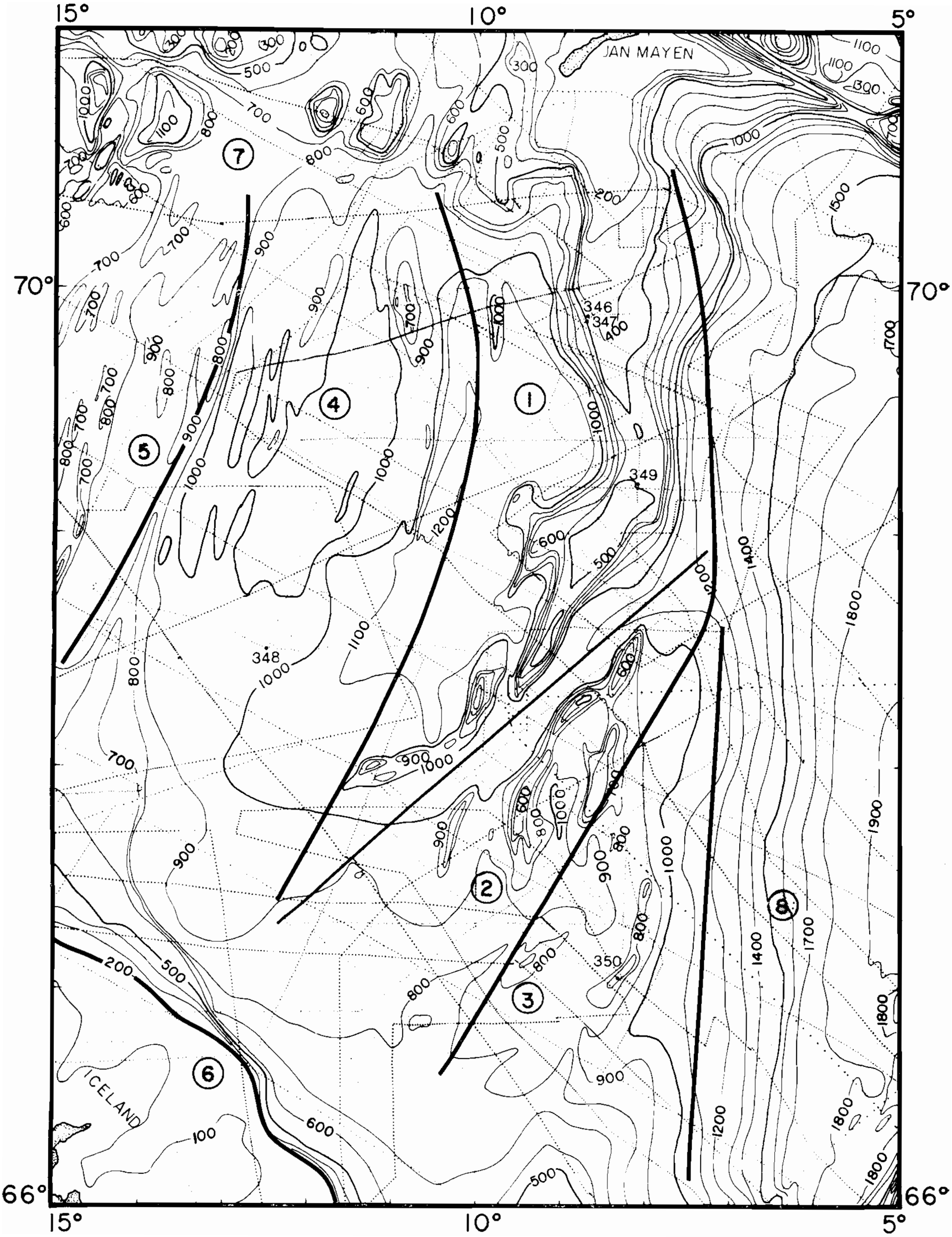

Fig. 3. *Bathymetric map of the area between Iceland and Jan Mayen Island. Contour interval 100 uncorrected fathoms (sound velocity 800 fms/s). Dotted lines indicate ship's tracks where satellite navigation was used.*

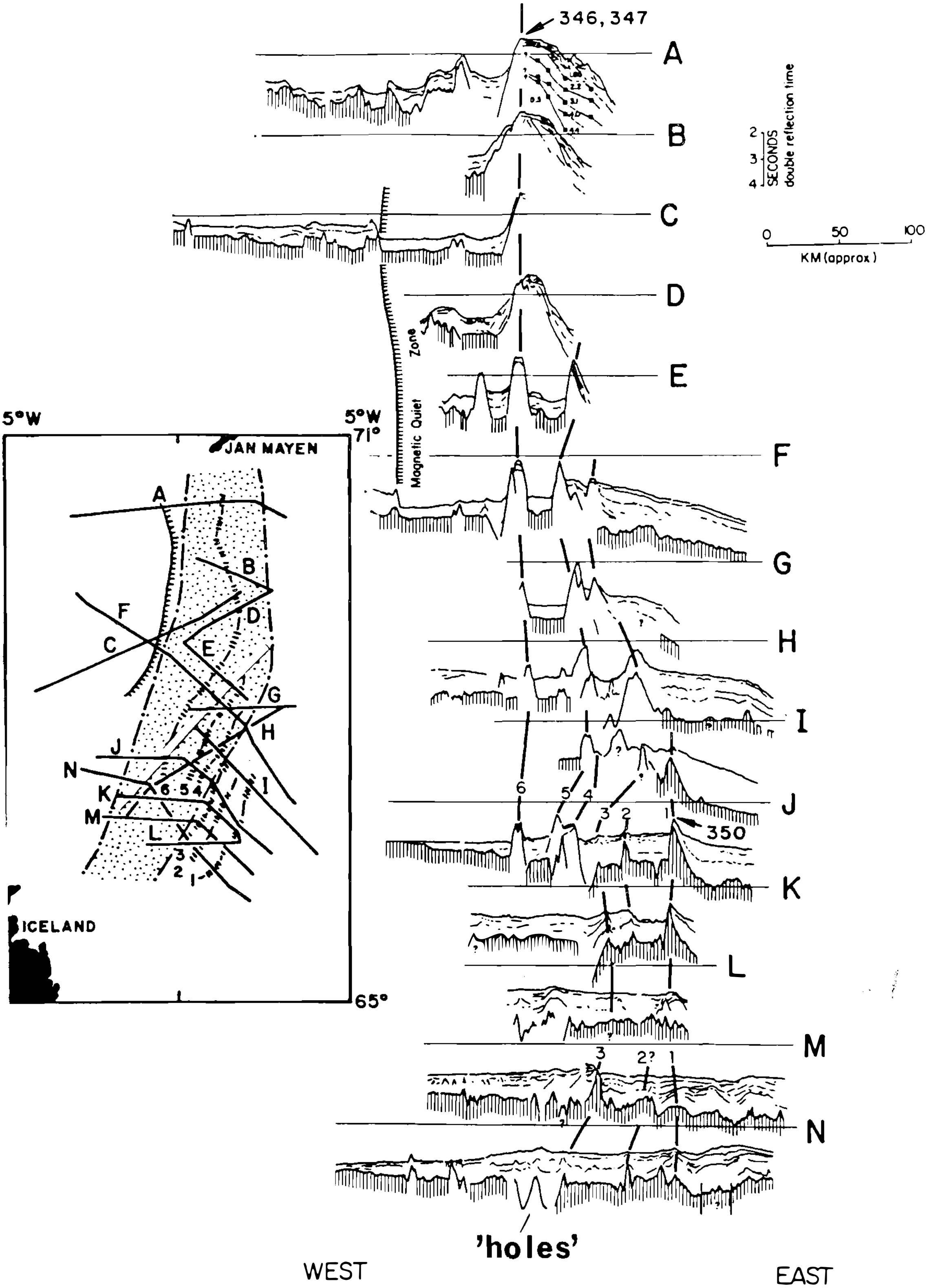

Fig. 4. *Tracing of seismic reflection profile records across the Jan Mayen Ridge (after Talwani 1977). Note the "holes" in the opaque layer.*

The area to the west of the Jan Mayen Ridge area can be divided into three depth regions and a zone of shallow seamounts in the north. The deepest area (lying partly in area 1 and partly in area 4) is found immediately to the west of the Jan Mayen Ridge (67°N to 70°N) and as far as 11°W, where the depth is up to 1200 fms. An escarpment (69–70°N, c. 11°W) separates the deeper area from a more shallow area further to the west which is the area where the extinct axis of the Iceland Plateau (4) was spreading. Further to the west, bounded by another escarpment is an even more shallow (less than 800 fms) area which is the eastern flank of the presently active Iceland–Jan Mayen Ridge (5).

The Jan Mayen Fracture Zone (western segment) is seen in the northeast corner of the map as a linear feature with strong topographic relief. The zone of rough topography (7) north of 70.5°N (and south of the Jan Mayen Fracture Zone) is rather shallow, with depths mostly less than 500 fms.

The bathymetry indicates the following:

A topographic depression separates the Jan Mayen Ridge area into two parts (Figs. 2 and 3). The northern block consists of a simple ridge and continues to 68°N and 11°W. The southern block divides into topographic ridges which can be traced as far south as 67.5°N. Area 3 which lies east of area 2, also consists of a ridge but with perhaps a more easterly strike. Within area 4 the depth is nearly uniform but the depth is larger than that of the presently spreading Iceland–Jan Mayen Ridge. Escarpments are present at the boundaries between areas 1 and 4 and 4 and 5.

Origin of the Bathymetric Features

I. JAN MAYEN RIDGE – A CONTINENTAL FRAGMENT

A. Seismic Results

Opaque acoustic layer

Eldholm and Windisch (1974) described and discussed the appearance of an opaque acoustic layer which is present over most of the area under discussion. Only in the Jan Mayen Ridge areas (1 and 2) is the reflector partly interrupted. It was suggested by Talwani and Eldholm (1977) that these "holes" (or windows) in the opaque layer might indicate the presence of an underlying continental crust. Figs. 4 and 5 show the opaque layer and "holes" in the ridge area. (For location of profiles in Fig. 5, see Fig. 6.) The opaque layer has been drilled by DSDP (sites 348 and 350) and has been shown to consist of basalt (Talwani, Udintsev et al. 1976).

Seismic refraction velocities

Talwani and Eldholm (1977) present a sonobuoy refraction section across the northern Jan Mayen Ridge (Fig. 4, profile A). The section shows eastward dipping layers with increasing velocities of 1.8, 2.2, 3.1, 4.0, 4.4, and 5.5 km/s. The velocities in the lower part of the section are rather high for Tertiary rocks,

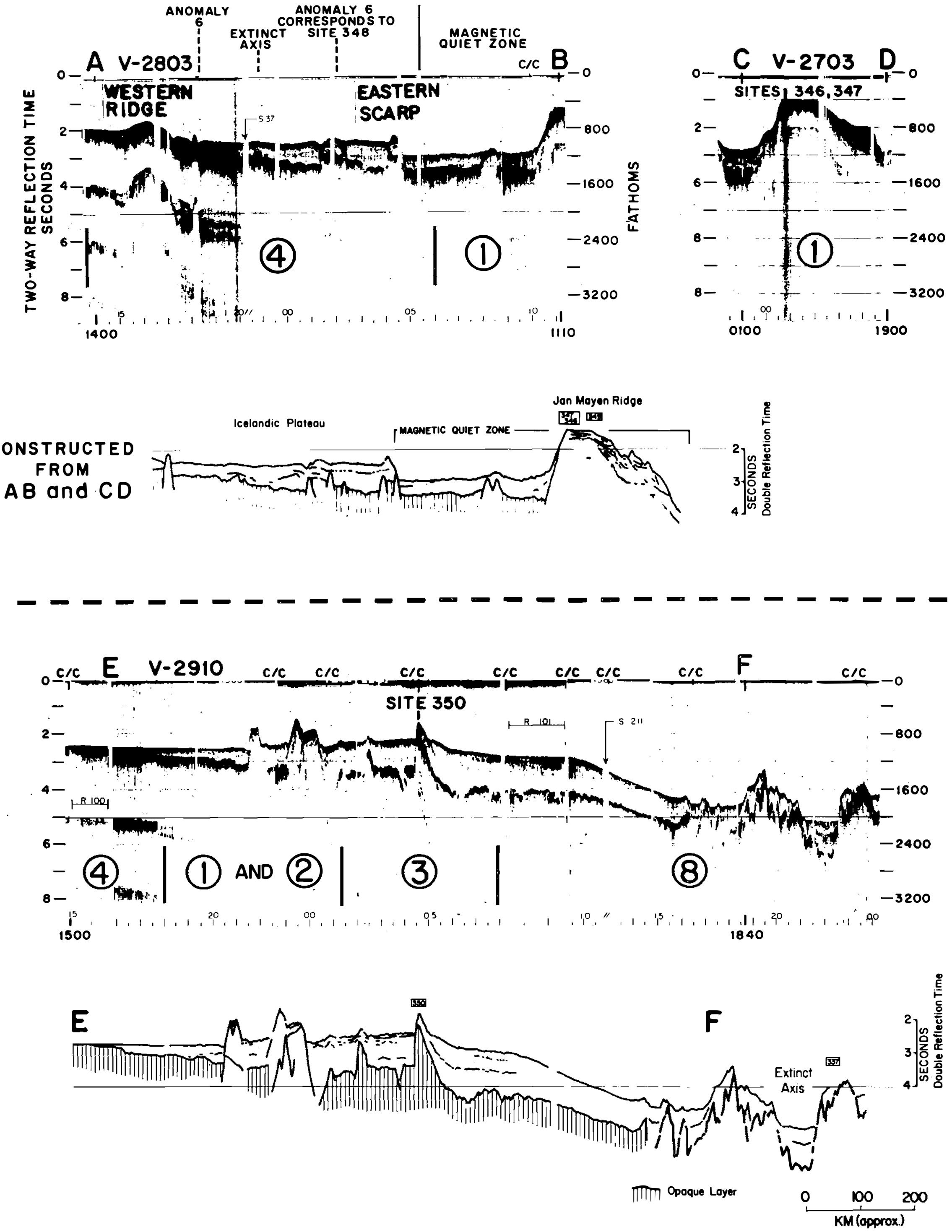

Fig. 5. *Seismic reflection records along profiles AB, CD, and EF (after Talwani and Udintsev 1976). These profiles are located in Fig. 6.*

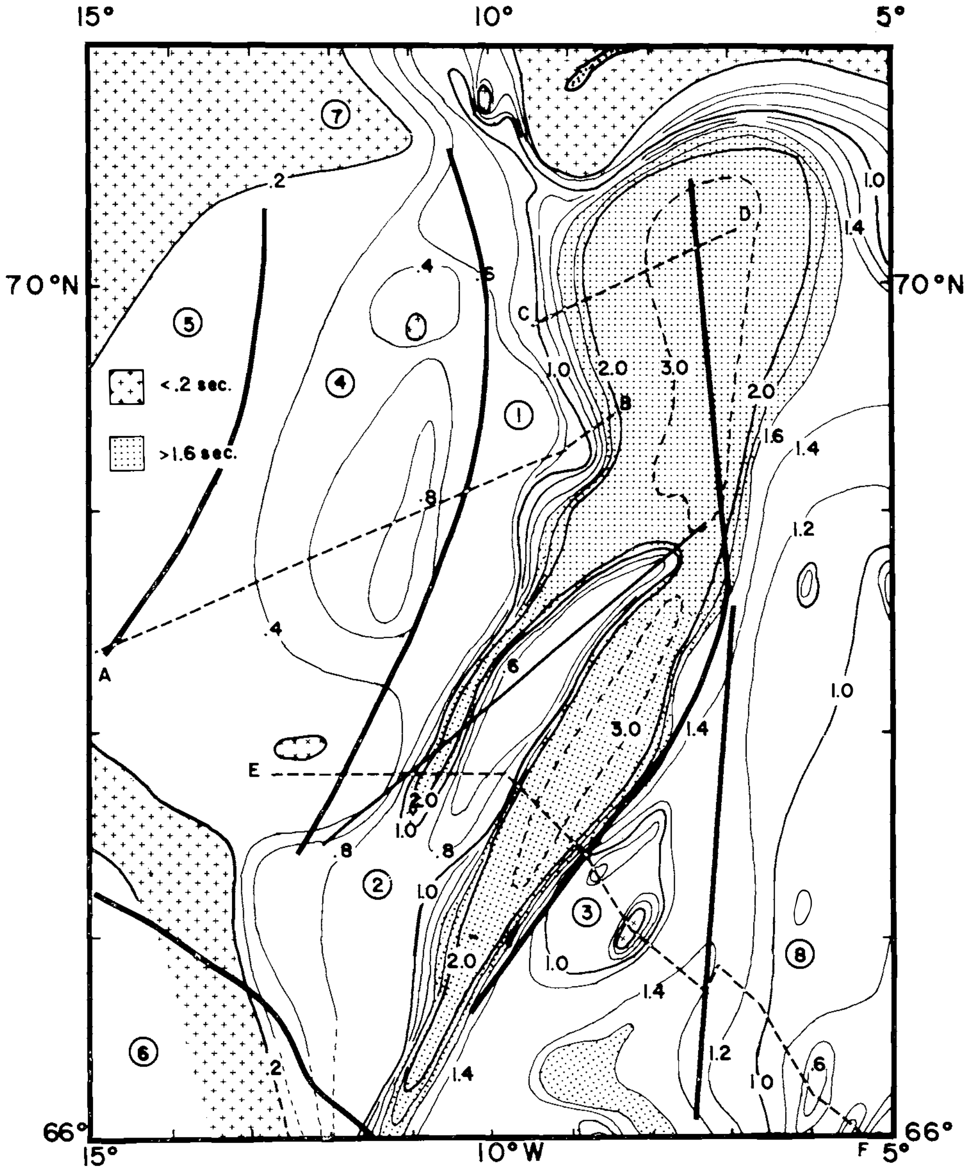

Fig. 6. *Isopach map of total sediment thickness. Contour interval 0.2 s total reflection time. Thicker lines represent 0.2, 1.0, 2.0, and 3.0 s contours.*

and Talwani and Eldholm (1977) by making a comparison with similar velocities which are found on the continental shelf off Norway, argue that these velocities are representative of old Mesozoic rocks.

Three DSDP sites (346, 347, and 349) were drilled on the ridge (Figs. 1 and 4) proper, close to the western flank where the sediment thickness was assumed minimal and where it was believed that basement might be closest to the surface. Sediments of Eocene age were encountered before drilling was stopped in sandy mudstones (Talwani, Udintsev et al. 1976). The drill string penetrated the 1.8 km/s reflector only, which would appear to indicate that metamorphic basement lies at considerable depth under the ridge.

Sediment isopach map (Fig. 6)

A sediment isopach map is presented in Fig. 6.

This map is based on data collected on VEMA cruises 23, 27, 28, 29, and 30. In areas 3, 5, 7, and 8 it is quite similar to the map by Eldholm and Windisch (1974), but differs significantly in the Jan Mayen Ridge areas (1 and 2) because of the new data (cruises 29 and 30) and the DSDP results. The sediment cover is more than 1–2 seconds two way reflection time over most of the Jan Mayen Ridge area, and only in the topographic depression is the cover less than 0.6 seconds.

The thickness of the sediment cover in the areas formed by sea floor spreading (4 and 5) is rather small, with less sediments in areas of young crust. Also the areas adjacent to Iceland and Jan Mayen Island have basement close to sea bottom.

We agree with the suggestions made by earlier authors that the rather large sediment thickness in the Jan Mayen Ridge area, the high refraction velocities, the holes in the opaque reflector, and the drilling results strongly suggest a continental origin, and that these sediments possibly were deposited on the Jan Mayen Ridge when it formed a part of the continental margin off Greenland.

B. Gravimetric Results

The free air gravity map (Fig. 7) is based on the map of the Norwegian-Greenland Sea at a contour interval of 25 mgals (Talwani and Grønlie 1976). Because of the large amount of data in this area we have been able to contour the area shown in Fig. 7 at a 10 mgal contour interval. In addition to the L-DGO data (V23, 27, 28, 29, and 30) we have used published data from Fleischer (1971) and unpublished data from CNEXO. The track intersections show agreement in gravity values generally better than 5 mgals and we believe the map has an accuracy of at least 5 mgals.

Free air gravity anomalies are strongly dependent upon topography and a comparison with the bathymetric map shows this quite clearly. The gravity high are associated with the topographic ridges both on the Jan Mayen Ridge proper and its possible continuation (2). Also in the other areas of the map, especially on the southern flank of the Jan Mayen Ridge (3), and in the areas generated by sea floor spreading (4 and 5) as well as in the area to the north (7) are gravity highs associated with topography.

Fig. 8 shows three gravity profiles across the Jan Mayen Ridge area (for location of profiles, see Fig. 7) with corresponding models and their computed gravity effect (Talwani et al. 1959). The models are based on the seismic sections in Fig. 4. An Airy type isostatic compensation (Talwani and Eldholm 1972) was assumed, although it is not shown in Fig. 8.

The observed gravity follows mostly the bottom and basement topography. We have assumed a rather thick sedimentary section (density 2.4 g/cm^3) under

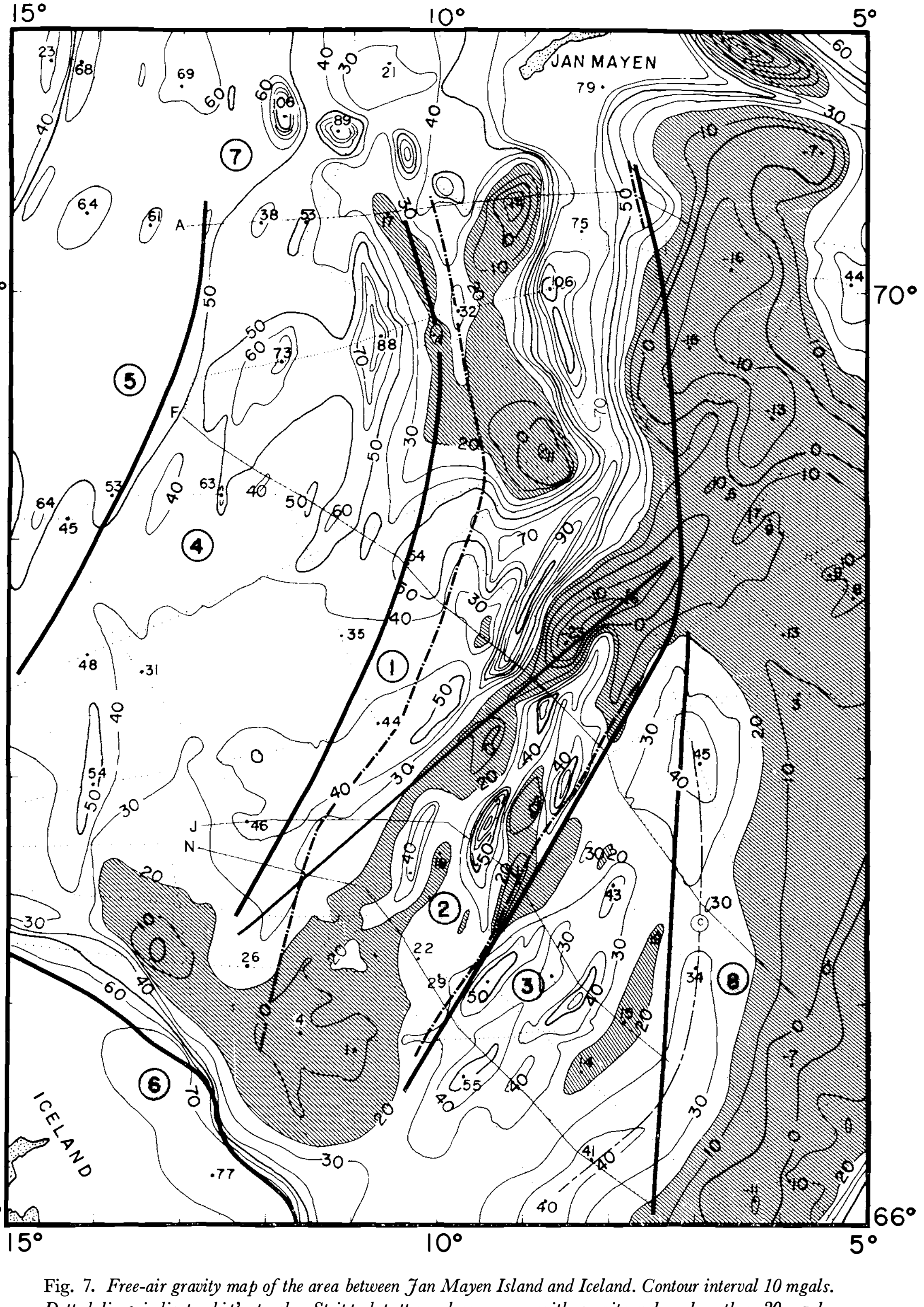

Fig. 7. *Free-air gravity map of the area between Jan Mayen Island and Iceland. Contour interval 10 mgals. Dotted lines indicate ship's tracks. Stripped pattern shows areas with gravity values less than 20 mgals. Solid lines and capital letters show position of the profiles in Fig. 8. Heavy dashed-dotted line indicates the gravity gradient discussed in the text. C is gravity high mapped by Talwani and Eldholm (1977).*

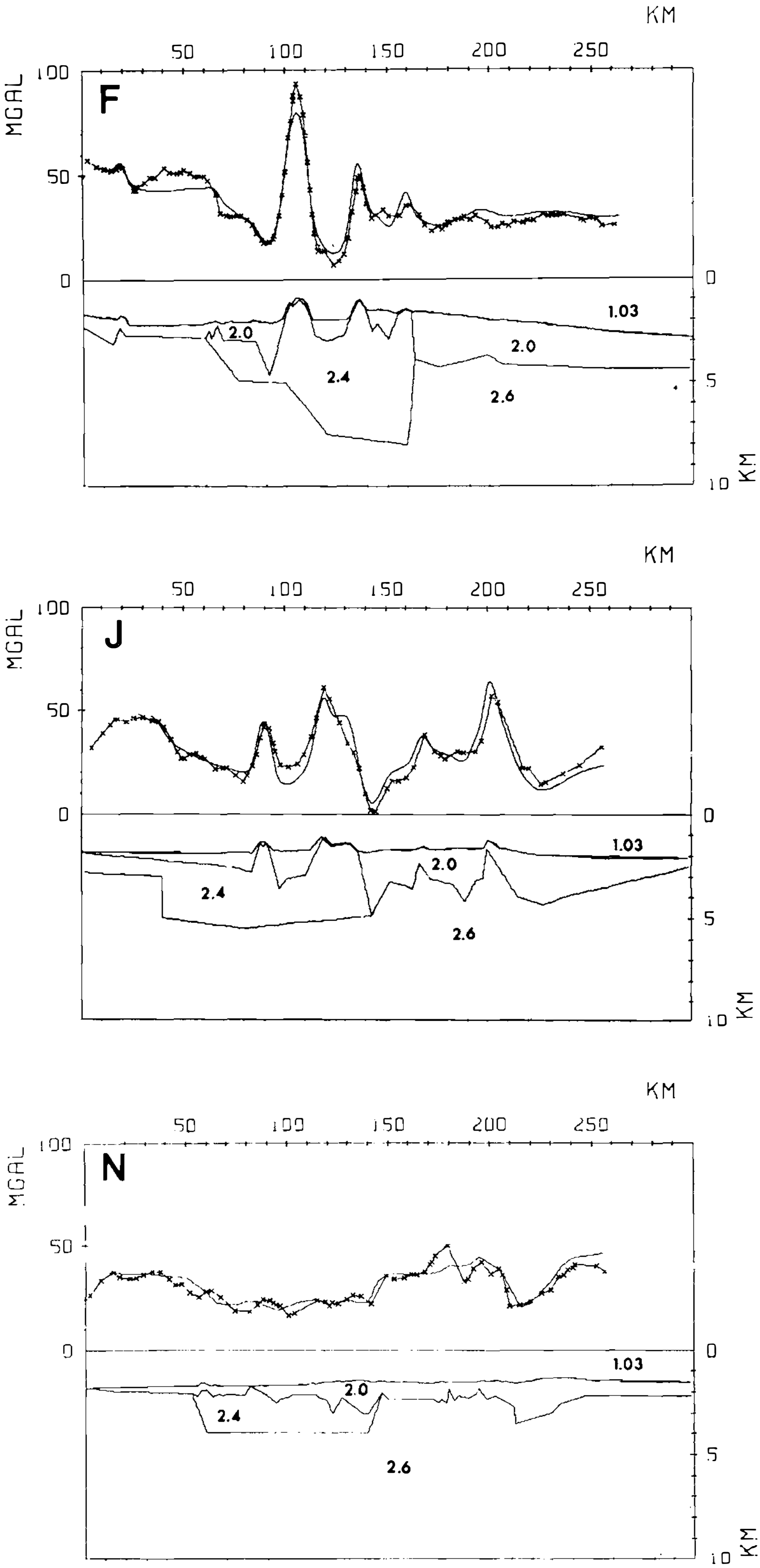

Fig. 8. *Three gravity profiles with corresponding crustal models across the Jan Mayen Ridge area (for location of profiles, see Fig. 7). Observed free air gravity is shown as solid line with crosses, computed gravity effect as solid line.*

the central Jan Mayen Ridge area and have obtained a satisfactory match between computed and observed gravity. We have also used the 2.4 g/cm^3 density where the opaque seismic layer is missing. The map shows also clearly the low values in regions 1 and 2, except over topographic ridges. These low values, compared to the values in regions 3, 4, and 5, led Talwani and Eldholm (1977) to associate the Jan Mayen Ridge with continental crust. This is also what our models indicate.

C. Magnetic Anomalies

Residual total magnetic intensity in the area is shown in Fig. 9. The magnetic quiet zone which is found in area 1 (Talwani and Eldholm 1977), is similar to quiet zones found on the continental margin off Norway. Small anomalies are found both in areas 2 and 3. The anomalies on the southeast flank of the Jan Mayen Ridge (3) appear to be parallel to the oceanic type anomalies which exist on the eastern slope of the Jan Mayen Ridge (8). The anomalies also seem to be associated with three basement ridges (1, 2, and 3 in Fig. 9).

The quiet field in the north and the subdued magnetic signature in the southern part (1 and 2) may be indicative of a continental origin of these areas with an outline expressed by the position at the regional gravity gradient (Fig. 7).

D. Suggested Boundaries of the Continental Part of the Jan Mayen Ridge (1 and 2)

Available geophysical and bathymetric data strongly support a continental origin for the Jan Mayen Ridge. Magnetic quiet zones in contrast to large magnetic oceanic anomalies are usually indicative of continental crust, and gravity gradients (with the low over the continental part) have been shown to exist across continent/ocean boundaries (Talwani and Eldholm 1972; 1977). Furthermore, both seismic refraction and reflection results usually give information on the type of crust one is dealing with. Based on this we suggest probable east and west boundaries of this microcontinent as shown in Fig. 2. We further suggest that the northern boundary is at approximately 70.5°N for two reasons: the area with rough topography which is associated with the Jan Mayen Fracture Zone intersects with the Jan Mayen Ridge at this latitude, and the magnetic field becomes disturbed again north of 70.5°N (Avery et al. 1968).

The southern boundary of the continental part of the Jan Mayen Ridge is formed by Iceland and the Iceland–Faeroe Ridge. Both the sediment map (Fig. 6) and the gravity map (Fig. 8) indicate a continuation as far south as 66°N–67°N (prominent gravity low and large sedimentary thickness). The south–east boundary is more difficult to ascertain. Following Talwani and Eldholm (1977) we have placed it between regions 2 and 3. We note that the presence of small magnetic anomalies in both these regions constitutes an unresolved problem.

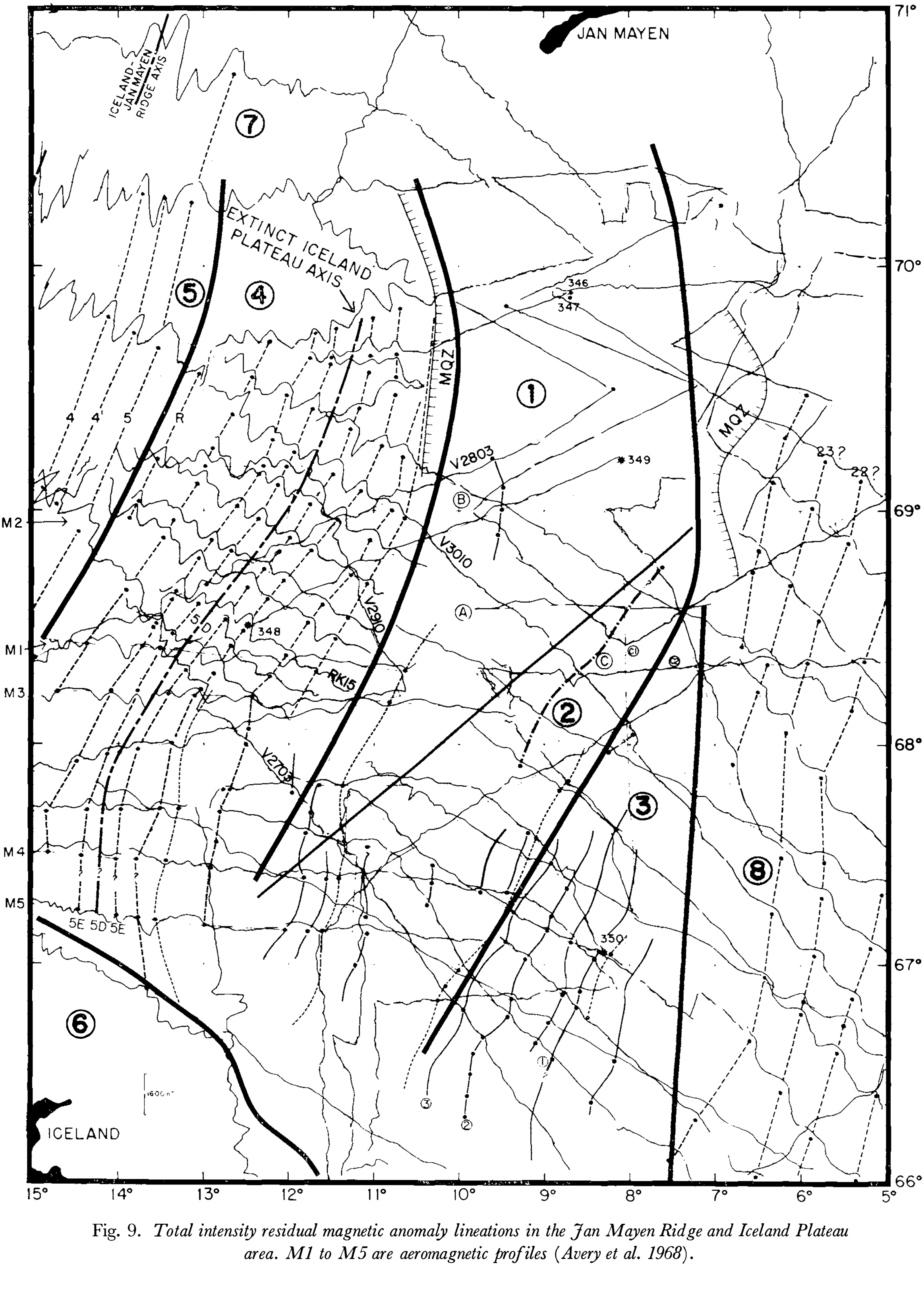

Fig. 9. *Total intensity residual magnetic anomaly lineations in the Jan Mayen Ridge and Iceland Plateau area. M1 to M5 are aeromagnetic profiles (Avery et al. 1968).*

II. ICELAND PLATEAU – AN EXTINCT SPREADING AXIS

Between the presently active Iceland–Jan Mayen Ridge and the continental Jan Mayen Ridge lies region 4, which contains sea floor spreading type magnetic anomalies. After an initial survey of the region Johnson et al. (1972) suggested that the area had been formed at a hitherto unknown spreading axis, prior to the formation of the Iceland–Jan Mayen spreading ridge. They interpreted a prominent magnetic minimum as the axis of symmetry, but did not identify the anomalies. On the basis of geophysical data collected by the VEMA (1966, 1969, 1970, 1972, 1973) AKADEMIK KURCHATOV (1971, 1973; Mirlin and Melikhov 1976) and GLOMAR CHALLENGER (1974; Talwani, Udintsev et al. 1976), we have identified a set of magnetic anomalies which provides strong evidence for the oceanic Iceland Plateau extinct axis and an axis of symmetry centered on a positive magnetic anomaly.

Currently, the Iceland–Jan Mayen spreading axis is an active center of sea floor spreading; the oldest magnetic anomaly on this ridge indicates spreading began just prior to anomaly 5 time. In the Norway Basin, the last spreading occurred at anomaly 7 (Talwani and Eldholm 1977), thus we have a gap in time of 15 million years. As we shall show, there was active spreading on the Iceland Plateau extinct axis during most of this time – from anomaly approximately 6B time to anomaly 5D time.

Bathymetry and Seismic Reflection Profiles

Bathymetrically the Iceland Plateau extinct axis in region 4 is a separate plateau distinct from the Iceland–Jan Mayen spreading axis to the west, and the Jan Mayen Ridge area to the east. Fig. 3 illustrates this three-fold division of the region. The eastern terminus of the Iceland–Jan Mayen spreading axis has a smooth sediment cover at 800 fathoms depth and a ridge 100 fathoms above this general depth; this ridge is herein called the western ridge. East of this ridge there is a drop in depth to 1000 fathoms to the plateau which is a region of parallel magnetic anomalies. DSDP hole 348 (Talwani, Udintsev et al. 1976) is located in the plateau. A scarp forms the eastern boundary of this plateau and the depth increases to 1100–1200 fathoms eastwards.

Seismic reflection records from V2803 (Fig. 5, line AB) indicate the various features of the Iceland Plateau region. The magnetic anomalies associated with the Iceland Plateau are confined between the Western Ridge and the Eastern Scarp, but the boundaries defined by seismic reflection are less clear. The smooth sediment cover in the eastern flank of the Iceland–Jan Mayen Ridge continues over the western ridge. The acoustically 'opaque' layer is clearly visible on this profile from 2000 hours to 1100 hours, so that it continues without interruption from the region of the magnetic quiet zone associated with the Jan Mayen Ridge. Also, the seismic profile does not indicate any possible extinct ridge as a basement feature. Thus, from the shallow fluctuating seismic reflection records it is difficult to identify the region of the extinct spreading axis and the associated anomalies.

Marine Magnetic Data

Marine magnetic data was collected in the area by the VEMA, AKADEMIK KURCHATOV, and the GLOMAR CHALLENGER; aeromagnetic data have also been collected (Avery et al. 1968). These data are plotted along the tracks and illustrated in Fig. 9. Prominent parallel magnetic anomalies are evident in the region. Anomalies 4, 4′ and 5 generated along the Iceland–Jan Mayen spreading ridge appear in the western portion of the map. This distinct anomaly of 700 gammas amplitude immediately east of anomaly 5 and labelled R on Fig. 9 is directly above the western ridge; because of this proximity it would appear to be causally associated with it. We are not sure about the origin of this anomaly. It could be entirely structural in origin or it could mark the first spreading anomaly for either the Icelandic Plateau series or the Iceland–Jan Mayen series of anomalies. Further east of this western ridge and associated distinct anomaly, are a series of parallel magnetic anomalies which trend N30°E in the northern section. Because of the history of the Norway Basin extinct axis and the Iceland–Jan Mayen spreading axis, we believe that these anomalies were created between anomaly 7 and anomaly 5 time at the Iceland Plateau extinct axis.

Continuity of the magnetic lineations of the Iceland Plateau extinct axis is demonstrated in Fig. 9. Although the magnetic anomalies are obviously lineated there are differences in the anomalies along strike in both width and amplitude of the individual peaks and troughs. However, the general character of the anomalies remains fairly constant between tracks.

After correlation between adjacent tracks it is possible to search for a center of symmetry. As there is no distinct topographic or basement ridge or gravity anomaly, we have no *a priori* reason for choosing any given vertical plane as the center of symmetry. Instead the general character of the anomalies was used to determine the center of symmetry – this center line is shown in Figs. 9 and 10. We note that this center is almost at the midpoint between the western ridge and eastern scarp in the northern section and it is not associated with any basement ridge. Any basement structure in this area appears to be buried under the opaque layer.

Correlation of the sequence of anomalies between tracks (projected to 120°) with the most recent magnetic reversal time scale (LaBreque et al. 1977) is shown in Fig. 10 (northern section). In addition, all profiles are reversed so that the center of symmetry can be demonstrated. In order for a correlation in time, we searched the magnetic anomaly pattern between anomaly 7 and anomaly 5. This resulted in the identification of 5D (17.3 MyBP) as the central anomaly with adjacent parallel anomalies 5E and 6, with the oldest anomaly being 6B at 22.7 MyBP. Modeling was done with a half-spreading rate of 1.5 cm/year. Our precise identification of the oldest and youngest anomaly assumes instantaneous initiation and cessation of sea floor spreading. This assumption then requires quiescent periods of 2.8 million years prior to and 7.3 million years after active spreading on the Iceland Plateau extinct axis. More realistically the spreading probably both began and ended gradually, with the initial and final magnetic anomalies (which we label 6B and 5E) possibly due to slower spreading over a larger time period. At the same time, the possibility of actual gaps in spreading in this area exists and has been discussed by Talwani and Eldholm (1977).

After identification of the anomaly sequence in the northern section of the Iceland Plateau extinct axis the correlation was extended to the southern section up to the Iceland shelf (Fig. 10 – southern section) where it is considered to be less reliable. Drilling results of the GLOMAR CHALLENGER for site 348 support our identification of these magnetic anomalies for the Iceland Plateau extinct axis. Hole 348 was drilled on anomaly 6, K/Ar dating of the basalt yielded ages of 18.2 ± 2.4 and 19.4 ± 2.2 MyBP (Kharin et al. 1976); our magnetic anomaly identification predicts an age of 20.2 MyBP.

III. JAN MAYEN FRACTURE ZONE – ORIGIN

The magnetic anomalies in the area where the two segments of different trends of the Jan Mayen Fracture Zone meet have tentatively been identified as anomaly 21–23 (Figs. 11 and 12). If these identifications are correct, they can be used to predict when the spreading ceased in the Norway Basin by rotating the corresponding anomalies on Mohns Ridge and seeing at what time they would line up together.

Fig. 11 shows that a rather good fit existed at anomaly 13 time, which then is evidence for an axis jump at this time in the Norway Basin. However, from consideration of magnetic anomalies and geometry, Talwani and Eldholm (1977) conclude that the jump from the Norway Basin took place close to anomaly 7 time. Consequently, we suggest that between 13 and 7 times two fracture zones and three segments of the mid-ocean ridge were active in the area (Fig. 13). On Mohns Ridge and the extinct axis in the Norway Basin spreading continued about the old axis, while a new fracture zone — the northern segment of the Jan Mayen Fracture Zone — came into existence. After anomaly 7 time the spreading axis in the Norway Basin jumped west and the new spreading axis apparently extended to the north up to the northern segment of the Jan Mayen Fracture Zone. Thus again there were only two spreading axes in the region: one about the Mohns Ridge and the other about the new extinct axis on the Iceland Plateau. The present location of the anomalies 7 to 13, generated between the two segments of the Jan Mayen Fracture Zone at a time when both segments were active, is uncertain. Their location would depend on the position of the Iceland Plateau axis relative to the area of these anomalies.

We thus believe that the western segment of the Jan Mayen Fracture Zone extends as far as anomaly 13 (Fig. 13). DSDP site 345 would then lie on oceanic crust of nearly anomaly 13 age rather than on fracture zone crust. The sedimentary history of site 345 (Talwani, Udintsev et al. 1976) is in accord with this hypothesis.

Fig. 10. *Magnetic anomalies on the Iceland Plateau extinct axis, track locations are shown in Fig. 9. In the northern section we have identified the extinct ridge axis, shown the central anomaly to be anomaly 5D and correlated the magnetic anomalies between tracks. Symmetry of profiles is indicated by comparison with the reversed profiles (dashed lines). In the southern section we have continued our correlation of anomalies up to the Iceland shelf.* →
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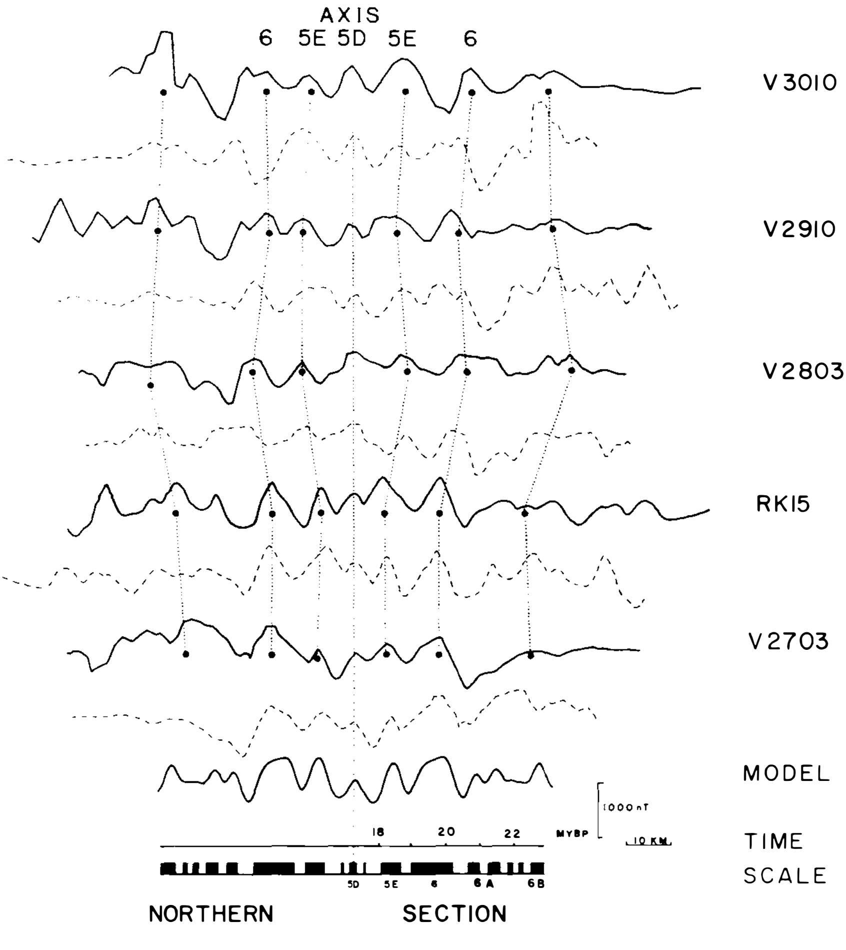
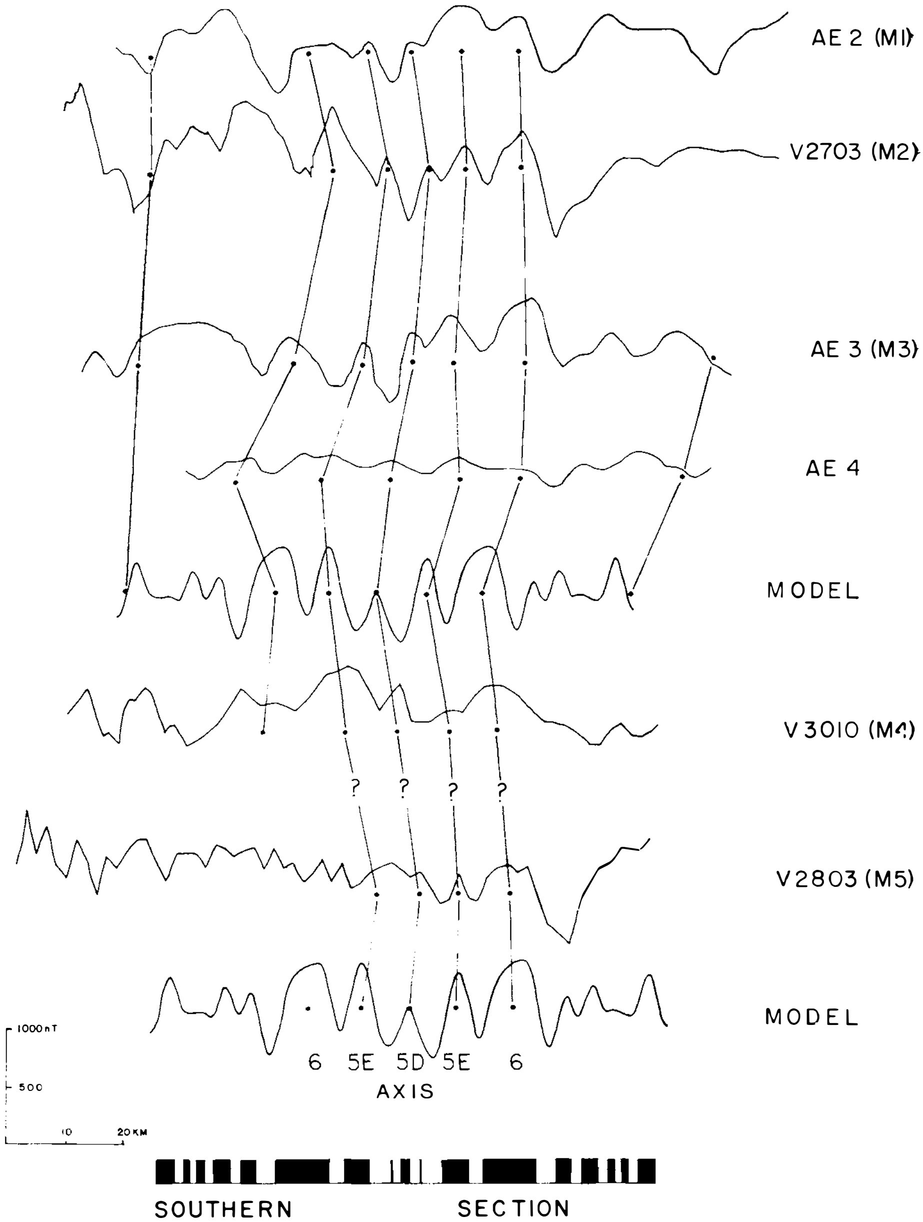


Summary of evolution of the Jan Mayen Ridge and Iceland Plateau

The evolution of the Norwegian–Greenland Sea north of Iceland has been relatively complicated. By using a large amount of marine geophysical data, the history of this region has been effectively deciphered (Talwani and Eldholm 1977; and this paper). Initial opening of the Norway Basin began sometime before anomaly 24 time (56 MyBP) and occurred uninterrupted from anomaly 23 time until approximately the time of formation of anomaly 13 (36 MyBP). At this time a jump of a small part of the spreading axis occurred



in the northern region, resulting in two active segments of the Jan Mayen Fracture Zone (Fig. 13). Thus, in addition to the spreading centers in Mohns Ridge and Norway Basin, a third spreading axis existed in between.

The major portion of the present Jan Mayen Ridge remained the eastern continental margin of Greenland. This situation continued until about anomaly 7 time when the Norway Basin axis shifted westward to form the Iceland Plateau and the Jan Mayen Ridge broke off from the Greenland continent.

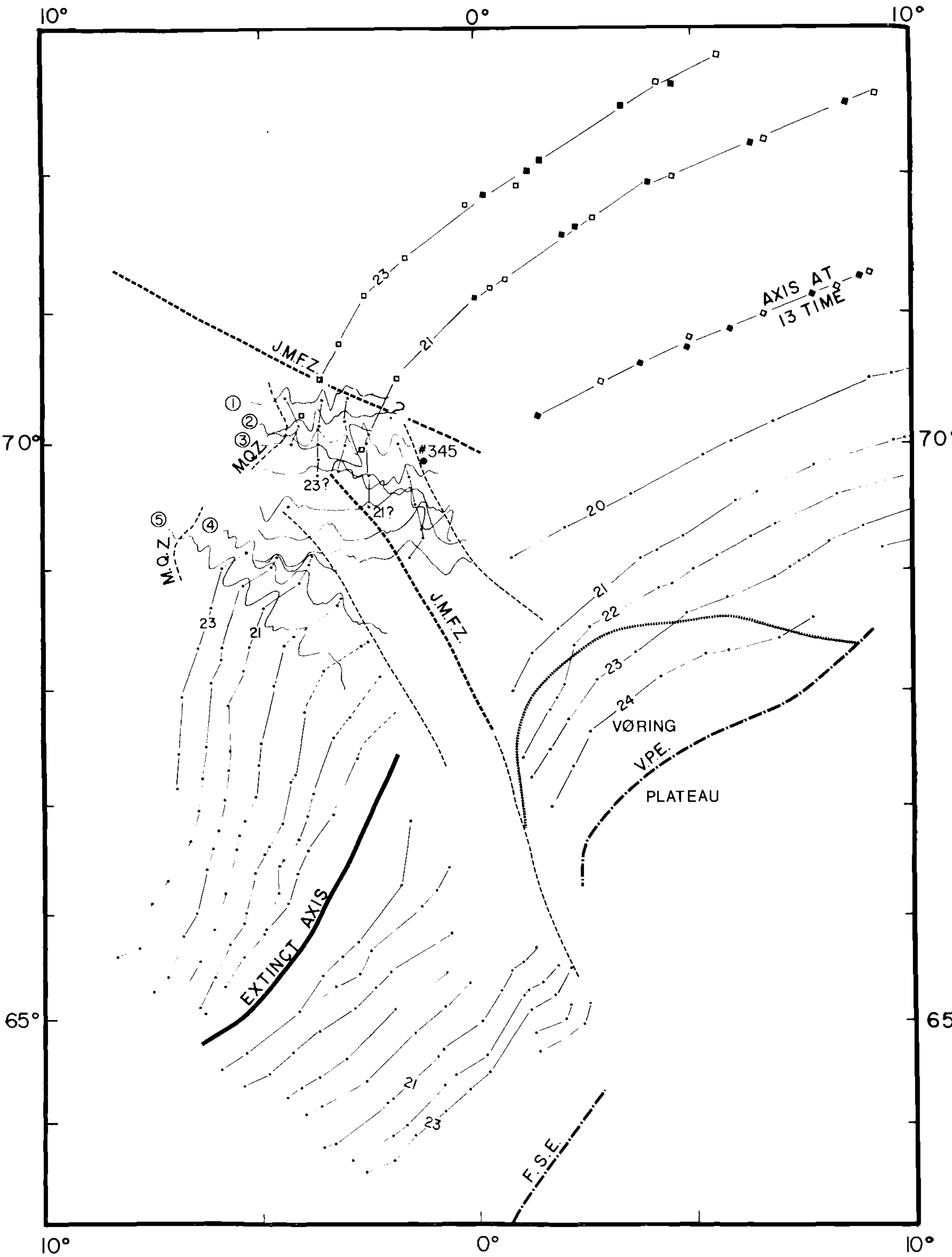


Fig. 11. *Magnetic lineations in the Norwegian Sea (based on Talwani and Eldholm 1977). We have extended their identification northwards from c. 69°N to the western segment of the Jan Mayen Fracture Zone. Black dots show correlatable anomaly peaks. North of the Jan Mayen Fracture Zone we notice the curved anomalies on the Vøring Plateau. The corresponding set of lineations to the VP-anomalies at anomaly 13 time will fall on the lines indicated by the open squares. We have also plotted the anomalies found on the Greenland side for 13 time. These anomalies are shown by the black squares. Stipled lines parallel to the Jan Mayen Fracture Zone indicate the limit of irregular topography. DSDP site 345 is shown.*

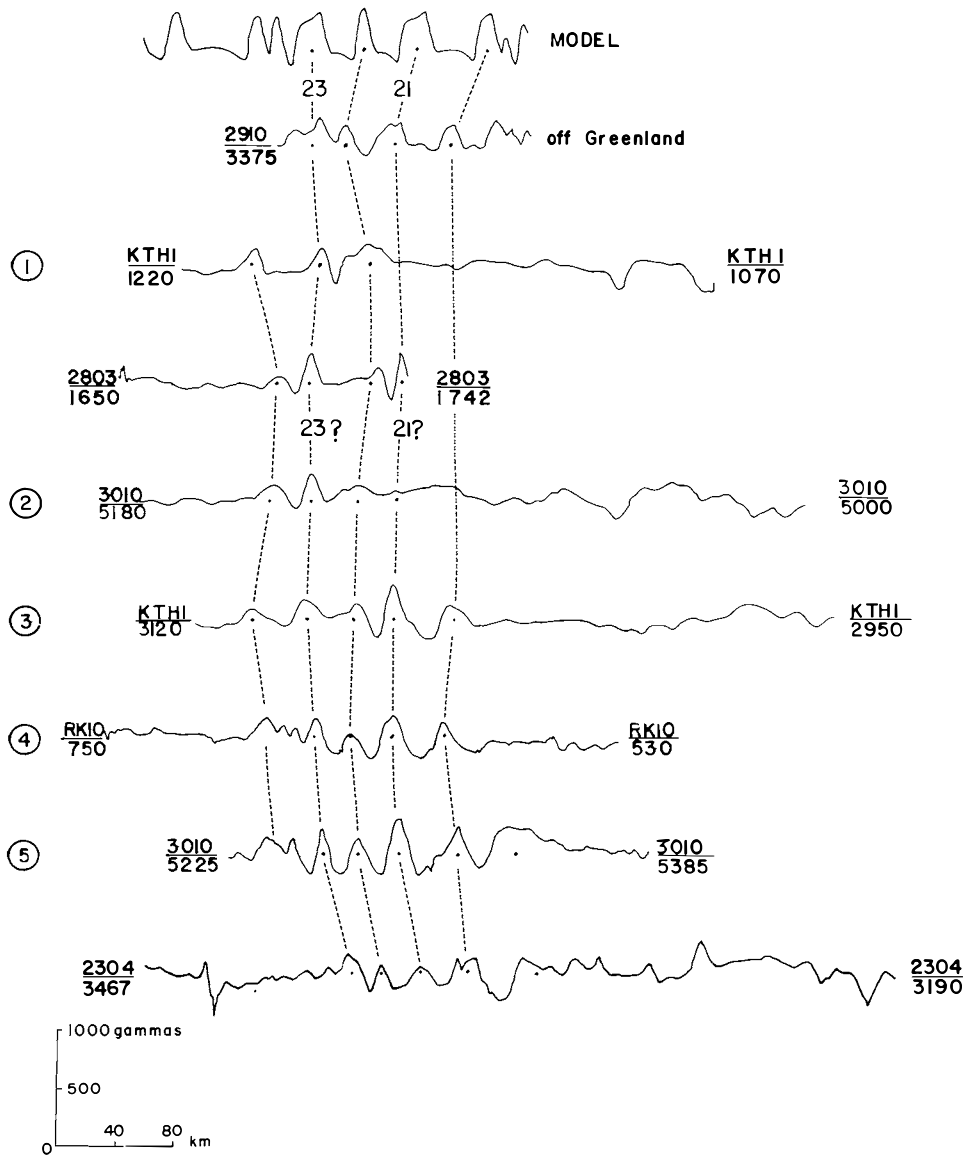


Fig. 12. *Correlation of magnetic anomalies in the area between the two portions of the Jan Mayen Fracture Zone. Location of profiles shown in Fig. 11.*

Creation of oceanic lithosphere continued at the Iceland Plateau extinct axis up to the formation of anomaly 5D (17.3 MyBP). Active spreading on the Iceland–Jan Mayen spreading axis commenced sometime prior to anomaly 5 time. This ridge has been continually active up to the present.

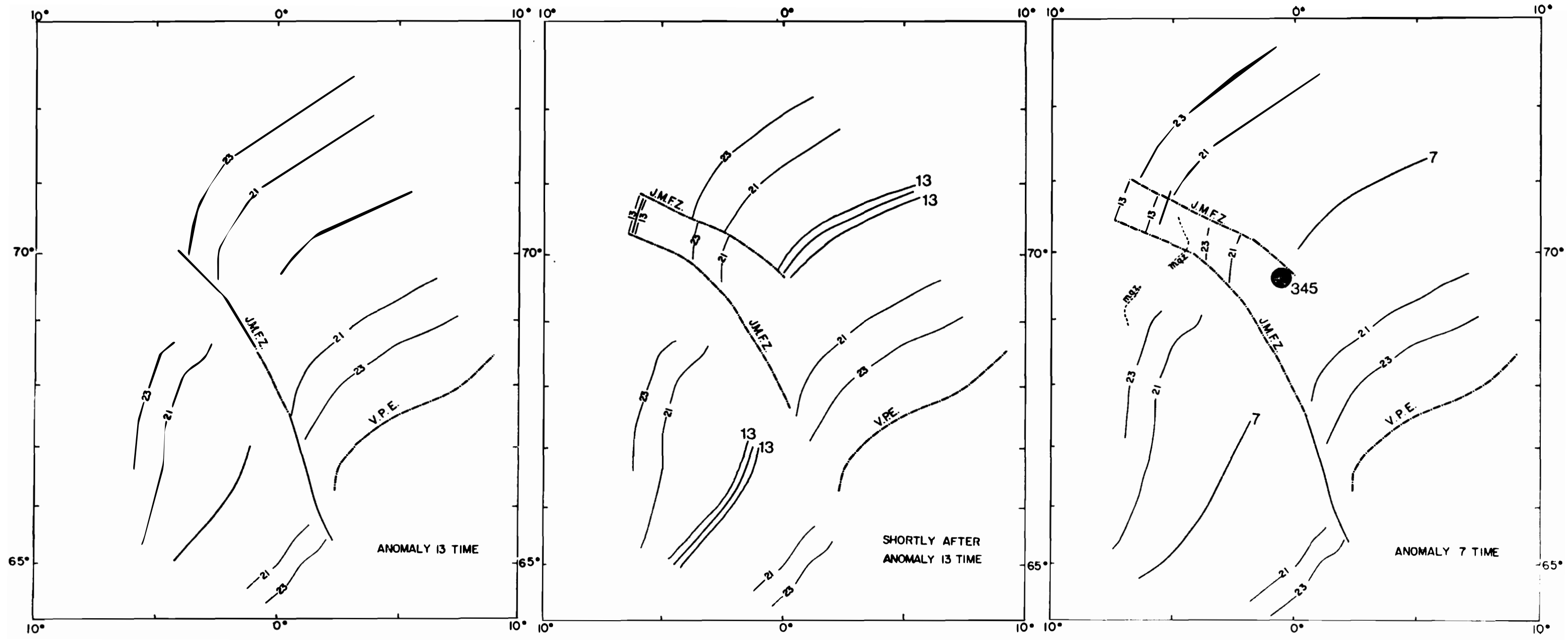


Fig. 13. *Attempted reconstruction of the area around the Jan Mayen Fracture Zone between anomaly 13 and 7 times.*

Acknowledgement

We acknowledge the effort of the scientists, officers, and crew of the R/V VEMA, without whose help and cooperation this work would not have been possible. We thank S. Cande and C. Windisch for critical review of the manuscript. This study was supported by the Office of Naval Research (Contract N00014–67–a00108–0004) and the National Science Foundation (Contract GA27281). Gisle Grønlie's stay at Lamont Doherty during which most of the work on this paper was accomplished, was supported financially by the Norwegian Scientific Council for Science and the Humanities (NAVF).

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Tertiary paleogeography of the Norwegian-Greenland Sea

By GISLE GRØNLIE[1]

Abstract

By making use of established poles of rotation, and a depth/age subsidence curve, we reconstruct the paleogeography of the Norwegian-Greenland Sea in Late Miocene, Early Miocene and Late Eocene times (10, 20, 40 My). We have, assuming that the subsidence curve of Sclater et al. (1971) is valid for the Norwegian-Greenland Sea, backtracked points along the curve to arrive at the relevant paleodepths. Results from the Deep Sea Drilling Project are used as a check.

Our results show that the Iceland-Faeroe Ridge probably was a land bridge until the Middle Miocene, parts of the Vøring Plateau were above sea level until the Late Eocene and parts of the Jan Mayen Ridge were above sea level from some time before the separation from Greenland until the Miocene.

Introduction

Recent scientific studies of the Norwegian–Greenland Sea have further refined the evolutionary history of the area in terms of sea floor spreading and plate tectonics (Talwani and Eldholm 1977). The results from the Deep Sea Drilling Project (DSDP, leg 38) (Talwani, Udintsev et al. 1976) have given detailed information about the sedimentary environment at different times since the initiation of sea floor spreading in the Norwegian–Greenland Sea in the Early Eocene (56 My ago).

In this paper a first order attempt is made in reconstructing the environment of the Norwegian–Greenland Seas at three different times, Late Eocene, Early and Late Miocene. We make use of the age/depth relationship established for oceanic crust by Sclater et al. (1971), a new bathymetric map of the area (Grønlie and Talwani 1979, Fig. 1) and the pattern of magnetic isochrons established by Talwani and Eldholm (1977) and Grønlie et al. (1979, Fig. 3).

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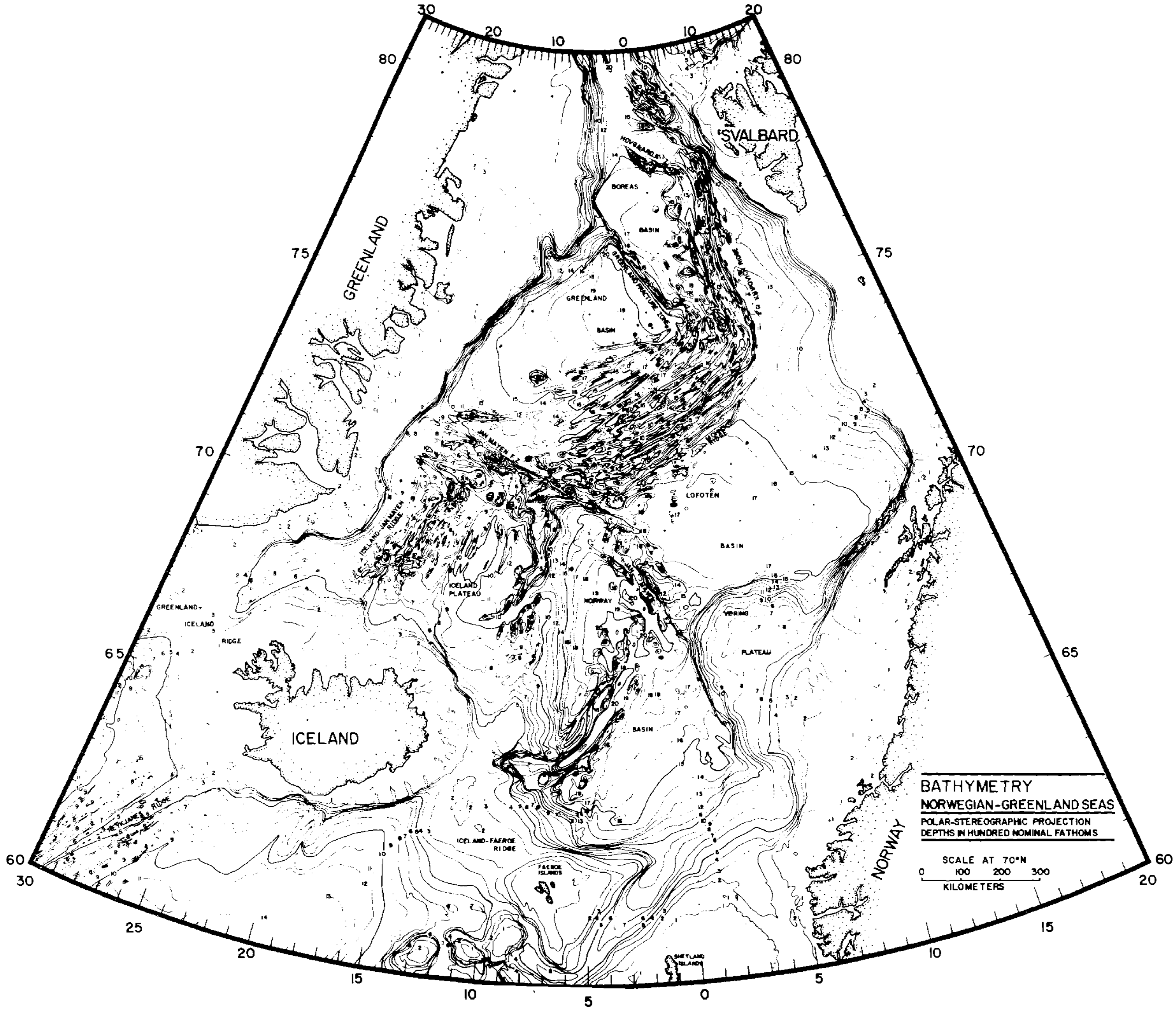

Fig. 1. *Bathymetry of the Norwegian-Greenland Seas (coloured version at the back of this volume).*

Basic assumptions

We assume that the general age/depth relationship established by Sclater et al. (1971) is valid for all the oceans of the world (Fig. 2). Cochran and Talwani (1977) have shown that the North Atlantic is anomalously shallow according to this relationship, especially the area around Iceland and parts

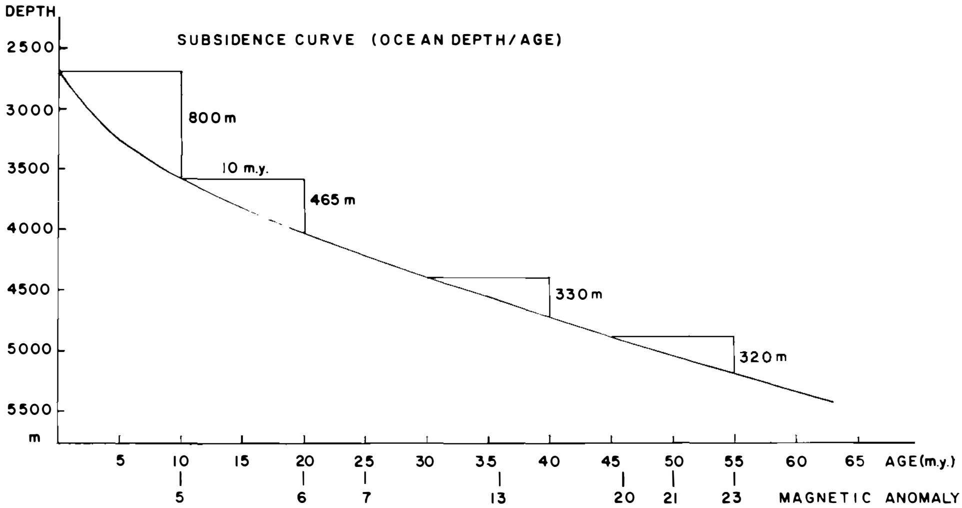

Fig. 2. *Subsidence curve for the world's oceans (from Cochran and Talwani 1977). The subsidence rate (i.e. shape of curve) is valid for the Norwegian-Greenland Seas, but the starting point (2700 m) is too deep. It is demonstrated how the subsidence varies according to age; the subsidence is 800 m for the crust during the first 10 My, while it is c. 325 m for c. 40 My old crust.*

of the Norwegian–Greenland Sea, but the subsidence agrees very closely. This means that although the absolute depth is incorrect according to the world average, a local Norwegian–Greenland Sea depth/age relationship exists (i.e. $D = D_O + D_A t^{1/2}$, where D_O varies from region to region, but D_A is a worldwide constant). For example: the subsidence from 10 My ago until the present will be c. 800 m for crust which was created 10 My ago, while the subsidence for Early Eocene crust is only 320 m during the same 10 My (Fig. 2). This relationship was also shown (Vogt and Avery 1974) to be the case on the Reykjanes Ridge (46–52°N) where the subsidence rate is as elsewhere, but the initial depth is different.

We furthermore assume that continental margins basically subside as a result of their sediment load and follow the law of isostasy. This means that the margins and the continental shelf areas mostly will get shallower very slowly as sediments are laid down. The Vøring Plateau landward of the escarpment should therefore follow a "continental margin type" of subsidence, while the outer Vøring Plateau, the Iceland–Faeroe Ridge, and the Iceland Plateau would follow the oceanic subsidence curve. This implies that the Vøring Plateau Escarpment has acted as a normal fault at all times with downthrow of the western side. There is seismic and sedimentary evidence for some movement at the escarpment (Caston 1976), but this is in favor of an uplift of the western part. Thus at the Vøring Plateau we assume that a coupling existed across the escarpment which mostly balanced the cooling effect and the sedimentary loading effect by keeping the Inner Vøring Plateau close to its present water depth from Eocene time until the present.

The Jan Mayen Ridge is probably of continental origin (Johnson and Heezen 1967; Talwani and Eldholm 1977; Grønlie et al. 1979). The ridge is treated as having continental subsidence until it separated from Greenland (approximately 24 My ago (Grønlie et al. 1979). From then we find it more correct to assume it underwent oceanic type subsidence because it is surrounded on all sides by oceanic crust.

We know very little about the details of ocean floor spreading in the Norwegian–Greenland Sea north of the Greenland–Senja Fracture Zones. We therefore limit our reconstruction of the paleogeography to the area south of these fracture zones.

The reconstruction has not been corrected for sediment load. The consequences of this are that the depths in Figs. 3–5 are too shallow. Close to the spreading axis where the sediment cover is absent or very thin is the depth correct, further away from the spreading ridge in the basins should the depth be increased by approximately one half of the sediment cover. The features we discuss are, however, ridges and basement highs, and they will probably show the correct depth because of a missing or rather thin sedimentary cover (see sediment map, Grønlie and Talwani 1978).

General geologic summary

Greenland and Norway separated sometime before anomaly 24 time (56 My according to a revised time scale by LaBrecque et al. (1977)). The spreading in the Norway Basin took place from about 23 time (55 My) to approximately 13 time (36 My) along an extinct axis (see Fig. 3, Grønlie & Talwani, this volume). Some time between anomaly 13 and 7 times (26 My) the axis jumped westward on to the east Greenland continental margin and thereby separated a continental fragment from Greenland to the Jan Mayen Ridge. Grønlie et al. (1979) suggest that this jump took place in two steps, where spreading in the area between the two parts of the Jan Mayen Fracture Zone stopped first (approximately at anomaly 13 time), while spreading in the Norway Basin went on until anomaly 7 time. The DSDP results from site 337 close to the extinct axis support the suggested timing for the jump in the Norway Basin, and site 345, which lies in the area between the two segments of the Jan Mayen Fracture Zone, has sediments of Eocene age, which certainly does not contradict this two-fold jump.

Ocean floor spreading took place on the Iceland Plateau from anomaly 6B (22 My) time. Spreading occurred first along an intermediate spreading axis, until anomaly 5D (Grønlie et al. 1979), and subsequently spreading has taken place along the present spreading ridge (Iceland–Jan Mayen or Kolbeinsey Ridge), although the configuration of the axis changed slightly by the development of the Spar Fracture Zone (Meyer et al. 1974).

The spreading in the Lofoten–Greenland Basins has been simple, and only one axis has existed from the opening until the present (Fig. 3, Grønlie and Talwani, this volume).

The area north of the Greenland–Senja Fracture Zones has been more complex. Several axis jumps or asymmetric spreading have probably occurred because the presently spreading Knipovich axis – particularly its northern part – is now very close to the Spitsbergen margin.

The DSDP drilling results as published by Talwani, Udintsev et al. (1976) confirm this evolutionary history of the Norwegian–Greenland Sea. The ages, both from the sediments and the basaltic basement all generally agree with the age predicted from the magnetic anomalies. We also note that submarine lava flows are only found at sites 337 and 356 (Kahrin 1976), which may indicate that basaltic basement at all other sites where basement was encountered could have erupted on land.

A. PALEOGEOGRAPHY IN THE LATE MIOCENE (Fig. 3)

Iceland-Faeroe Ridge

Because subsidence rates decrease with increasing crustal age (Fig. 2) we have assumed an age distribution along the ridge as follows:

1. it was formed by sea floor spreading while the extinct axis was spreading (55 to 24 My) and
2. the extinct ridge axis cut across the Iceland–Faeroe Ridge in the same manner that the present mid Atlantic axis crosses Iceland.

Judging from the distance between the sites and the southern continuation of the extinct axis, we have used an age of 45 My for sites 336 and 352.

Sites 336 and 352 which lie on the flanks of the Iceland–Faeroe Ridge were at water depths of approximately 500 and 700 m in Late Miocene time. The ridge which is about 400–500 m higher than the sites, were probably close to sea level, and some parts were above water (Fig. 3). The sedimentary record of both sites 336 and 352 show (Talwani, Udintsev et al. 1976) that Plio/Pleistocene sediments overlie sediments of Oligocene age, and that Miocene sediments are missing. One way of explaining the missing sedimentary section is to assume that because of shallow water, strong currents (possibly the North Atlantic current) must have swept over parts of the ridge thereby preventing deposition and possibly eroding preexisting sediments.

Vøring Plateau

Sites 338 and 342 drilled on or in the vicinity of the Vøring Plateau were on the structural high west of the Vøring Plateau Escarpment, site 343 at the foot of the outer plateau in the Lofoten Basin, and sites 339, 340, and 341 in the sedimentary basin inside the Vøring Plateau Escarpment. Caston (1976)

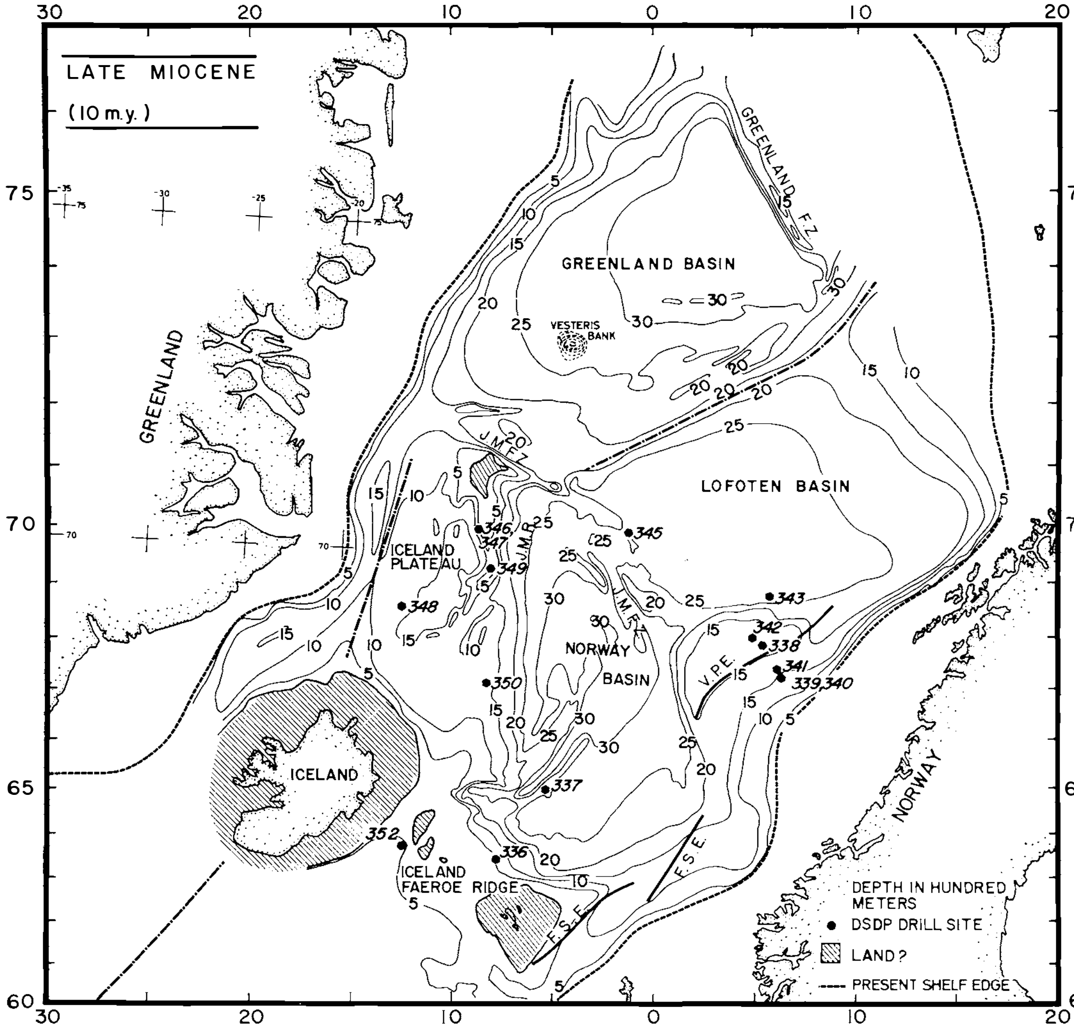

Fig. 3. *Paleogeography of the Norwegian-Greenland Seas in the Late Miocene (10 My).*

has discussed the Tertiary sediments on the Vøring Plateau in detail. Site 338 has a complete sedimentary history from the Early Eocene, and it is assumed that this site was close enough to sea level before this time to prevent sedimentation. From a study of the seismic reflection records, Caston (op. cit.) was able to show that three areas on the outer Vøring Plateau had no Paleogene sediments deposited. Site 343 has Eocene sediments with overlying Plio/Pleistocene sediments. Both Oligocene and Miocene sediments seem to be missing.

Of the sites on the inner Vøring Plateau, only site 341 can be used in this context. Both sites 339 and 340 were drilled on mud diapirs, and it is assumed this diapirism took place in the Plio/Pleistocene (Caston 1976). Site 341 was drilled 456 m into Middle Miocene sediments.

If we assume ocean floor subsidence for the outer Vøring Plateau, then holes 338 and 342 were at approximately 1000–1100 m water depth 10 My ago, and site 343 at c. 2800 m.

The sedimentary records of all holes on the Vøring Plateau are consistent with the predicted paleodepths.

Iceland Plateau and the Jan Mayen Ridge

Iceland–Jan Mayen Ridge was at this time (anomaly 5) just beginning to spread. Sites 348 and 350 both show a continuous sedimentary history from the present until this time, and their respective paleo-water depths are approximately 1400 and 1000 m, assuming a basement age of 40 My for site 350 and 20 My for site 348. These ages are in agreement with both magnetic anomalies and radiometric dates from the two sites (Kahrin 1976).

The three sites on the Jan Mayen Ridge were at water depths between 300 and 500 m at 10 My if one assumes that the ridge follows an oceanic type subsidence curve. The area which surrounds Jan Mayen Island is only half a million years old (Fitch et al. 1965). However, the sands in the miocene sediments (Talwani, Udintsev et al. 1976) suggest that the northern part of the continental Jan Mayen Ridge at this time was actively being eroded.

The Norway, Lofoten and Greenland Basins

At 10 My the paleo-depths of the basins were more than 2500 m (Lofoten and Norway Basins) and 3000 m (Greenland Basin), and the ridges stood at about 2000 m depth. The Jan Mayen Fracture Zone and Greenland Fracture zone are features going up to approximately 1500 and 1000 m paleodepth, respectively.

Both sites 337 and 345 had deep water conditions at this time. The section at site 337 shows pelagic clays and muds from the Plio/Pleistocene boundary until Oligocene above basaltic basement. Site 345 has a continuous section of sediments from Plio/Pleistocene to Eocene.

B. PALEOGEOGRAPHY IN THE EARLY MIOCENE (Fig. 4)

Conditions were largely similar to those of the Late Miocene for most of the Norwegian–Greenland Sea, except for the area north of Iceland. Here spreading was now taking place along an intermediate spreading axis (Grønlie et al. 1979) on the Iceland Plateau.

The amount of subsidence during this time span (20 My) has been approximately 1250 m for 20 My crust, and about 650 m for Early Eocene crust (Fig. 2).

Iceland–Faeroe Ridge

Both sites 336 and 352 were at paleo-water depths of c. 200–300 m, and consequently the highest elevated parts of the Iceland–Faeroe Ridge rose approximately 100–200 m above sea level. One can therefore assume that substantial parts of the ridge were above sea level at this time, which was also

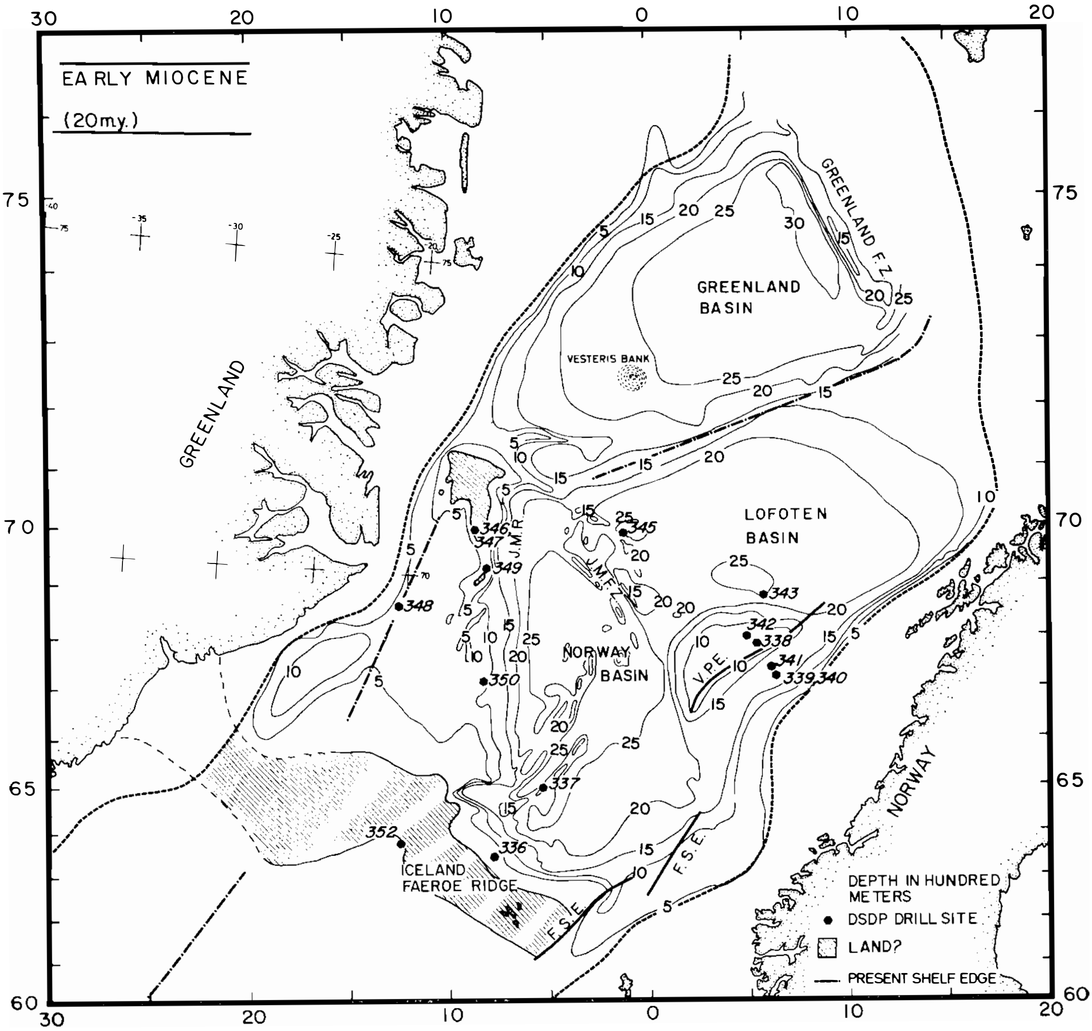

Fig.4. *Paleogeography of the Norwegian-Greenland Seas in the Early Miocene (20 My).*

argued by Vogt (1972) and Talwani and Udintsev (1976). This is not contradicted in the records from sites 336 and 352, as the faunas indicate a land barrier until Middle Miocene times.

Vøring Plateau

Sites 338 and 342 now lie approximately at 700–750 m water depths. This water depth and a possible current may have been enough until this time to prevent sedimentation at site 342, which is lying at a structural high.

Iceland Plateau and Jan Mayen Ridge

Site 348 is now situated on the spreading ridge itself, and the depth is approximately 800 m. We believe the whole Iceland Plateau, including the ridge, was at a paleo-water depth of between 500 and 1000 m or less.

The sites on Jan Mayen Ridge proper (346, 347, and 249) were at or above sea level, and a substantial part of the Jan Mayen Ridge was probably emergent. The sandy contents of the Miocene sediments probably reflects erosion of parts of the ridge, as mentioned previously.

The oceanic area close to site 350 lay at a paleo-water depth of approximately 600 m. Terrigenous sediment of Miocene age in the section at this site support the argument that land existed on the Jan Mayen Ridge.

The sediments of Early Oligocene and younger age are flatlying in this area, indicating even subsidence over both the Jan Mayen Ridge and the Iceland Plateau, and no strong bottom currents.

Norway, Lofoten, and Greenland Basins

The basins have Early Miocene water depths in excess of 2500 m (Norway and Lofoten Basins) and 3000 m (Greenland Basin). Topography along the Jan Mayen Fracture Zone locally rises above 1000 m depths. Sediments at site 345 indicate quiet current conditions with dominantly pelagic sedimentation at this time.

C. PALEOGEOGRAPHY IN THE LATE EOCENE (Fig. 5)

The extinct axis (Aegir Ridge) was active in the Norway Basin and the Jan Mayen Ridge was still attached to Greenland during the Late Eocene. Total subsidence since then ranges from approximately 1900 m (40 My old crust) to 1400 m (55 My old crust).

Iceland–Faeroe Ridge

Sites 336 and 352 must have been close to the Late Eocene spreading axis, which crossed the Iceland–Faeroe Ridge (Talwani and Eldholm 1977); and calculated paleo depths for these sites are well above sea level. The Iceland–Faeroe Ridge at this time was probably rather similar to what Iceland is today, and it is reasonable to suppose the existence of a land bridge, as proposed by Vogt (1972) and Talwani and Udintsev (1976).

Vøring Plateau

Sites 338 and 342 on the outer Vøring Plateau exhibit Late Eocene depths near sea level (40 m water depth and 20 m above sea level, respectively), and at the foot of the Vøring Plateau (site 343), 1800 m. At 40 My ago therefore parts of the outer Vøring Plateau may have been emergent (Fig. 5).

The sedimentary record show no Oligocene or Eocene sediments overlying basement at site 342. Also the sediments at site 338 and 343 indicate a source area close to site 338.

Western part of Norway Basin and the Greenland Margin

The Jan Mayen Ridge was still part of Greenland during the Late Eocene. The separation of the Jan Mayen Ridge from Greenland in Oligocene time (at about anomaly 7 time) was probably a complex event, and both uplift

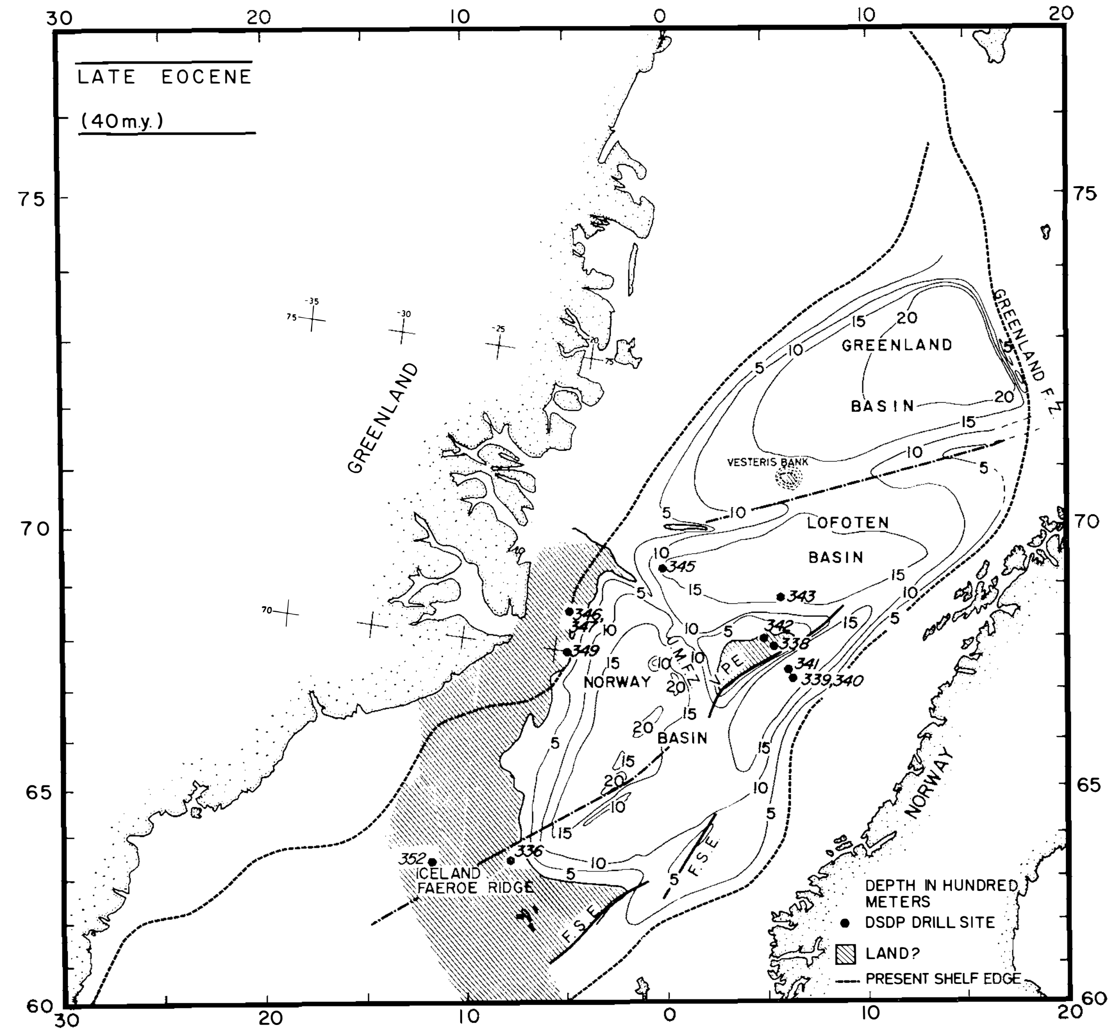

Fig. 5. *Paleogeography of the Norwegian-Greenland Seas in the Late Eocene (40 My).*

of Eocene sediments and tilt of the whole Jan Mayen Ridge can be seen in the seismic and sediment records (Talwani, Udintsev et al. 1976). In Fig. 5 we show a subaerial Jan Mayen Ridge attached to Greenland. We cannot however say how far above sea level the ridge was. The Eocene sediments at the site 346, 347, and 349 probably represent deep water deposits (Talwani, Udintsev et al. op. cit.); thus, a considerable amount of uplift over some period of time is suggested before the actual separation took place.

Site 350 results indicate that the oceanic crust next to the Jan Mayen Ridge was probably also emergent at this time. The subsidence curve clearly suggests land at this time; high vesicularity suggests the basalts were probably extruded subaerially (Talwani, Udintsev et al. 1976). The sediments immediately overlying the basalt have a tentative Late Eocene age although an Oligocene age

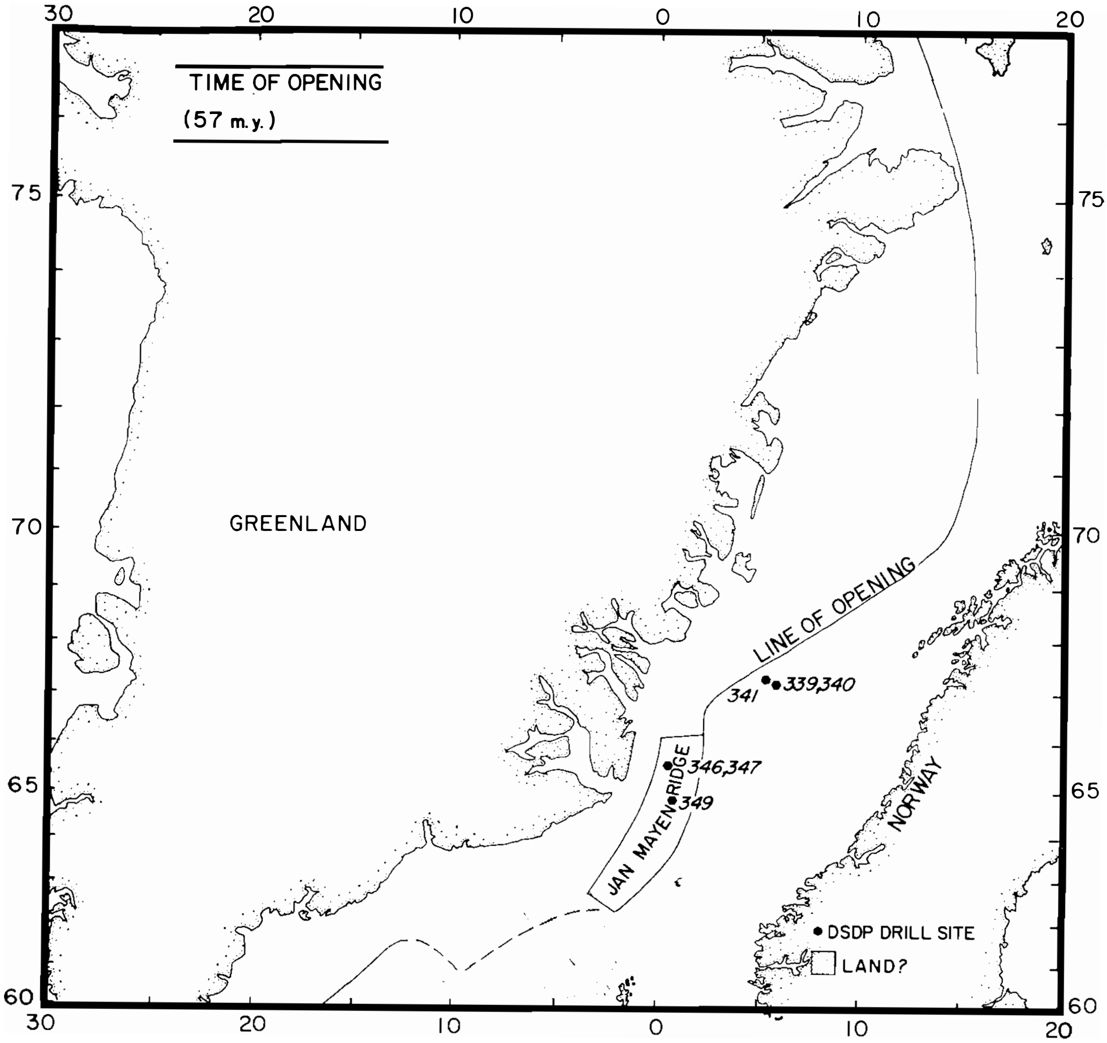

Fig. 6. *Reconstruction of the time of opening.*

is also possible. The low amplitudes of magnetic anomalies in the area (Talwani and Eldholm 1977; Grønlie et al. 1979) may be due to subaerially extruded lava flows which would extend over relatively greater areas, thus resulting in more nearly horizontal contacts between alternating polarities. Oxidation at shallow depths, or subaerially, would also reduce basalt magnetization.

Norway, Lofoten and Greenland Basins

The Late Eocene water depth in the Norway Basin was mostly shallower than 1500 m with only small parts deeper than 2000 m. In the Lofoten Basin the deepest part is also approximately 1500 m, and the Greenland Basin is about 2000 m deep. The Jan Mayen Fracture Zone is rather shallow and land is probably present on the Vesteris bank and on the southern part of Mohns

Ridge. (Alternatively, Vesteris bank could be like Jan Mayen, primarily a Quaternary volcanic feature, and did not exist during the Late Eocene.)

Changes in water circulation and sedimentation

Especially two events are of importance in this respect:

1. the submergence of the Faeroe–Iceland–Greenland Ridge in Middle Miocene time, and
2. the opening of the Greenland Sea after anomaly 13 time.

When the Faeroe–Iceland–Greenland Ridge subsided, the North Atlantic warm current was given free passage into the Norwegian–Greenland Sea resulting in similar faunas on each side of the ridge. A limited passage had existed prior to this through the Viking Graben in the North Sea (Talwani, Udintsev et al. 1976). The opening of the Greenland Sea means that a full water exchange with the Arctic ocean started. Calcareous and siliceous faunas and floras show great similarities with those found of the same age along the Caucasus mountains (Talwani, Udintsev et al. 1976).

Drastic changes in the sedimentary environment took place on the Faeroe–Iceland–Greenland Ridge where erosion probably started after submergence. There is also evidence of strong currents which probably prevented sedimentation on the Vøring Plateau and the Jan Mayen Ridge during the early periods after submergence (Talwani, Udintsev et al. 1976).

Conclusions

Bearing our assumptions in mind, we may conclude with the following:

1. The Iceland–Faeroe–Greenland Ridge was probably a land bridge from Eocene to Middle Miocene.
2. Parts of the outer Vøring Plateau were emergent until the Later Eocene.
3. Parts of the Jan Mayen Ridge were at or above sea level from some time before the separation from Greenland until the Middle or Late Miocene.
4. The oceanic area immediately to the east of the southern part of the Jan Mayen Ridge (site 350) was above sea level at the time of its origin at the spreading axis (Eocene). This may explain why no magnetic anomaly lineations are recognized in the area.

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