34. TECTONIC SYNTHESIS

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INTRODUCTION

The tectonic evolution of the Norwegian Sea has been complex, and thus seeking evidence of this evolution has represented a unique target for deep-sea drilling. The Norwegian Sea lies between Greenland on the west and Norway and the Barents Shelf on the east. Only a portion of it, that with the Mohns Ridge in the center and the Greenland and Lofoten basins on either side, is morphologically typical of the North Atlantic. In other parts of it the axis of the mid-ocean ridge does not occupy a median position, and areas of unusually high elevation are distributed asymmetrically. Continental fragments appear to lie within the boundaries of the Norwegian Sea. Iceland, a subareal part of the mid-ocean ridge, lies on the southern end of the Norwegian Sea, and two aseismic ridges, the Iceland-Greenland Ridge and the Iceland-Faeroe Ridge, connect Iceland with Greenland and Norway, respectively. It is by no means universally accepted that the Norwegian Sea was formed by sea-floor spreading and, in order to assemble details about its evolution, drilling into the basement was important.

Regardless of what model for its evolution is accepted, it has been clear that the land connection between Eurasia and North America persisted for a long time in the area of the Norwegian Sea. Precise dates for the termination of the land bridge were needed. One consequence of the land bridge was that it provided a barrier in the circulation of water between the Arctic and the Atlantic oceans. This in turn had a profound influence on faunal differences in the two areas.

In part, because of its youth, the thickness of sediments is less in the Norwegian Sea than in the rest of the Atlantic and consequenctly the oldest basement rocks are within the reach of the drill in some areas of the Norwegian Sea. Leg 38 thus provided a unique opportunity to sample basement even as old as that produced at the time of its first opening (Table 1).

Continental fragments are believed to exist in the Norwegian Sea, and an attempt was made to obtain samples of basement in those areas. Under the hypothesis of sea-floor spreading, continental pieces within the Norwegian Sea imply a jumping of the axis of spreading. By drilling and dating basement one could indeed verify if and why jumps took place.

Further, it was of interest to inquire into the nature of the chemistry of basement rocks in areas of unusual elevation in the Norwegian Sea.

STRUCTURAL FRAMEWORK

The morphological provinces, important structural features and the earthquade epicenters which clearly define the location of the mid-ocean ridge, are shown in Figure 1. Only the Mohns Ridge portion of the mid-ocean ridge occupies a typical median position with the Greenland Basin to the northwest and Lofoten Basin to the southeast. Profiles III and IV along which geophysical data were obtained across the Mohns Ridge are shown in Figure 2. Thereon can be seen that the rift valley is associated with a large positive magnetic anomaly over the crest. In fact, there is a well-developed pattern of magnetic anomalies over all of Mohns Ridge. In particular, attention is called to anomaly 23 on the southeast side of the ridge, lying at the foot of the Vøring Plateau. Site 343 was located on this lineation. Sediment thickness is small on Mohns Ridge but increases rapidly on either side; in the northern part of the Lofoten Basin it is beyond reach of the single-channel seismic reflection profiler.

Although Mohns Ridge continues north into the Knipovich Ridge which also has a well-defined rift (Profiles I and II, Figure 2), the Knipovich Ridge clearly does not have a median position between Svalbard and Greenland. The Boreas Basin is developed only on the western side of the Knipovich Ridge; the eastern side is buried under a thick sediment cover. The rift axis lies closer to the eastern side. A consistent magnetic anomaly pattern has not been found over the Knipovich Ridge although many profiles do show a magnetic high over the rift. The question arises as to the kind of prcess that can generate the two ridges which are so different in their morphology and apparently in their geophysical structure.

The area lying north of Iceland and the Iceland-Faeroe Ridge is even more complicated. Here the deep part, represented by Norway Basin, lies on the east side. The presently active mid-ocean ridge, known as the Iceland-Jan Mayen Ridge (or the Kolbeinsey Ridge), lies on the west directly north of Iceland. South of the island of Jan Mayen and west of the northern part of the Norway Basin lies the Jan Mayen ridge. The 500-fathom contour defines the highest part of this ridge which is believed to be a continental fragment. The area lying west of it that is between the Jan Mayen Ridge and the Iceland-Jan Mayen Ridge has generally been included in the "Iceland Plateau."

The Iceland Plateau area has been subject of considerable discussion in the literature. One view is that it

TABLE 1
Faunal, radiometric, magnetic ages, Leg 38 Sites

Site	Age Range Determined from Fauna in Oldest Overlying Sediment	Radiometric Age (m.y.)	Magentic Lineation Observed or Predicted by Model of Talwani and Eldholm (in press)	Corresponding Age[a] from Heirtzler et al. Time Scale
336	Late Eocene/middle Eocene 38-49 m.y.	40-43	Between #7 and #24	Between 27 and 60 m.y.
337	Middle Oligocene/late Eocene 29-43 m.y.	18-25	4 m.y. older than #7[b]	31 m.y.
338	Early Eocene 49-53 m.y.	46.6	Between #24 and #25	Between 60 and 63 m.y.
339	Basement not reached			
340	Basement not reached			
341	Basement not reached			
342	Early Miocene[c]	44	Between #24 and #25	Between 60 and 63 m.y.
343	Early Eocene 49-53 m.y.	28.5	#23	58 m.y.
344	Pliocene/late Miocene 3-10 m.y.	3[d]	Younger than #5	Less than 10 m.y.
345	Early Oligocene/late Eocene 34-43 m.y.	27	Between #13 and #20	Between 38 and 43 m.y.
346	Basement not reached			
347	Basement not reached			
348	Early Miocene/Oligocene 16-37 m.y.	18.8	#6	21 m.y.
349	Basement not reached			
350	Late Eocene 38-43 m.y.	40-44	Between #7 and #20	Between 27 and 49 m.y.
352	Basement not reached			

[a]Heirtzler's time scale is probably too old in the early Tertiary by 5-7 m.y.
[b]Assuming a half spreading rate of 0.5 cm/yr.
[c]Eocene and Oligocene sediments are missing from seismic reflection record.
[d]Intruded sill is younger than overlying sediments.

is a part of the Jan Mayen continental fragment; the opposing view being that a large part of the Iceland Plateau has also been generated by sea-floor spreading. The Iceland-Faeroe Ridge lies east of Iceland and southwest of Norway Basin and is flat topped at about 400 meters with a rather thin sediment cover. Magnetic anomalies over it are high in amplitude, but do not reveal a discernible sea-floor spreading type pattern. Its morphology is unusual compared with the rest of the Norwegian Sea.

A number of authors including Johnson and Heezen (1967), Pitman and Talwani (1972), Johnson et al. (1972), Vogt et al. (1970), Talwani and Eldholm (in press), have suggested that the Norwegian Sea has been formed by the process of sea-floor spreading. Talwani and Eldholm (in press) have described the evolution of the Norwegian Sea in considerable detail. The drill plan for Leg 38 was chosen to test their model, to supply various details relevant to it, and to present arguments for and against it.

Their model depends on the identification of magnetic anomalies in the Norwegian Sea (Figure 3). On one hand, an orderly succession of them, from the axial anomaly through anomaly 24, is identified on Mohns Ridge, on its flanks, and in the Greenland and Lofoten basins, with anomaly 24 extending onto the Vøring Plateau. This sequence suggests an orderly development of this part of the Norwegian Sea without any jumps in the ridge axis.

On the other hand, south of the Mohns Ridge segment, the ridge spreading axis appears to have jumped several times. The Iceland-Jan Mayen Ridge is the present axis of spreading. Meyer et al. (1972) and Talwani and Eldholm (in press), as well as Johnson et al. (1972), have described its magnetic anomaly pattern. Magnetic anomaly 5 is continuous on either side (Figures 3 and 8) even though the ridge axis has two small shifts in it which presumably have taken place since anomaly 5 time. South of Jan Mayen Island lies the (presumably) continental Jan Mayen Ridge. Johnson et al. (1972) have proposed that, prior to the establishment of the spreading axis at the Iceland-Jan Mayen Ridge, spreading took place in an area between this presently spreading ridge and the Jan Mayen Ridge. Chapman and Talwani (in preparation) have identified an axis of symmetery which they believe to have the age of

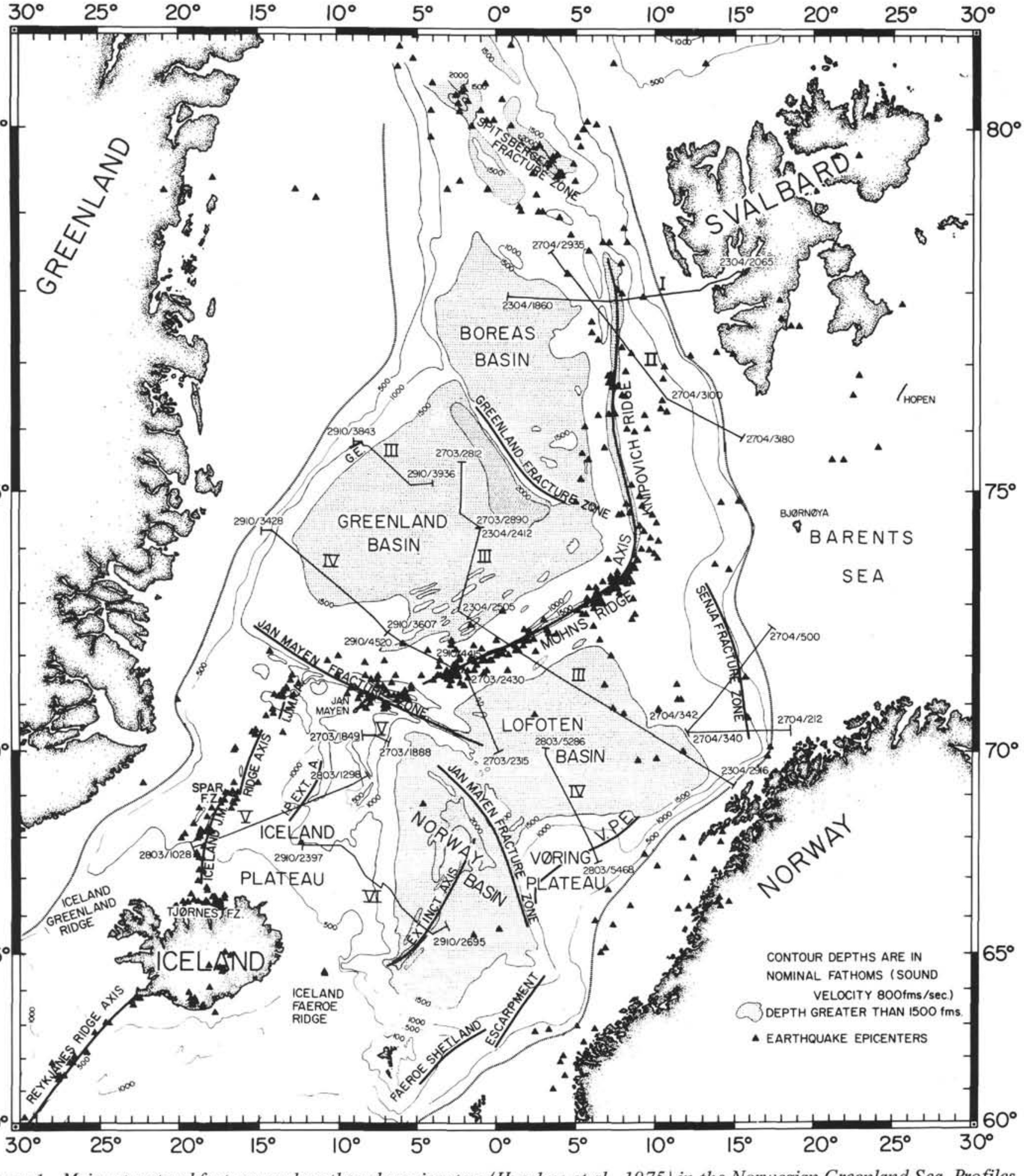

Figure 1. *Major structural features and earthquake epicenters (Husebye et al., 1975) in the Norwegian-Greenland Sea. Profiles I-IV of Figure 2 are located on this map (after Talwani and Eldholm, in press).*

anomaly 5D (according to the time scale of Blakely, 1974) and that the anomaly pattern in this area extends from 5D to 6A.

Prior to the establishment of this axis of spreading, another axis, now extinct, was present in the Norway Basin. Therein, anomalies 20 through 23 have been identified; anomalies younger than 20 exist, but they have not been definitely correlated with a magnetic time scale. Talwani and Eldholm (in press) believe that this axis became extinct close to anomaly 7 time. According to them it is likely that, prior to anomaly 23, still another spreading axis existed in the area between the

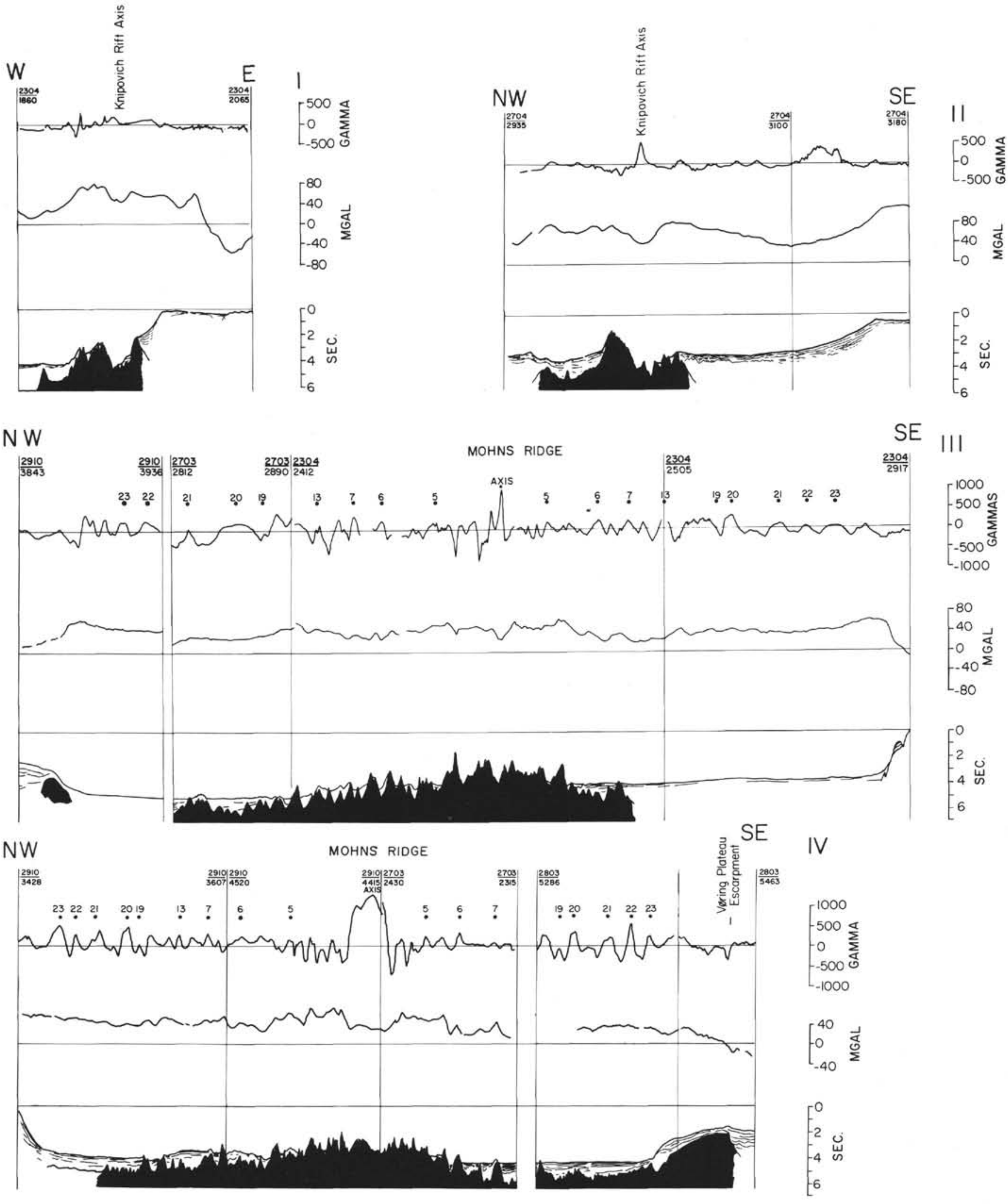

Figure 2. *Composite profiles showing total intensity magnetic data (IGRF removed), isostatic gravity anomalies (two-dimensional airy-type with depth of compensation 30 km), and reflection profiler data (basement is shown black). For location of profiles see Figure 1 (after Talwani and Eldholm, in press).*

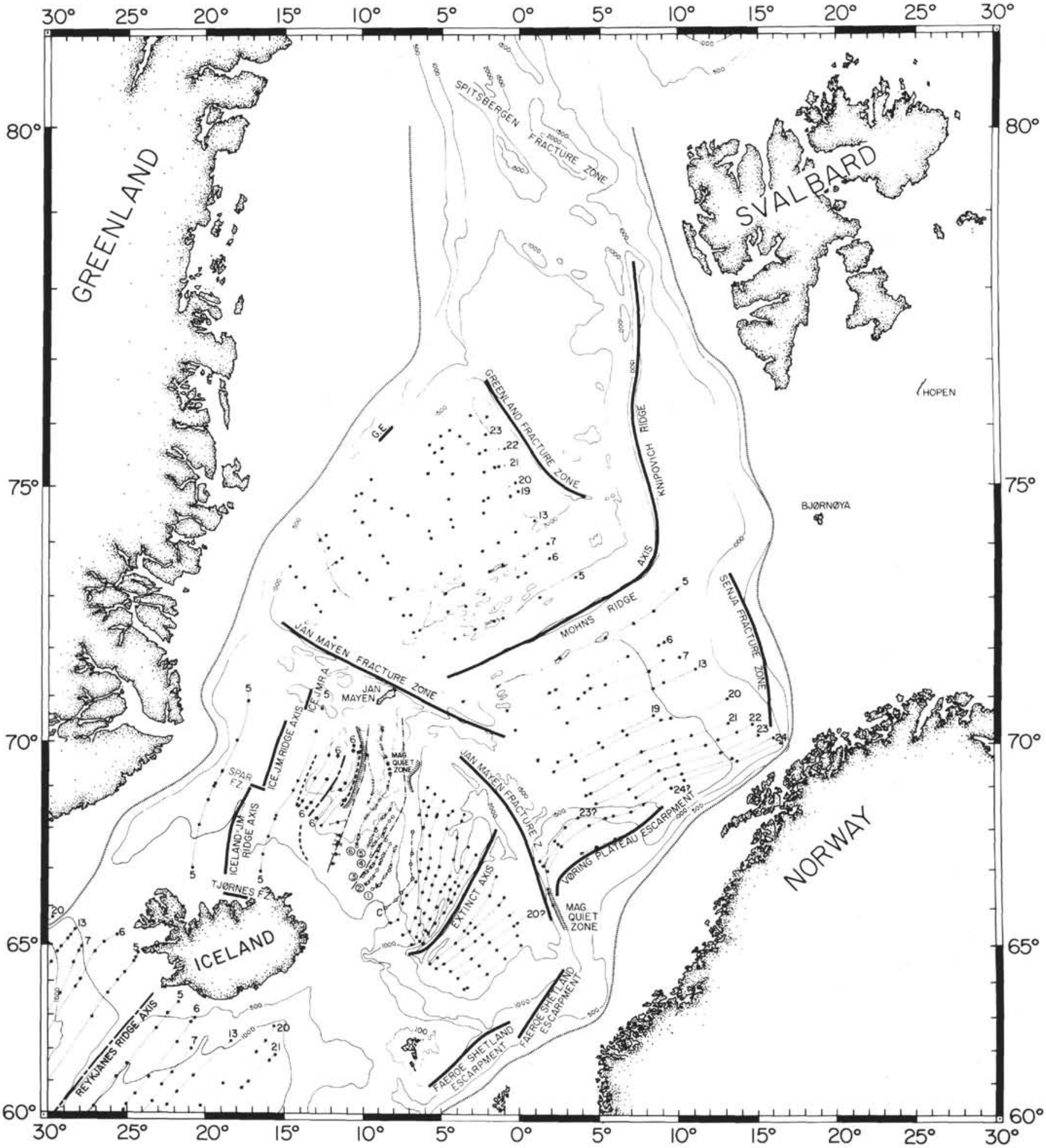

Figure 3. *Identified magnetic lineations in the Norwegian Sea. For details in the area of the Norway Basin and the Icelandic Plateau, see Figure 8. (After Talwani and Eldholm, in press.)*

Faeroe-Shetland Escarpment and the 1500-fathom contour in the Norway Basin.

The shift of the ridge axis from the Norway Basin has been discussed by several authors. Johnson and Heezen (1967) first postulated the jump on the basis of the asymmetric position of the presently active Jan Mayen Ridge between Greenland and Norway. Vogt et al. (1970) and Le Pichon et al. (1971) also favored this hypothesis of shift in the ridge axis. The three jumps described above have been detailed by Talwani and Eldholm (in press).

The first axis that was active between the time of opening until shortly before anomaly 23 time lies on the slope east of Norway Basin. The axis then jumped to form the prominent extinct axis of the Norway Basin. After spreading continued to about anomaly 7 time, the axis jumped again. In doing so, it broke off a fragment of the Greenland margin. This fragment now forms the Jan Mayen Ridge. Spreading anomalies between 6A and 5D have been identified with this axis of spreading west of the Jan Mayen Ridge. A final jump of the spreading axis to the presently active Iceland-Jan Mayen Ridge; anomalies from 5 through the present active anomalies are identified with it.

Sea-floor spreading type magnetic anomalies have not been definitely identified on the Iceland-Faeroe Ridge; its flat-topped morphology does not suggest a typical mid-ocean ridge. However, the Norwegian Sea has been created by moving apart of Greenland and Norway to produce new sea floor, and because no important transform faults have been identified within Norway and Greenland perpendicular to their continental margins, it follows, from geometrical considerations, that the Iceland-Greenland Ridge, Iceland, and Iceland-Faeroe Ridge also represent new sea floor. Talwani and Eldholm (in press) have suggested that Iceland-Faeroe Ridge was created by sea-floor spreading between the time of opening of the Norwegian Sea to about anomaly 7 time. At the same time that the axis of spreading shifted from the extinct axis in the Norway Basin to a new axis west of the Jan Mayen Ridge, the spreading axis also jumped west from the Iceland-Faeroe Ridge to Iceland, which was formed subsequently. In this hypothesis, the Iceland-Faeroe Ridge is, in a sense, considered to be a submarine extension of Iceland. Because of the subsidence of the mid-ocean ridges with time, it would be expected that at one time, the Iceland-Faeroe Ridge was above sea level. The question of when it subsided below sea level thus becomes important.

In the north, where despite the fact that the present Knipovich Rift is continuous with Mohns Ridge, there seems to be no prominent magnetic anomaly pattern associated with it. In addition, Knipovich Rift lies anomalously closer to Svalbard than it does to Greenland, and no deep basins exist between the rift and Svalbard. Nevertheless geometrical arguments again demand that the area between Svalbard and Greenland must also have been created by the same process that created the rest of the Norwegian Sea.

Within the framework of plate tectonics, the movement of a rigid plate on a spherical earth can be described by its motion with respect to a pole of rotation. To describe the opening of the Norwegian Sea in quantitative terms, Talwani and Eldholm (in press) identified four prominent sets of lineations on either side of the mid-ocean ridge in the Norwegian Sea. These were lineations corresponding to anomalies 5, 13, 21, and 23. By trial and error the location of a finite pole of opening, as well as an amount of rotation, were determined such that if anomaly 5 on the west side was correspondingly rotated to the east side, the rotated lineation matched the lineations on the east side. This gave a finite pole of opening since anomaly 5 time. Similarly finite poles of opening since anomaly 13 time, anomaly 21 time, and anomaly 23 time were determined. The finite rotations were subtracted from each other to obtain the finite difference poles to represent the motion between, for example, anomaly 5 time and 13 time. By assuming that the pole of opening remained fixed during each such interval of time, these finite difference poles were assumed to give instantaneous poles of rotation during the corresponding interval. In this manner instantaneous poles of rotation were obtained since the time of opening. A check on the procedure is to obtain the flow lines corresponding to the poles of rotation. These flow lines would match fracture zones.

The instantaneous poles of rotation thus obtained can be used to synthesize the flow lines and the isochrons in the Norwegian Sea. These are shown in Figure 4. To demonstrate the match of the synthetic data to the observed data, flow lines can be compared with the fracture zones and the isochrons with the identified magnetic lineations. It can be noted that the match is fairly good in the Reykjanes Ridge and the Mohns Ridge as well as on the presently active Jan Mayen Ridge.

In the Norway Basin it can be seen that the observed anomaly 21 cuts across the isochrons showing that the synthetic motions do not accurately represent the actual motions. Talwani and Eldholm (in press) suggested the following explanation for this mismatch. During a portion of the time that the Norway Basin was opening, there was another axis opening to the southwest of the Norway Basin. Thus, for a period of time, two spreading axes, rather than a single opening at the prominent extinct axis of the Norwegian Sea, together provided the total opening. The synthetic model at any rate provides a basis for comparison of ages actually determined from samples obtained by drilling.

OUTSTANDING PROBLEMS, SELECTION OF SITES, AND DRILLING RESULTS IN DIFFERENT AREAS

Iceland-Faeroe Ridge

The bathymetry of the Iceland-Faeroe Ridge obtained from detailed surveys conducted by the German Hydrographic Office (Fleischer et al., 1974) is shown in Figure 5. The top of the Iceland-Faeroe Ridge is nearly flat, at about 400 meters depth. Depths increase rapidly northeast towards Norway Basin and towards the southwest into Reykjanes Basin. The map of residual total magnetic intensity constructed by Fleischer et al. (1974) (see Site Survey Chapter 2, this volume) shows large amplitudes, short wavelength magnetic anomalies, but without a discernible lineated pattern. A sediment isopach map (Figure 6) of the Iceland-Faeroe Ridge has been constructed (Kristofferson and Talwani, in preparation). This map shows that basement outcrops at a number of places on the Iceland-Faeroe Ridge. At other places the sediment thickness is less than 0.2 sec double reflection time. The sediment thickness increases rather notably to the southeast. It also increases to the southeast and to the west of the ridge immediately southeast of Iceland.

We have stated earlier that because of geometrical considerations, it appears reasonable to assume that the

Figure 4. *Magnetic anomaly locations are as follows: Circles (anomaly 5), squares (anomaly 13), triangles vertex up (anomaly 21), triangles vertex down (anomaly 23), asterick denotes anomaly 6 in the Icelandic Plateau area. Using the total opening poles (as developed by Talwani and Eldholm, in press), the anomaly locations on the west side rotated to the east side are indicated by solid circles, squares, and triangles. As explained in the text, the isochrons and flow lines used are generated from the "finite difference poles." Where the observed anomalies do not agree with the synthetic isochrons, the simplified model is in error (after Talwani and Eldholm, in press).*

Iceland-Faeroe Ridge was caused by some form of sea-floor spreading as Greenland and Norway moved apart. However, it is clear that the processes involved are different from those operating at typical mid-ocean ridges. Relief typical of mid-ocean ridge does not exist here. The magnetic pattern also does not show any identifiable sea-floor spreading type anomalies. Because of these reasons, no spreading axis could be postulated for constructing synthetic isochrons shown in Figure 4. However, Talwani and Eldholm (in press) have suggested that an axis of spreading probably existed on the Iceland-Faeroe Ridge from the time of opening of the Norwegian Sea to about anomaly 7 time (about 27 m.y. ago) and that at this time the axis jumped westward to form Iceland; simultaneously the axis in the Norway Basin jumped west to form the Icelandic Plateau. Under this hypothesis the range of ages expected on the Iceland-Faeroe Ridge would be between approximately 27 m.y. to about 55 m.y. (time of initial opening). From the initiation of spreading to the time of the shift, the spreading axis could have shifted many times on the Iceland-Faeroe Ridge. We do

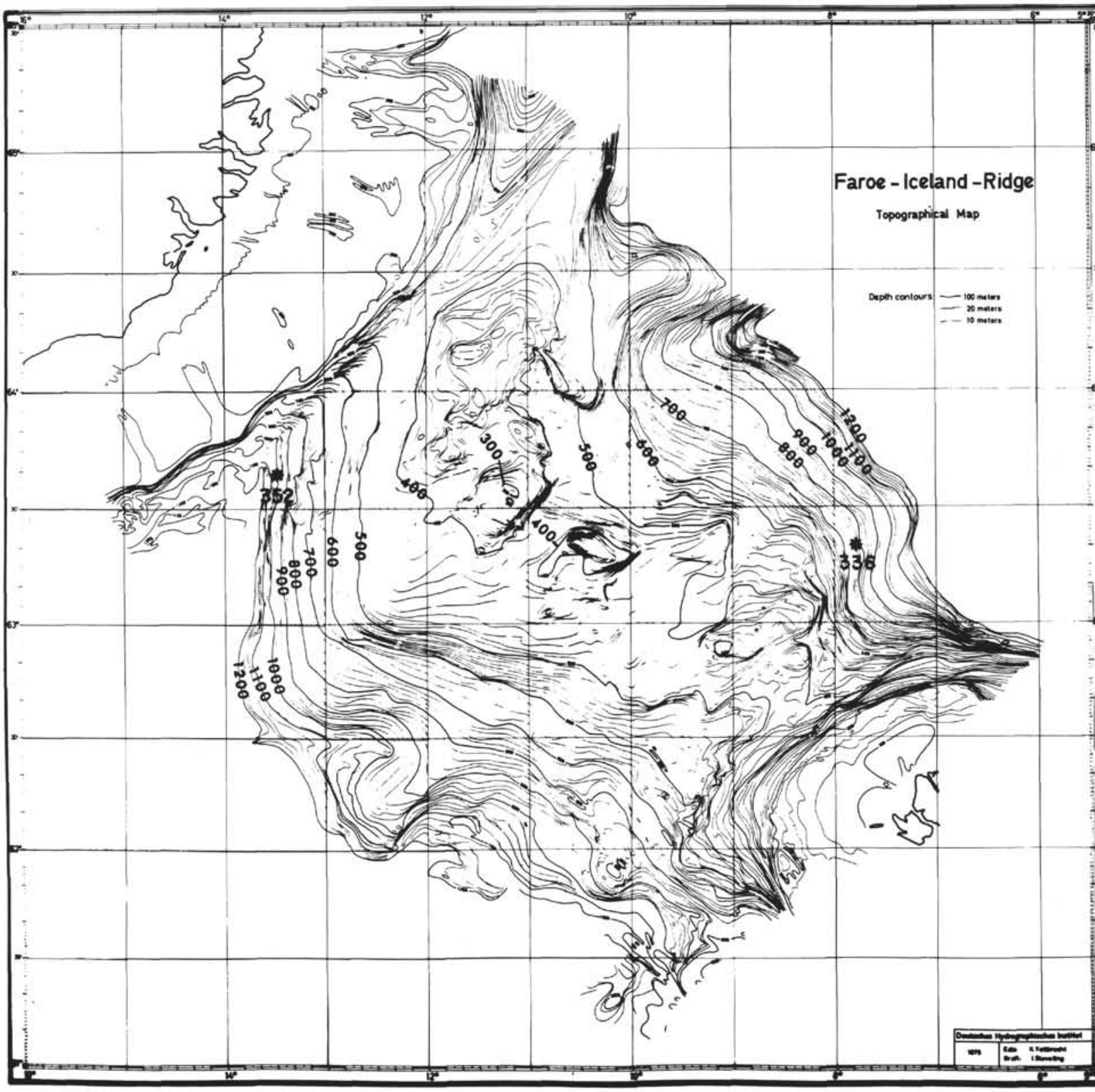

Figure 5. *Bathymetry of the Iceland-Faeroe Ridge obtained by detailed surveys conducted by the German Hydrographic Office (from Fleischer et al., 1974).*

not know whether or not this happened. Perhaps the simplest assumption is that there was a single axis. If the Iceland-Greenland Ridge was also created by spreading at this single axis, then this extinct axis on the Iceland-Faeroe Ridge lies somewhat closer to Iceland than the Faeroes.

In choosing sites for drilling, we wanted the sediment thickness to be small enough so that basement could be reached, but at the same time we wanted a thick enough sequence of sediments in order to learn as much about sediment history as possible. Since it is generally difficult on *Glomar Challenger* to drill at depths less than 500 meters, the sites had to be located off the top flat portion of the Iceland-Faeroe Ridge. The sediment thickness at the two sites selected (336 and 352) is seen in the isopach map in Figure 6, as well as in the reflection profiler sections in Figure 7. Figure 6 shows that the sites are located in what appear to be sediment-filled valleys. One may speculate that originally submarine canyons existed in both locations and these sites are located above the walls of the now filled-in canyons. Therefore it would not be surprising if part of the sedimentary section was missing.

Drilling at Site 336 showed the presence of "rubble" immediately above the basalts which suggests subaerial weathering. The basalt, which is petrologically not atypical of mid-ocean ridge basalts, was extruded above sea level. It now lies at a depth of more than 1300 meters below sea level, therefore at least a subsidence of this amount has taken place. Although the actual situation may have been considerably more complicated, let us for the sake of simplicity assume that isochrons on

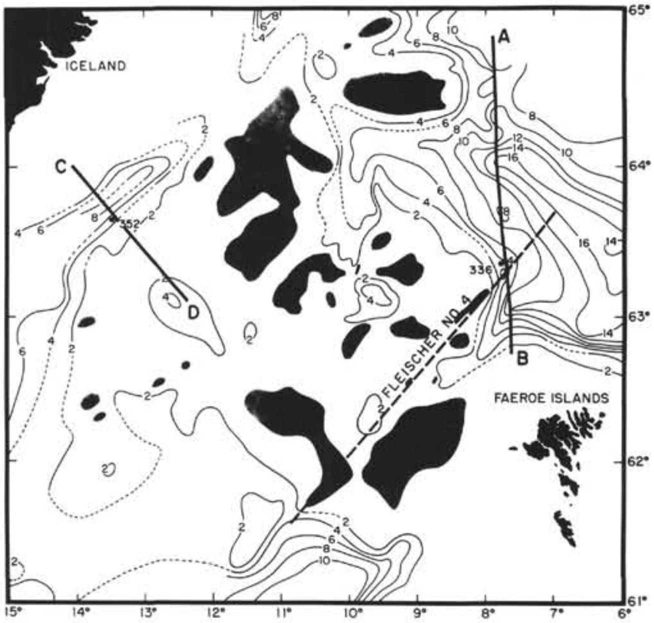

Figure 6. *Sediment isopach map of the Iceland-Faeroe Ridge after Kristoffersen and Talwani (in preparation).*

the Iceland-Jan Mayen Ridge have a roughly northeast-southwest strike, that is, perpendicular to the length of the ridge. Site 336 lies on the northern flank of the Iceland-Faeroe Ridge. The isochron passing through it also passes over the crest of the ridge where basement is now exposed at nearly 400 meters. Therefore basement at Site 336 lies at a depth more than 900 meters greater than the minimum depth of basement of the same age on the Iceland-Faeroe Ridge. Ignoring erosion and differential subsidence due to loading, the point on the crest of the Iceland-Faeroe Ridge with the same age as basement at Site 336 was more than 900 meters above sea level when basement close to sea level was extruded at Site 336. It took about 30 m.y. for the crest to subside below sea level. The age of basement here is approximately 45 m.y., it, therefore, subsided below sea level at 15 m.y.

At this time, the points at the crest of the Iceland-Faeroe Ridge at which the age of basement was younger than 45 m.y. were still above sea level, those with ages older than 45 m.y. had already subsided below sea level. The erosional history of the subaereal Iceland-Faeroe Ridge is not known; nor can we say with certainty that all points of the Iceland-Faeroe Ridge, when first formed, stood at the same elevation. Yet if the Iceland-Faeroe Ridge was formed between 55 m.y. and 27 m.y., we can hazard a guess that the oldest points in the Iceland-Faeroe Ridge probably did not subside below sea level until about 25 m.y. (55-30 m.y.), and the youngest points subsided even later than 15 m.y. ago. Thus at 25 m.y. ago, the time of the jump of the ridge axis westward from Iceland-Faeroe Ridge to create Iceland, part of Iceland-Faeroe Ridge had begun to subside. This, therefore, can be taken as the best estimate of the date at which the land bridge was breached between Eurasia and Greenland. Even after this time, parts of the Iceland-Faeroe Ridge were still presumably above sea level. It was not until sometime in the Miocene that the entire Iceland-Faeroe Ridge subsided below sea level.

The faunal evidence at Sites 336 and 352 suggests that there was indeed a barrier to circulation between these two sites until late middle Oligocene. The faunal evidence is thus not in conflict with the deduced history of subsidence of the Iceland-Faeroe Ridge. A hiatus extending through the Miocene and Pliocene exists at both sites. It is perhaps possible to explain this hiatus by examining the location of the sites on both sides. Both of them lie in areas where the sediment isopach map (Figure 6) suggests that submarine canyons were present at one time, but have been buried by later sediments. The submarine canyons, when active, may have, through erosion and nondeposition, been responsible for the absence of the missing sediments.

Before the land bridge was breached, the Norwegian Sea was cut off from the North Atlantic. According to Talwani and Eldholm (in press), the Greenland Sea did not open until the early Oligocene. Thus, when Norway Basin and Lofoten Basin first began to form as a result of sea-floor spreading in the Norwegian Sea, these basins were cut off by the Iceland-Faeroe Ridge from the Atlantic to the south. They were also cut off in the north from the Arctic because the opening between Svalbard and Greenland had not taken place. To the west lay the Jan Mayen Ridge which was still attached to Greenland and formed part of its continental slope and, to the east, Norway. The only circulation was with the North Sea and through it to the basins in northern Europe which accounts for the faunal similarities in the Eocene between the Norwegian Sea with the basins in the North Sea and in northern Europe.

The age of basement is of considerable interest at Site 336 where basement rocks were recovered. Radiometric determinations are 40.4 ±3.2 m.y. by the Russian group and 43.4 ±3.3 m.y. by the German group. Sediments immediately overlying the basalt (Cores 38 to 40) are barren of sediments. The older sediments, dated paleontologically, are at least as old as late Eocene. It is possible to extend this date back to middle Eocene on the basis of benthic foraminifers. It seems that an age of 45 m.y., close to the late/middle Oligocene boundary, is the best that can be given for this site. The age of formation of the Iceland-Faeroe Ridge is the same as that of the Norway Basin as Talwani and Eldholm (in press) have suggested, that is, from about 55 m.y. to 27 m.y. The age determinations are not in conflict with this hypothesis, but the age is less than that of the youngest basalt series found on the Faeroes.

Norway Basin

The identified magnetic lineations on the Norway Basin and the bathymetry contoured at 500-fathom intervals are shown in Figure 8. Various topographic profiles and magnetic profiles across the Norway Basin are shown in Figures 9 and 10, respectively.

Figure 10 clearly shows the presence of magnetic lineations of the type associated with sea-floor spreading. The topographic profiles show the linear depression which has been identified by Talwani and

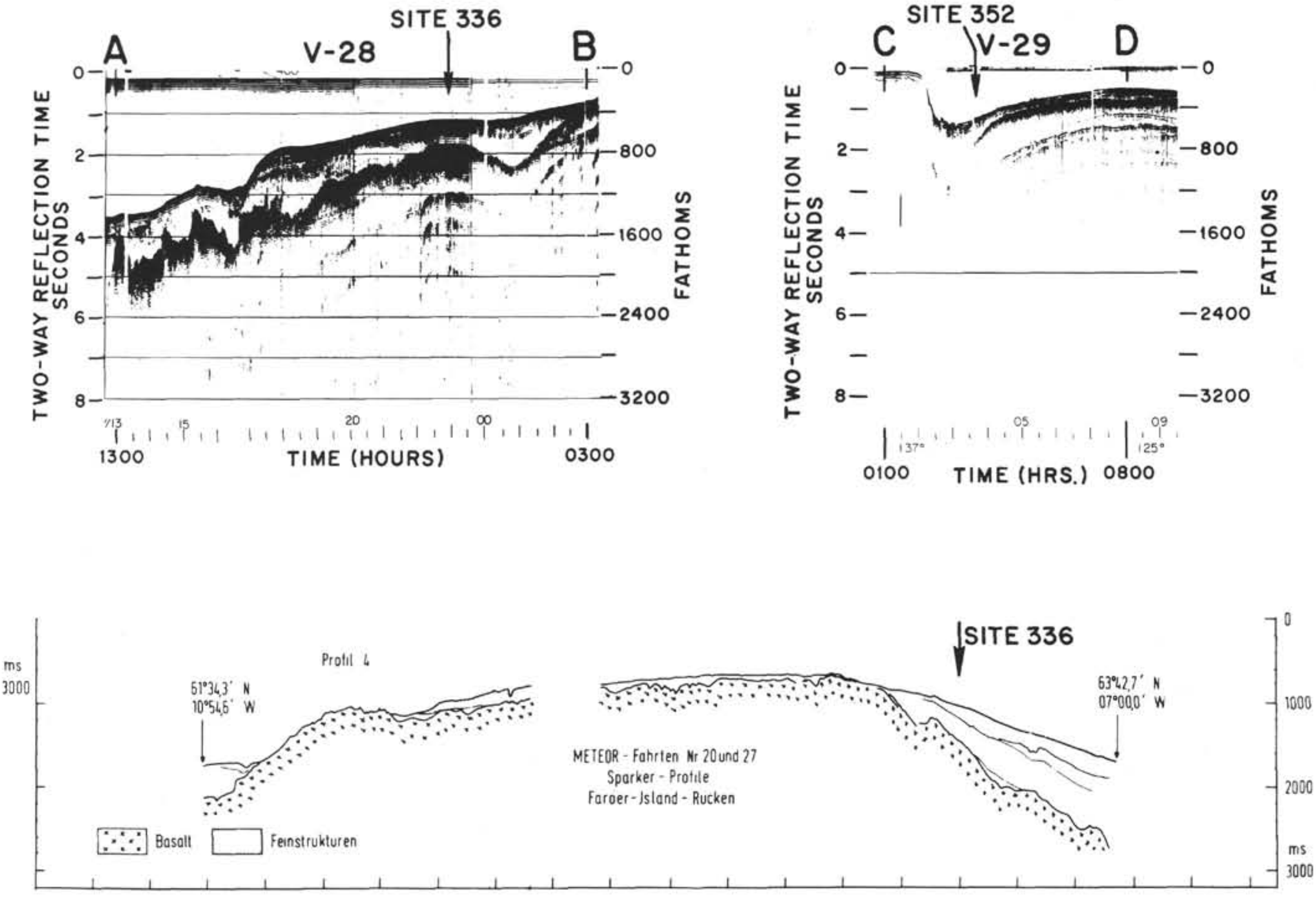

Figure 7. *Seismic reflection profiles over the Iceland-Faeroe Ridge. The location of these profiles is given in Figure 6.*

Eldholm (in press) as the extinct rift in the Norway Basin. Coincident with this extinct rift axis is the axis of symmetry of the magnetic lineations—a magnetic high. Only the older magnetic anomalies in the Norway Basin have been identified with certainty. These are anomalies 20, 21, and 22. The magnetic lineations converge southwards around the extinct axis (Figure 8). This has made it difficult to identify the magnetic lineations at the extinct axis.

We wanted to drill as close to the extinct axis as possible in order to determine its age. Sediment thickness in the extinct rift is generally quite large; therefore a site was picked on the "rift mountains" on the east side of the rift valley. Profiler records obtained on *Vema* Cruise 30 (Site Survey chapter) show the thickness and distribution of sediments close to Site 337. The sediment thickness is also depicted in the *Glomar Challenger* records obtained over the site (Site Report Chapter 3). The eastward continuation of profile E-F in Figure 14 shows the sediment distribution on the rift mountains although at a point which is some distance northeast of Site 337. Over the rift mountains the sediment thickness is variable, ranging from nearly zero to a few hundred meters. One has to go a considerable distance east of the extinct axis to reach an area where the sedimentation is not disturbed by shallow basement relief, but in such areas the thickness of sediment is so large that basement cannot be reached by drilling from *Glomar Challenger*.

As far as the magnetics are concerned, Site 337, located about 20 km east of the extinct axis lies on the steep slope in the magnetic anomaly between the central maximum and the first minimum to the east. Basement consists of tholeiitic basalt typical of mid-ocean ridges. The presence of several horizons of breccia believed to represent pillow lavas leaves little doubt that the basalt here was extruded.

The age of the sediments immediately above basement has been difficult to determine. On one hand the best estimate comes from silicoflagellates which indicate a range from middle Oligocene to late Eocene (29 m.y. to 43 m.y.). On the other hand, radiometric ages determined for basement are much younger—17.5 ±1.5 m.y. by the Russian group and 25.5 ±2.4 m.y. by the German group (Kharin et al., this volume). They also suggest that argon loss may have occurred leading to a smaller determined age for basement. To reconcile the two kinds of data, we have tentatively assigned the youngest paleontological date to the sites, which is 29 m.y. We can use this age to estimate the age at which the spreading axis became extinct in the Norway Basin. The half spreading rate in the Mohns Ridge just prior

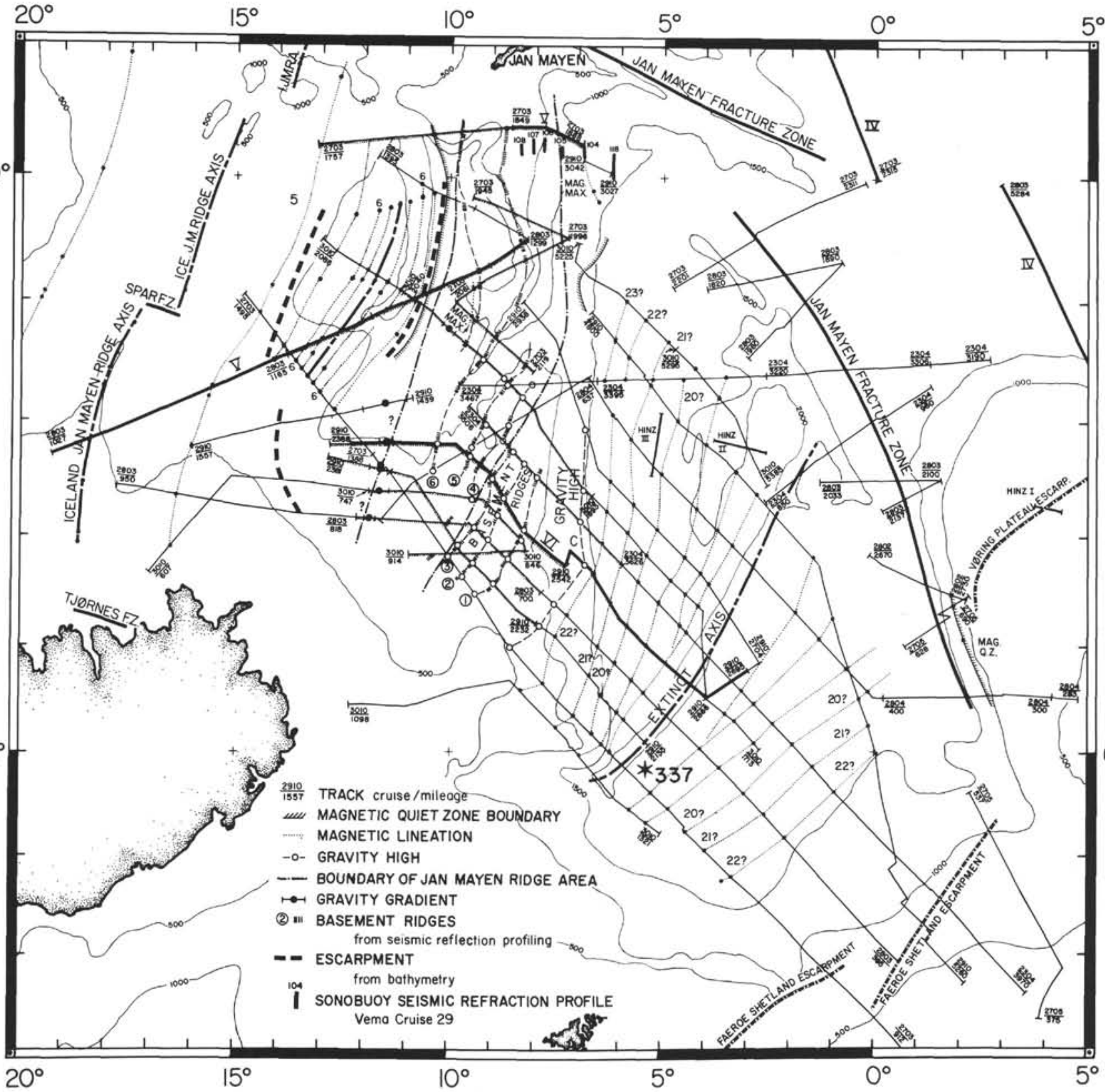

Figure 8. *Map of area between Jan Mayen Fracture Zone and the Iceland-Faeroe Ridge. This area can be defined into four parts* (i) *the Norway Basin which roughly lies within the 1500-fathom contour and has an extinct axis;* (ii) *the Jan Mayen Ridge region whose east and west boundaries are indicated by dot-dash lines;* (iii) *the region produced by spreading about the extinct Icelandic Plateau axis. Between roughly 69°N and 70°N, this region is bounded by topographic ridges or escarpments denoted by the heavy dashed lines. Spreading took place from between anomaly 6A time to anomaly 5D time;* (iv) *the now active Iceland-Jan Mayen Ridge. Spreading about roughly the present axis has gone on since anomaly 5 time. Six basement ridges, numbers 1, 2 . . 6 have also been mapped from seismic reflection and isostatic gravity profiles. The three western ridges interrupt the opaque layer and have progressively greater elevation northward, finally coalesce to form the Jan Mayen Ridge block. The three eastern ridges 1, 2, and 3 on the other hand, are covered or formed by the opaque layer as seen in seismic reflection profiles (Eldholm and Windisch, 1974). In our interpretation the area of these eastern ridges which lie between the southern part of the Jan Mayen Ridge and the area of the prominent anomalies of the Norway Basin, is oceanic; it was formed by sea-floor spreading in a complementary fashion to the fan-shaped lineations of the Norway Basin. This map also serves as an index map for the profiles across the Norway Basin (Figures 9 and 10) (after Talwani and Eldholm, in press).*

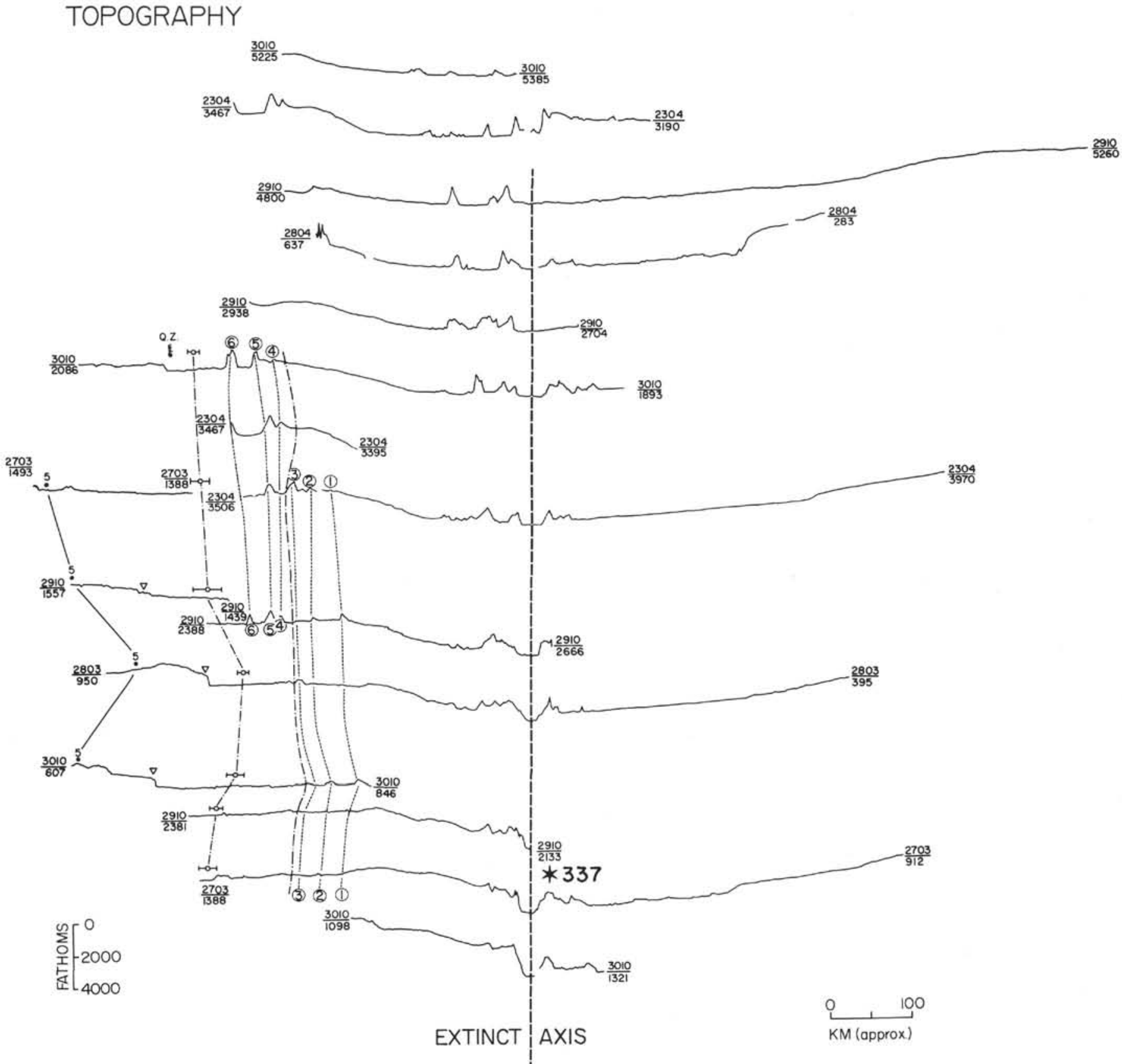

Figure 9. *Projected topographic profiles across the Norway Basin and the southern part of the Jan Mayen Ridge area. See also caption of Figure 10 (after Talwani and Eldholm, in press).*

to anomaly 7 time was 0.5 cm/yr and subsequent to anomaly 7 was 0.8 cm/yr. Ignoring the contemporaneous axis of spreading at this time, and using these spreading rates and the distance of 20 km from Site 337, an age of about 25 to 27 m.y. would be indicated for the spreading axis which agrees well with the age of anomaly 7 (27 m.y.). Shortly after that time the spreading axis jumped west of the Jan Mayen Ridge. It must be pointed out however, that because the large range in the paleontologically determined age for overlying sediments and the discrepancy with the radiometrically determined age of the basalt, our determination of the age of the spreading axis is not absolutely certain.

Jan Mayen Ridge

A physiographic diagram of the area north of Iceland which includes the Jan Mayen Ridge is shown in Figure 11. A smaller area is outlined within this physiographic diagram and a detailed bathymetric chart of the smaller area and the magnetic anomalies plotted along track in the smaller area are shown in Figures 12 and 13, respectively.

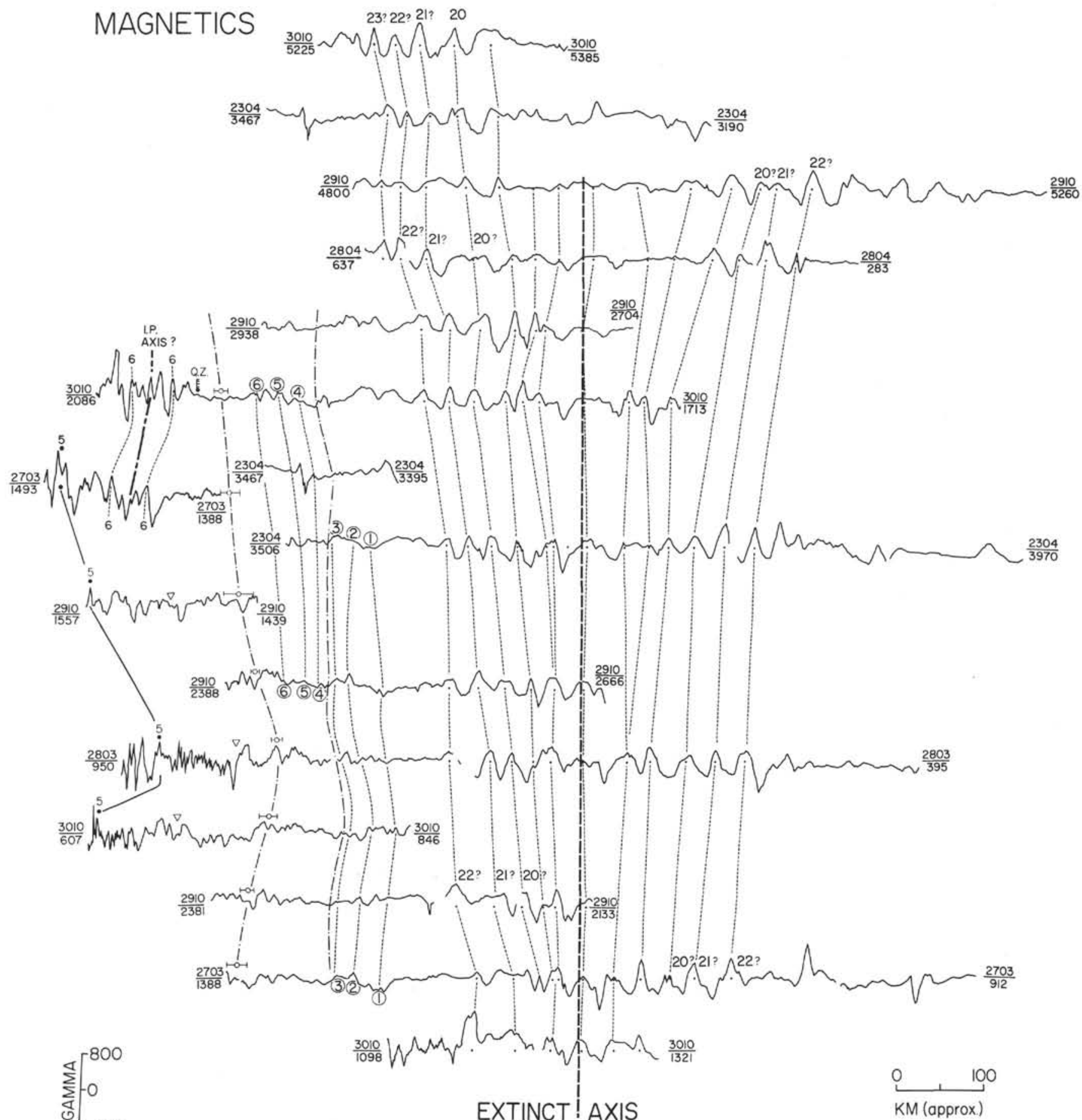

Figure 10. *Projected magnetic (total intensity, IGRF removed) profiles across the Norway Basin and the southern part of the Jan Mayen Ridge area. Identification of anomalies younger than anomaly 20 in the Norway Basin is uncertain. The location of the extinct axis, as well as ridges 1 through 6, is based on gravity data. The region of strong gravity gradients on the western side of the Jan Mayen Ridge area is indicated by the bars with a circle in the center. The western and eastern boundaries of the Jan Mayen Ridge region are indicated by the dot-dash lines. Triangles in the Icelandic Plateau area indicate topographic escarpments (after Talwani and Eldholm, in press).*

Grønlie and Talwani (in preparation) have divided the area near the Jan Mayen Ridge into eight regions (Figures 12 and 13). Region 1, which possesses a magnetic quiet zone, contains the main block of the Jan Mayen Ridge. This main block contains Sites 346, 347, and 349 and is clearly seen in the physiographic diagram. South of Region 1 lies Region 2 which has a somewhat more disturbed magnetic field. Regions 1

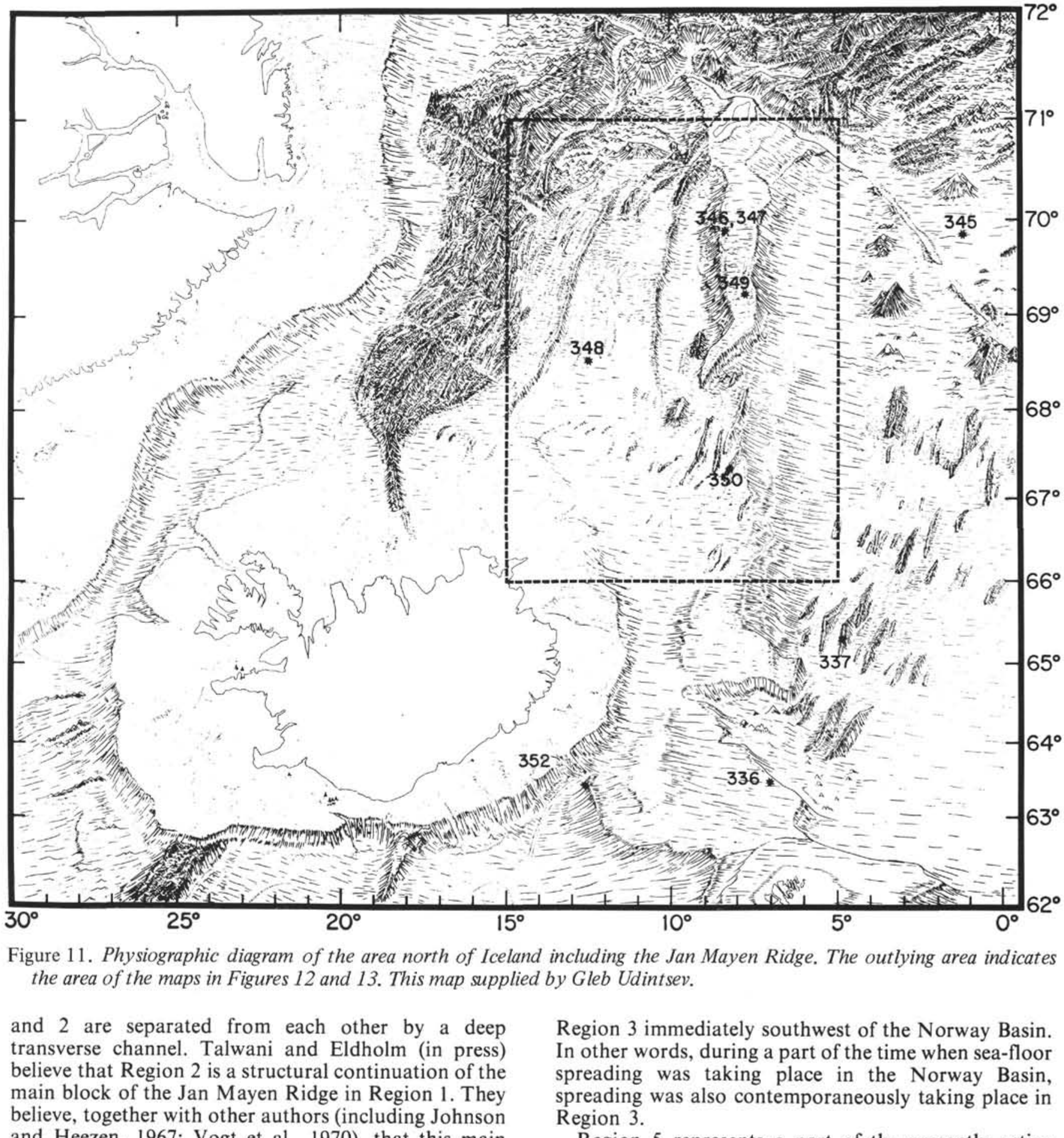

Figure 11. *Physiographic diagram of the area north of Iceland including the Jan Mayen Ridge. The outlying area indicates the area of the maps in Figures 12 and 13. This map supplied by Gleb Udintsev.*

and 2 are separated from each other by a deep transverse channel. Talwani and Eldholm (in press) believe that Region 2 is a structural continuation of the main block of the Jan Mayen Ridge in Region 1. They believe, together with other authors (including Johnson and Heezen, 1967; Vogt et al., 1970), that this main block is a continental fragment. The ridges in Region 2 also represent continental material, but they are more subsided than in Region 1. However, Region 3, although it appears to be morphologically a part of the Jan Mayen Ridge, is believed to have a different origin.

The fan-shaped pattern of magnetic anomalies in the Norway Basin has been mentioned earlier. From geometrical conciderations, the presence of the fan-shaped pattern demands that a contemporaneous sea-floor spreading must also take place in another area. Talwani and Eldholm (in press) believe this area to be Region 3 immediately southwest of the Norway Basin. In other words, during a part of the time when sea-floor spreading was taking place in the Norway Basin, spreading was also contemporaneously taking place in Region 3.

Region 5 represents a part of the presently active Iceland-Jan Mayen Ridge. The oldest anomaly identified with this spreading axis is anomaly 5 (Figure 13). Johnson et al. (1972) believed that when the shift of the ridge axis took place in the Norway Basin, it did not immediately move to the present Iceland-Jan Mayen Ridge, but that there was an intermediate axis of spreading which produced the anomalies in Region 4. Chapman and Talwani (in preparation) have identified the magnetic anomalies in Region 4 (Figure 13). The lineations range in age from anomaly 5D to anomaly 6A according to the time scale of Blakely (1974).

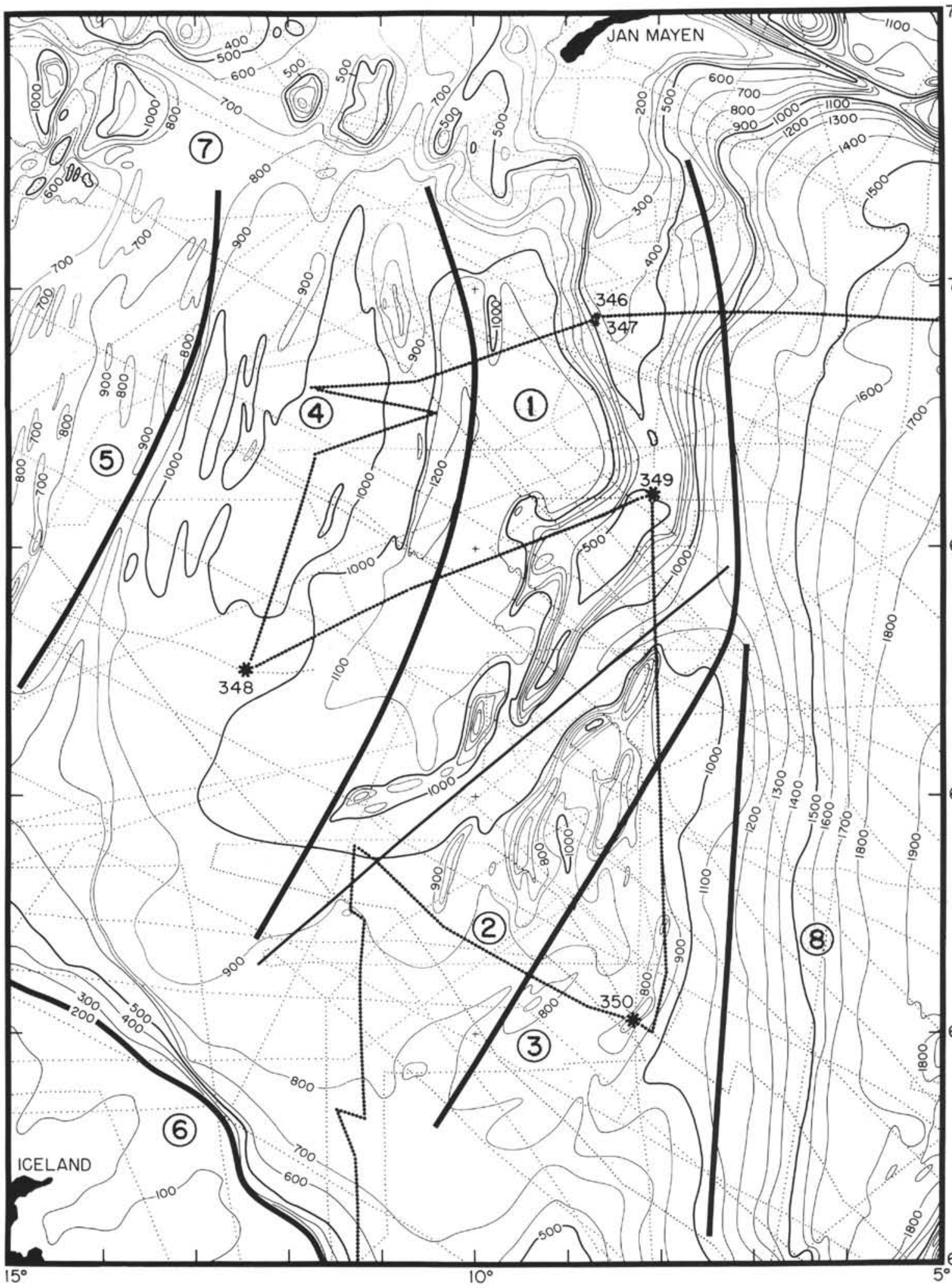

Figure 12. *The bathymetric map of the Jan Mayen Ridge area is a portion of a larger map constructed by Grønlie et al., (in preparation). The depths are in uncorrected fathoms. Track of the* Glomar Challenger *and the drill sites are indicated. The division into different areas 1 through 8 is discussed in the text.*

Anomaly 5D lies on the extinct axis, its age is about 18.3 m.y. Anomaly 6A has an age of 24.3 m.y., therefore the intermediate axis spreading roughly encompasses the period between 18 and 24 m.y. ago.

The physiography of the northern block-like part of the Jan Mayen Ridge is shown in Figures 11 and 12. Seismic reflection records in the area are shown in the Site Report chapter. Reflection records along profile C-

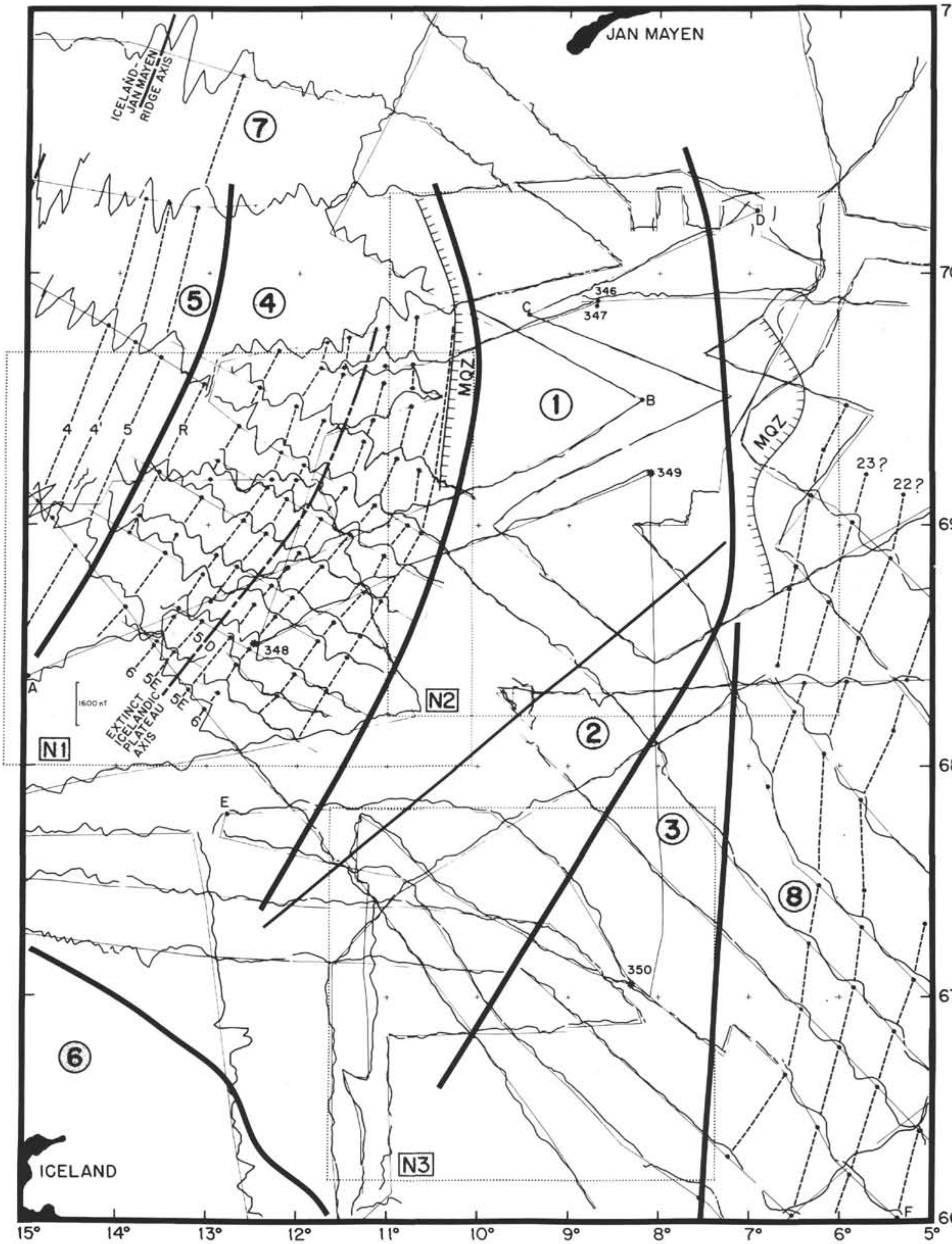

Figure 13. *Magnetic anomalies plotted along track in the area of the Jan Mayen Ridge (after Grønlie and Talwani, in press). The anomaly identification in the area of the extinct Icelandic Plateau axis is from Chapman and Talwani (in preparation).*

D are shown in Figure 14. A composite picture of the Jan Mayen Ridge from the reflection data and from the refraction data (Figure 15) is also shown in Figure 14. From Figures 14 and 15 we see that on the block-like Jan Mayen Ridge parallel reflectors exist just underneath the bottom. These sediments have a velocity of about 1.85 km/sec associated with them. The refraction results show that below the flat-lying top layers

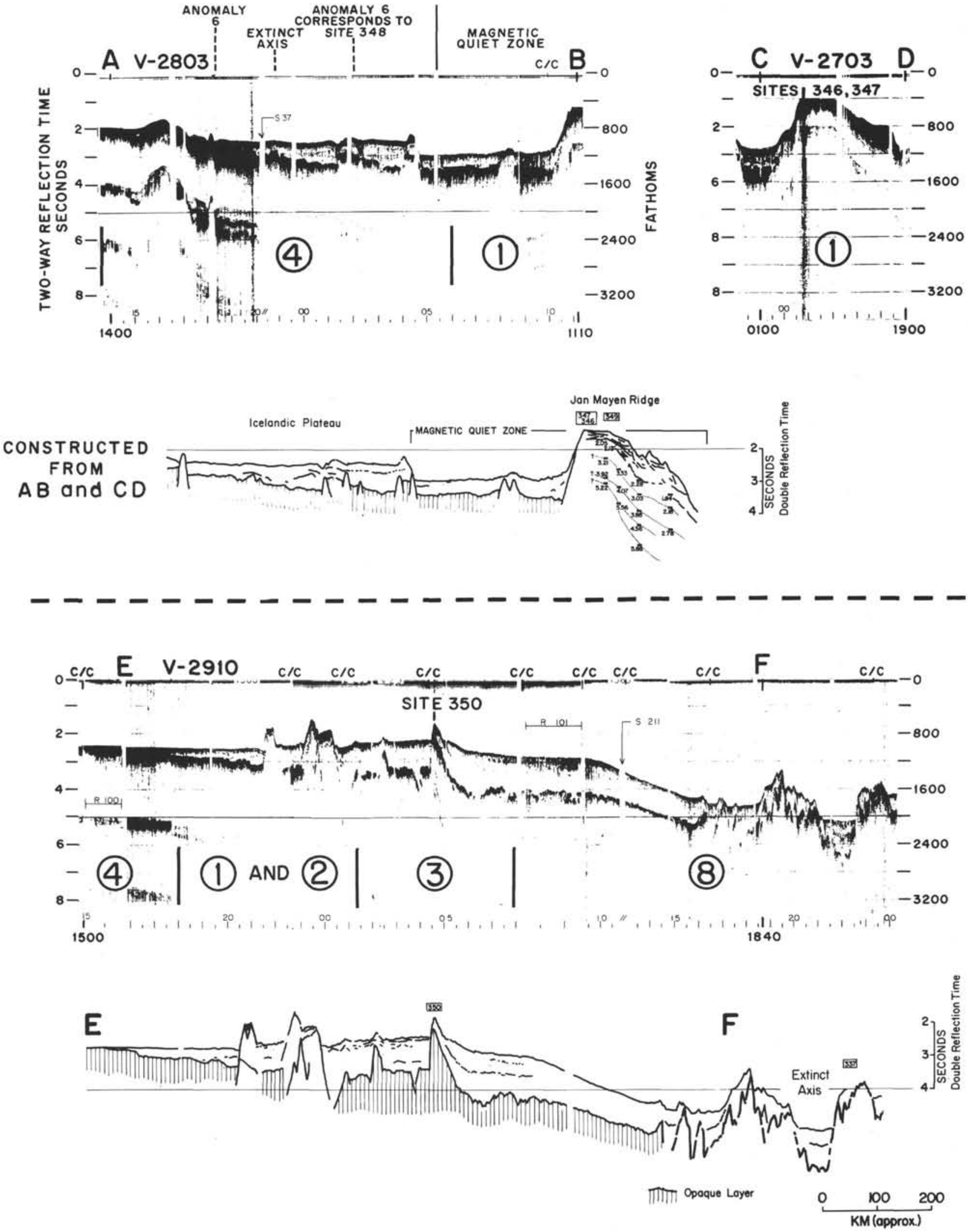

Figure 14. *Seismic reflection records along profiles A-B, C-D, and E-F. These profiles are located in Figure 13.*

lower layers exist which dip to the east. These are also seen in some of the reflection profiles (Site Survey chapter). Steeply dipping, they are truncated by a prominent reflector which forms the base of the flat-lying sediments on top.

We believe that the layer with a velocity of greater than 5 km/sec probably represented basement. Neither the reflection records nor the refraction results are clear on where basement lies near the western edge of the block. Extrapolating the apparent steep slope of the basement surface westwards, and noting the steep topographic western slope of the Jan Mayen Ridge, we believe it possible that basement outcrops on the topographic slope and that it may represent the western part of a basement ridge. Site 346 was located toward the western edge of the topographic platform. It had two principal objectives: to penetrate through the flat-lying sediments on the top through the unconformity associated with the prominent reflector and into the dipping reflectors below it. Because of the steep easterly dip, a site on the western edge of the platform was most likely to sample the oldest sediments; secondly, if the arguments presented above are correct, it provided the best opportunity to reach basement. Basement, however, was not reached at Site 346 and therefore, in an attempt to reach it, we located Site 347 even further to the southwest, closer to the slope.

At Site 347, as at Site 346, the prominent reflector was penetrated and drilling progress was very slow below it in a siliceous mudstone. Basement was not reached and from the drilling results it seems quite probable that it is the mudstone which probably forms the steep western boundary of the Jan Mayen Ridge and not a basement ridge. Site 349 was located on a more central portion of the block and the objective here was to try again to penetrate the prominent reflector and drill into the dipping reflectors below.

At all three sites the prominent reflector was penetrated at about 120 meters. It represents an unconformity which is especially clear lithologically in Site 349 where it is marked by a basal conglomerate. Above the unconformity are "glacial" sediments as well as sediments extending from middle Miocene to middle Oligocene in age. Below the unconformity are sediments that range in age from early Oligocene to late (and middle?) Eocene. The unit below the unconformity consists primarily of massive terrigenous sandy mudstone. Turbudite layers are often present in the lower part of the unit. It is paleontologically barren except for some arenaceous benthic foraminifers and a few badly preserved calcareous foraminifers. Above the unconformity, the middle Miocene to late/middle Oligocene unit consists of sandy mud and biogenic siliceous oozes that are characterized by a very high percentage of spine spicules, especially in the lower part of the unit. When the lower unit of Site 349 is compared with those at Sites 346 and 347 it is found that, at the same depth, sediments that are in a stratigraphically higher position are undeformed. This confirms the eastward dip of the older reflectors.

Because basement was not reached at any of these sites and because the oldest sediments found are not older than middle Eocene and therefore do not predate the opening of the Norwegian Sea, one cannot directly deduce that the Jan Mayen Ridge is a continental fragment that existed before the Norwegian Sea opened. However, several factors indicate that basement possibly much older than Eocene underlies the Jan Mayen Ridge.

In Figure 15 we note that a large thickness of sediment underlies sediments with velocities of 2.2 km/sec. It was this 2.2 km/sec layer that was penetrated by the drill holes on the Jan Mayen Ridge and which yielded Eocene fauna. Presumably the sediments at the base of the sedimentary column are much older. Elsewhere in the Norwegian Sea and in the North Sea the boundary between the 2.2 km/sec and 3.1 km/sec layers is the boundary between the Tertiary and the Cretaceous, and the 4.4 km/sec layers represent Mesozoic and perhaps even Paleozoic sediments. A similar situation could exist here.

The age of the older sediments cored on the Jan Mayen Ridge does not predate the opening of the Norwegian Sea, but if the situation described above holds, then some of the older sediments deposited on the Jan Mayen Ridge predate the time of opening of the Norwegian Sea, and it is quite possible that they lie on continental basement. The prominent unconformity at about 120 meters on the Jan Mayen Ridge can be associated with the jump of the spreading axis from the Norwegian Sea to west of the Jan Mayen Ridge. The sediments below the unconformity are mainly terrigenous in origin and could have been sediments deposited on what was then the eastern continental slope of Greenland. It is quite likely that just prior to the development of the new axis of spreading west of the Jan Mayen Ridge the area of the Greenland continental slope (including the area that later became the Jan Mayen Ridge) was uplifted due to thermal causes. Subsequent erosion can perhaps explain the unconformity at 120 meters. After the creation of the new sea floor between the Jan Mayen Ridge and Greenland, terrigenous sediments from Greenland could not reach the Jan Mayen Ridge. The increase of the biogenic components at the expense of the terrigenous component in the flat-lying sediments above the unconformity may reflect this. The dates check quite well, the oldest

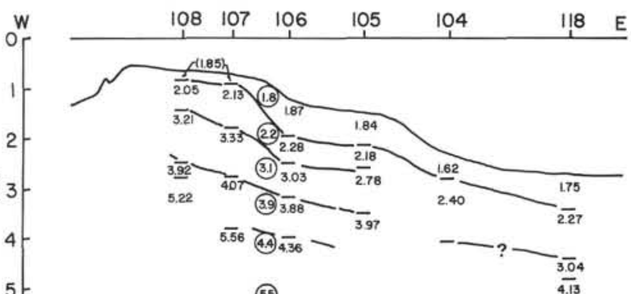

Figure 15. *Refraction data across the Jan Mayen Ridge (after Talwani and Eldholm, in press). Location of these stations is indicated in Figure 8.*

sediments above the unconformity are late Oligocene in age which corresponds nicely to the shift of the spreading axis from the Norway Basin to the Icelandic Plateau.

Site 350 lies in Region 3 (Figures 12 and 13). As discussed earlier, morphologically, Region 3 has been considered a part of the Jan Mayen Ridge; it lies at an elevation higher than the elevation of the Norway Basin. However, Talwani and Eldholm (in press) have suggested that it was probably created by sea-floor spreading, contemporaneously with the development of the Norway Basin. The reason for this suggestion is as follows. The magnetic lineations in the Norway Basin (Figure 8) show, that while anomalies 20 and older are parallel to each other, the younger anomalies tend to crowd southward into a fan-shaped pattern. From geometrical considerations, therefore, another area must exist where new ocean crust was created between anomaly 20 time and anomaly 7 time (the time that the Norway Basin spreading axis became extinct). It can be seen in Figure 8, that the northern segment of the Faeroe-Shetland Escarpment, which forms the eastern boundary of the Norway Basin, is not parallel to the 1000-fathom curve which forms the eastern boundary of the morphological Jan Mayen Ridge, but rather is parallel to the western boundary of Region 3. In other words, if Region 3 is included within the Norway Basin, then the Norway Basin does not diminish in width from north to south, a geometrical condition which is imposed by the motion of rigid plates.

All of these considerations prompted Talwani and Eldholm (in press) to suggest that Region 3 was created contemporaneously with the Norway Basin by some form of sea-floor spreading. If this hypothesis is right, the age of basement in this area would lie between the ages of anomalies 20 and 7, that is between 50 and 26 m.y. ago. An "opaque" layer underlies sediment within Region 3. This opaque layer, as the seismic reflection profile in Figure 14 shows, continues eastward into the Norway Basin.

Drilling revealed the opaque layer at Site 350 to consist of basalt. There is considerable scatter in the radiometric ages (Kharin et al., this volume), but values of 40-44 m.y. are indicated. These are not in conflict with the age of late Eocene determined paleontologically from the overlying sediments and falls within the range suggested by Talwani and Eldholm (in press) for this area, assuming of course that the opaque layer forms "true basement" or is very close to it in age.

Site 348 was drilled in the Icelandic Plateau in the area containing magnetic lineations surrounding the extinct axis of spreading in the Icelandic Plateau. Site 348 was located on a prominent positive magnetic anomaly which Chapman and Talwani (in preparation) have identified as anomaly 6. An "opaque" layer was present in the seismic profiler records at this site (see profile A-B in Figure 14). As at Site 350, the opaque layer here also was basalt. Its age, determined radiometrically, is 18.8 $\pm$1.7 m.y. (Kharin et al., this volume). Paleontologically the age for the overlying sediments is early Miocene to Oligocene (?). The possible Oligocene age is from a single species of foraminifers with a range from late Oligocene to early Miocene. It is therefore quite possible that the oldest sediment at this site is early Miocene and the age of basement is about 21 m.y., the age of anomaly 6. Correspondingly, the age of the magnetic anomaly 5D at the extinct axis, which gives the time of extinction of the spreading axis, is 18.5 m.y.

The extinction of spreading and the development of a new axis of spreading at the present Iceland-Jan Mayen Ridge may be reflected in the prominent lithological boundary between the middle Miocene and early Miocene sediments used at Site 348. Early Miocene and Oligocene sediments have a large terrigenous component. They are poor in fauna which consists usually of arenaceous foraminifers and some nannofossils. These sediments may reflect a situation where it was possible to obtain terrigenous sediments directly from Greenland. After the opening of a new spreading center to the west, the terrigenous sediment supply decreased and the biogenic component became more important. This middle Miocene-early Miocene discontinuity is also very clearly reflected in the pollen/dinocyst ratios (Manum, this volume). The ratios diminish very rapidly at this boundary implying again the difficulty of terrigenous sediments from Greenland reaching the site after the new spreading center was opened.

Vøring Plateau

The Vøring Plateau is a prominent feature of the Norwegian Continental Margin. It has a nearly flat surface at a depth between about 1200 and 1400 meters. An important buried feature known as the Vøring Plateau Escarpment divides the Vøring Plateau into an Inner and an Outer part. The Vøring Plateau Escarpment is associated with minimal surface relief, but it does not separate two very different geological areas. A bathymetric chart of the Vøring Plateau is given in Figure 16. Magnetic anomalies along selected ships' tracks are plotted in Figure 17. Three seismic reflection profiles which cross the escarpment (Figures 18 and 19) show various geophysical data across the escarpment including deep information from seismic refraction as well as isostatic gravity anomalies.

The magnetic and seismic reflection data give the impression that the Vøring Plateau is tectonically continuous with the Lofoten Basin to the north. Magnetic lineation 23 in the Lofoten Basin continues to the base of the Vøring Plateau, and magnetic lineation 24 continues from the Lofoten Basin on up to the Vøring Plateau cutting across the 1500-meter isobath (Figure 17). An important negative magnetic anomaly exists just seaward of the Vøring Plateau Escarpment. It has been explained by Talwani and Eldholm (in press) as arising due to the juxtaposition of highly magnetized oceanic basement rocks against very weakly magnetized rocks east of the Vøring Plateau Escarpment.

Basement in the Outer Vøring Plateau dips steeply down towards the Lofoten Basin. The steeply dipping basement can be seen in profile E-F in Figure 18. While this profile shows a break in the basement layer in the vicinity of Site 343, other profiles (not shown here) in general, appear to demonstrate a continuity of the Vøring Plateau basement in the Lofoten Basin without any

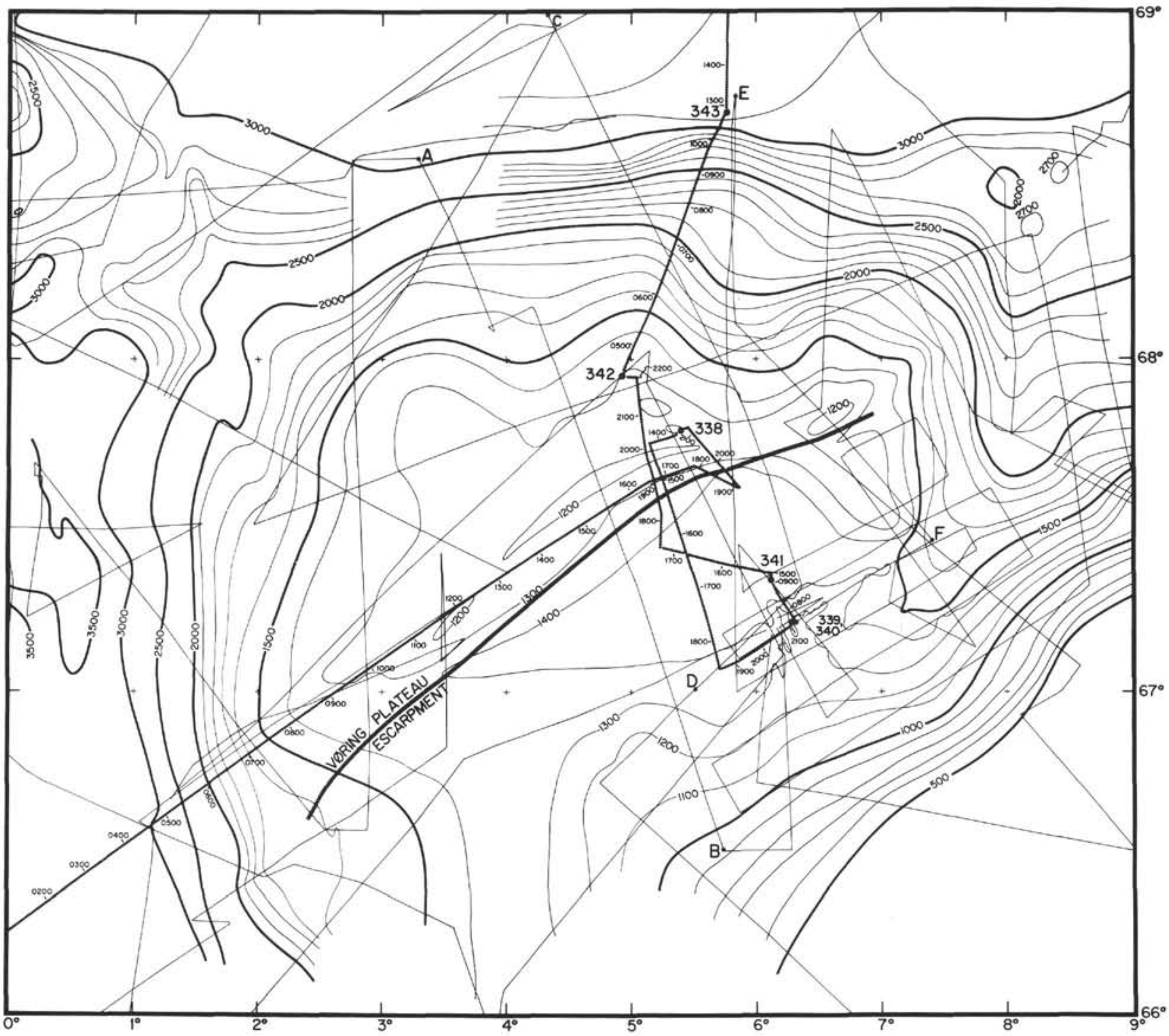

Figure 16. *Bathymetric chart of the Voring Plateau. This map is principally based on soundings obtained on* Vema *surveys. The track of* Glomar Challenger *and Sites 338 through 343 are also shown.*

major presence of faulting at the base of the slope of the Vøring Plateau. Identification of the smooth prominent reflector on the outer part of the Vøring Plateau basement was made on the basis of sonobuoy measurements (Figure 19). The refraction measurements yielded a velocity of about 5.2 km/sec. However, results of multichannel seismic reflection profiling available to us after the drilling program shows that in the vicinity of the escarpment on the Outer Vøring Plateau the prominent reflector is underlain by closely spaced dipping reflectors and that "true basement" lies some distance below this prominent reflector. This information has been provided by the Bundesanstalt fur Bodenforschung (K. Hinz, personal communication) and IFP (L. Montadert, personal communication). The results available to us suggest that the lower series of reflectors exist in limited area confined between anomaly 24 and the escarpment (Figure 17); Sites 348 and 342 lie within this area.

East of the escarpment in the magnetic quiet zone the prominent reflector is not seen, and the thickness of sediments increases considerably (Figures 18, 19, and 20). By comparison of the seismic velocities shown in Figure 19 with seismic velocities on the Norwegian Margin and in the North Sea, it is believed that pre-Tertiary sediments exist in this area. The boundary between the layer of velocities 2.5 and 3.5 km/sec is believed to indicate the base of the Tertiary. The layers with 4.4 km/sec are believed to be Mesozoic or perhaps even Paleozoic sediments. By contrast, on the Inner Vøring Plateau, sediments with velocities only under about 2.2 km/sec are found, thereby indicating a large disparity in the age of the base of the sedimentary section in the Inner and Outer Vøring Plateau areas. The sediment layers in the Inner Vøring Plateau are generally flat over a large area, although the sediment layers do slope up towards the escarpment and they also slope upwards in the vicinity of diapiric bodies (Figures 18 and 20).

The principal objectives of the sites on the Vøring Plateau were to test the salient points of the hypothesis that has been presented above, that is: (1) Whether the

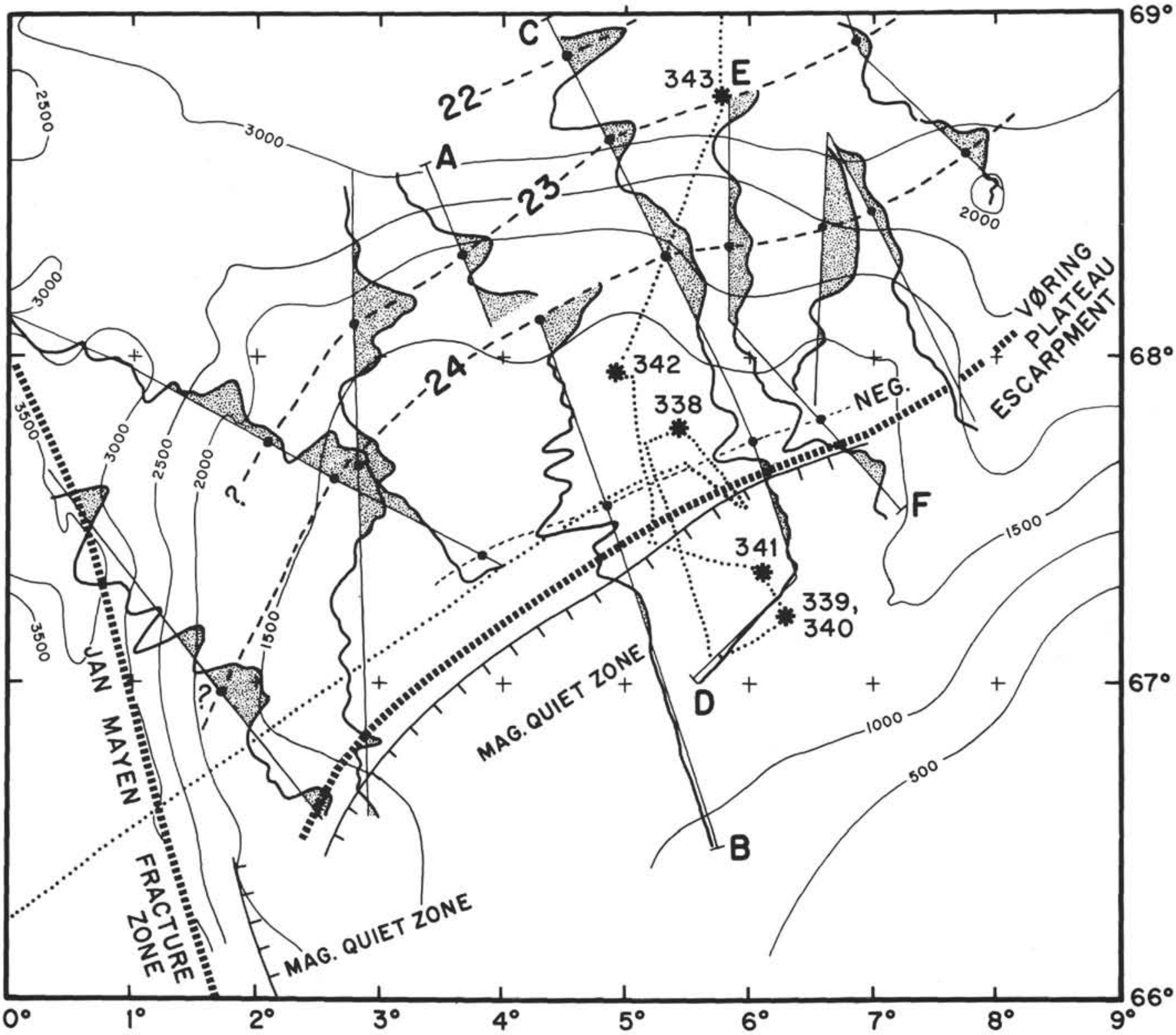

Figure 17. *Magnetics plotted along selected ship tracks on the Voring Plateau.*

shallow reflector under the Outer Vøring Plateau represents igneous oceanic basement formed immediately after the opening of the Norwegian Sea, and if so, why does basement here stand higher than elsewhere in the Lofoten Basin? (2) Whether the Vøring Plateau Escarpment indeed forms "oceanic-continent" boundary. (3) Whether the age of the thick sedimentary column in the Inner Vøring Plateau includes Mesozoic or earlier sedimentary accumulations.

The shallow reflector under the Outer Vøring Plateau was found, by drilling at Sites 348, 342, and 343, to consist of basalt. Age determination results by the potassium-argon method are summarized by Kharin et al. (this volume). Ages of 46.6 ±2.5 m.y. were determined for basalts at Site 348, and an age of 24.5 ±2 m.y. for the basalt at Site 343. At Site 342, the age determined was close to 44 m.y. At Sites 338 and 343 the oldest sediments found over the basalt are early Eocene in age. It is important to emphasize that they are not middle Eocene, nor are they Paleocene. No Paleocene sediments have been recovered from the Norwegian Sea either by drilling or by piston coring of outcrops. Site 338 lies landward of anomaly 24. Anomaly 25 is not seen on the Vøring Plateau or anywhere else in the Norwegian Sea. If the basalt at Sites 338 and 342 was extruded between anomaly 24 time and anomaly 25, its age, according to the Heirtzler time scale, lies between 60 and 63 m.y. However, in the early Tertiary this time scale is too old by perhaps 5-7 years (there is no general agreement on exactly what the error in the time scale is; different estimates have been made by different authors). An error of 5-7 m.y. would, from magnetics, place the expectable range at Sites 338 and 342 to be 53-58 m.y. A single best guess for the initiation of opening of the Norwegian Sea can therefore be approximately placed at 55 m.y.

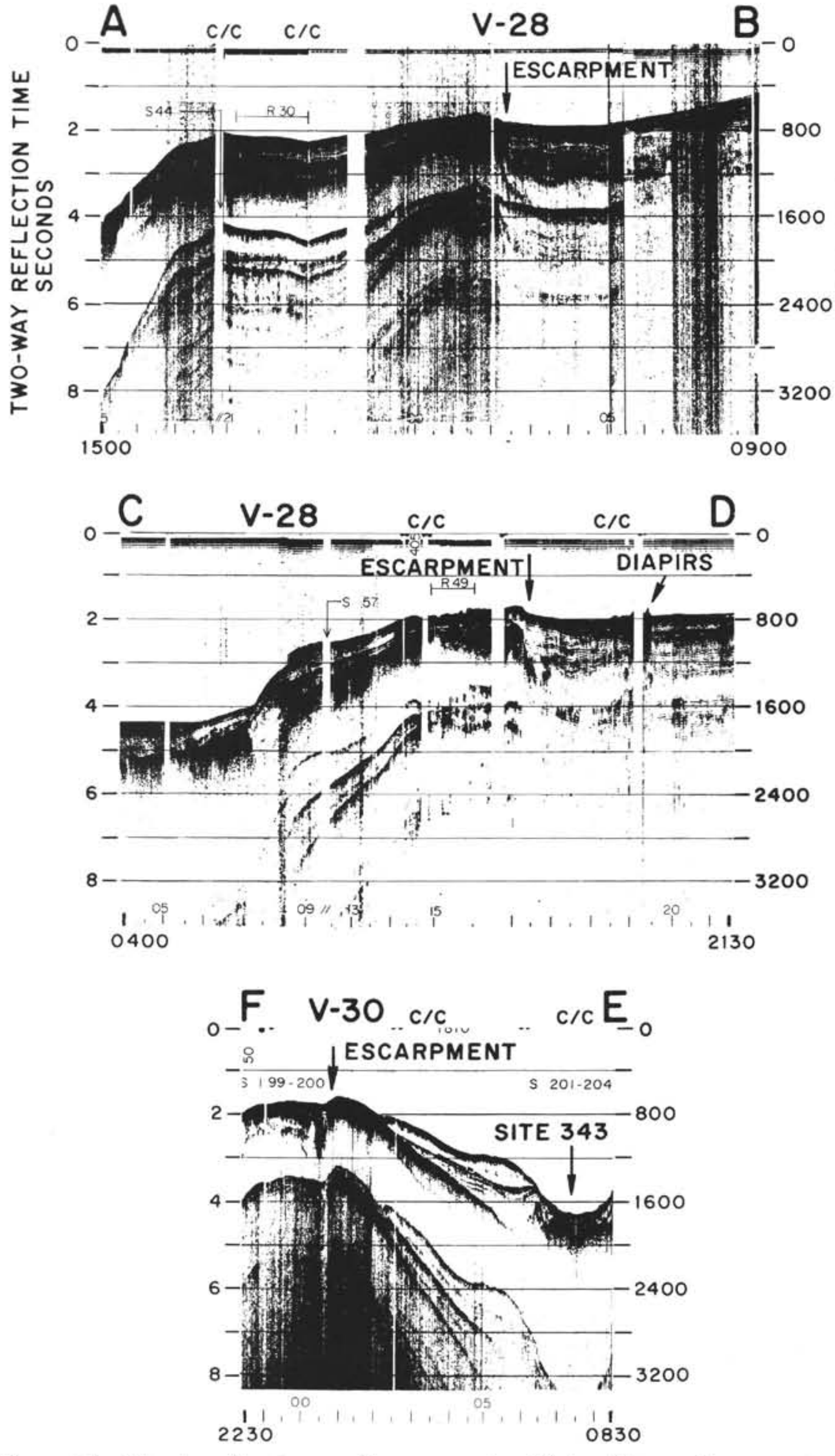

Figure 18. *Seismic reflection profiles across the Vφring Plateau Escarpment. This information was obtained on* Vema *Cruises 28 and 30.*

Thus, the ages at Site 338, determined by different methods, roughly agree but we note that radiometric age is the youngest at 46.6 m.y., and the magnetic age is the oldest lying between about 53-58 m.y. The age determined from fossils in the overlying sediments is in between, at early Eocene (49-53.5 m.y.). Fine-grained, sandy limestone overlies about 76 cm of basalt breccia at Site 338. Fauna in the sandy limestone is early Eocene and appears to be found also in the underlying breccia. Although the ages do not exactly match, the basalts at Site 338 can be characterized as normal ocean floor tholeiites and can be associated with the early opening of the Norwegian Sea.

The age of the basalts at Site 342 is similar, but the overlying sediments are early Miocene, not Eocene. The profiler record in Figure 20 shows that the layers

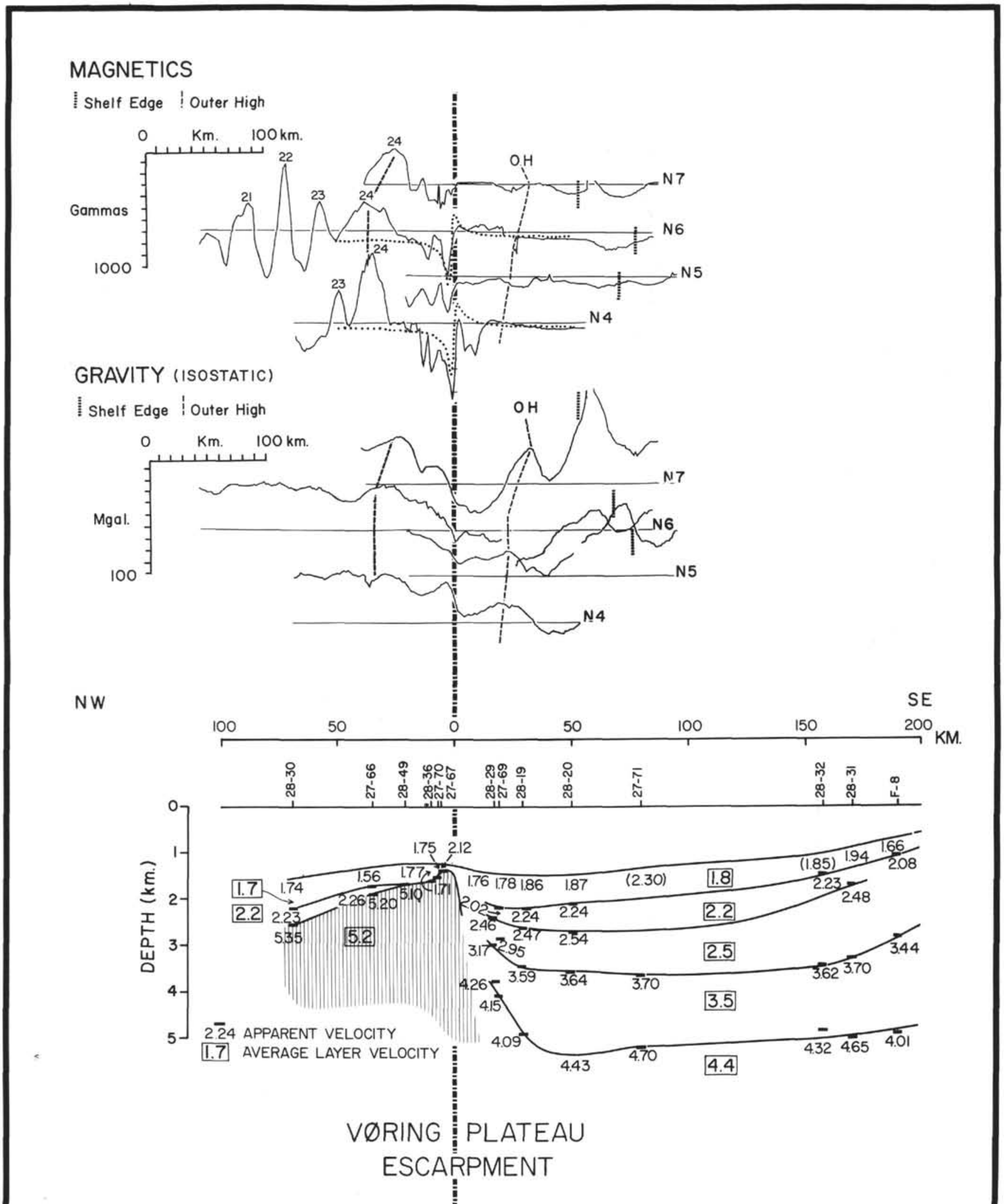

Figure 19. *Geophysical data obtained across the Vøring Plateau Escarpment (modified from Talwani and Eldholm, 1972).*

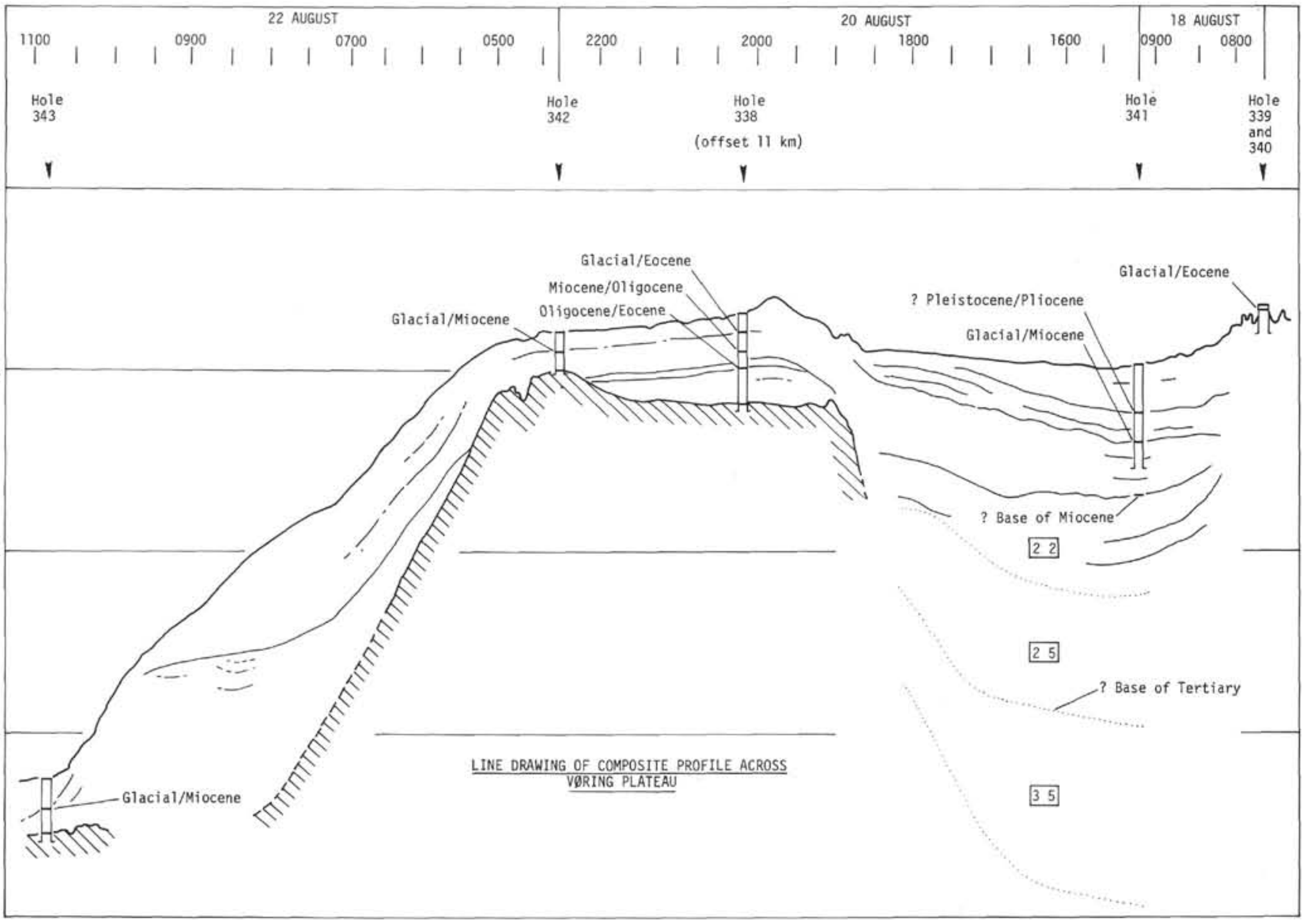

Figure 20. *Line drawing composite of seismic reflection profile across the Vøring Plateau obtained aboard* Glomar Challenger. *Reflectors are shown as thin lines, basement is emphasized by oblique shading. Refraction data (layers shown by dotted lines and velocities given in boxes) taken from Talwani and Eldholm (1972), and plotted on the assumption that base of 1.8 km/sec layer is equivalent to presumed base of Miocene.*

corresponding to Eocene and Oligocene at Site 338 are absent at Site 342 and therefore one would not expect to reach them by drilling. The age of anomaly 23 at Site 343 is 58 m.y. on the Heirtzler time scale. Assuming an error of 5-7 m.y., the age is 51-57 m.y. This overlaps the range of the age of the overlying early Eocene sediments, but is considerably older than the age which has been radiometrically determined—28.5 m.y. As Kharin et al. (this volume), discuss the discrepancy has to be explained either by stating that the basalt at Site 343 is intrusive or by assuming a large amount of alteration.

We have mentioned earlier the presence of dipping reflectors below the prominent reflector that was penetrated at Sites 338 and 342. It could be argued that the basalts found at Sites 338 and 342 do not represent basement associated with the early opening of the Norwegian Sea, but that they represent basalt flows on an older, perhaps continental crust. We do not support this view because anomaly 24 is seen on the Vøring Plateau, at points lying above the 1500-meter isobath. That part of the Vøring Plateau is thus apparently formed by sea-floor spreading and it seems unreasonable to divide the Outer Vøring Plateau into two parts, one formed by sea-floor spreading, the other representing older continental crust. We believe that it is more likely that the reflector penetrated at Sites 338 and 342, is only slightly younger than the "true basement" underneath, and the intervening reflectors may represent rapidly deposited pyroclastics associated perhaps with a volcanic activity during the time just after opening started.

Data on sediments suggest the continued submergence of the Outer Vøring Plateau since it was formed. It is quite possible that parts of it, at the time of formation, lay above sea level. One way to explain the large sandy component of the muds of the Eocene at Sites 338 is to erode nearby subaereal peaks. Sometime after early Eocene there is a sudden change in the lithological character of the sediments with a great decrease in the terrigenous component suggesting that these peaks subsided below sea level. It is pointed out that this change in sediment lithology is also reflected very strongly in the dinocyst/pollen ratio which increased markedly and suddenly at this time (see Manum, this volume). It can be noted that the thickness of the Miocene sediments at Site 341 is several times the thickness of Miocene sediments at Site 338, suggesting that even though the Outer Vøring Plateau was subsiding, it remained topographically elevated with respect to the Inner Vøring Plateau. A shallower Outer Vøring Plateau, with the consequent erosional and nondepositional environment associated with fast currents, may be used to explain the smaller thickness of the Miocene sediments there relative to thickness found on the Inner Vøring Plateau.

Even though full proof requires drilling through the subbasalt reflectors in the Outer Vøring Plateau and drilling to basement, the present drilling results together with earlier geophysical data confirm the great importance of the Vøring Plateau Escarpment and do not deny the suggestion that it might define the boundary between older continental crust and the newly formed oceanic crust.

A comparison of the ages and the sediments found at Site 341 compared with the results obtained from seismic reflection/refraction by Talwani and Eldholm (1972) generally confirm the presence of a thick sequence of sediments on the Inner Vøring Plateau. Pre-Tertiary sediments were not reached at Site 341 because drilling had to be terminated. Confirmation of the presence of sediments deposited before the time of opening of the Norwegian Sea requires further drilling.

The presence of diapiric activity was confirmed by recovering Eocene and Miocene fauna at very shallow depths at Sites 339 and 340. Displaced Miocene/Oligocene fauna within a section of the Pleistocene at Site 341 suggest that older sediments have been obtained from the high-standing diapirs by erosion and slumping. We are not certain about the time of diapirism. Some diapirs are now covered by flatlying undisturbed Pleistocene sediments suggesting that they are, at present, not rising. However, as the outcrops are covered only by a thin sediment veneer, this could suggest continued activity at the present time, or possibly that no sedimentation has occurred on the steep slopes of the diapirs.

Site 345, Jan Mayen Fracture Zone, and the Southern End of Mohns Ridge

The location of Site 345, together with the magnetic lineations and the bathymetric contours in the neighboring area, is given in Figure 21. Reflection profiler records along track ABC which passes through the site are shown in Figure 22. Site 345 lies in an area of complex structure. To the northeast of Site 345, the magnetic lineations corresponding to Mohns Ridge are shown. The two segments of the Jan Mayen Fracture Zone are indicated. Norway Basin lies southwest of the southern section of the Jan Mayen Fracture Zone. Magnetic lineations 21? and 22? in Norway Basin are shown. We have stated earlier that at nearly anomaly 7 time the spreading axis in the Norway Basin jumped westward.

Grønlie and Talwani (in preparation) suggest that, in fact, the jumping of the ridge axis was more complicated. The jump of the spreading axis actually took place in two steps. North of the northern segment of Jan Mayen Fracture Zone, no ridge axis jump occurred and spreading has continued since the opening of the Norwegian Sea. In the area that lies between the two segments of Jan Mayen Fracture Zone, the spreading axis jumped at nearly anomaly 13 time. Thus, between anomaly 7 time and anomaly 13 time, there were three segments of the mid-ocean ridge in the area. One segment lay north of the northern segment of the Jan Mayen Fracture Zone; a second segment lay between the two segments of the Jan Mayen Fracture Zone, and a third segment coincided with the extinct axis of the Norway Basin. Three lineations, 21?, 22?, and 23?, are shown west of Site 345. They belong to the intermediate area among the three mentioned above. Site 345 must also belong to this intermediate area and, judging roughly from the tentatively identified lineations to the west of it, the age of Site 345 lies somewhere between anomaly 13 time and anomaly 20 time, that is between 38 m.y. and 49 m.y. according to the Heirtzler time scale (the age is somewhat younger if corrections are applied to the Heirtzler time scale). If a jump in ridge axis in this area took place during anomaly 13 time, the Jan Mayen Fracture Zone segment to the north of it must connect anomaly 13 in the Mohns Ridge with anomaly 13 in this intermediate area. In other words, the northern segment to the Jan Mayen Fracture Zone must extend further to the east than is shown in Figure 21.

Track segments C-B lies on the flank of the Mohns Ridge. This can probably be appreciated better from Figures 1 and 2, noting that point B corresponds to point marked 2703/2315 in Figures 1 and 2. In Figure 22, the higher elevation of basement in the vicinity of Site 345 can be attributed to the proximity of the Jan Mayen Fracture Zone, but the fracture zone in this area only came into existence at anomaly 13 time, while the crust at Site 345 was emplaced, as suggested earlier, prior to anomaly 13 time. When basement was formed at Site 345, it was formed in an area of normal oceanic crust away from a fracture zone, but subsequently the site was elevated due to the establishment of a fracture zone. These considerations might explain the lithologies of the sediments cored at Site 345.

The lowermost sediments, which are Eocene indicate deposition in deep water with a large number of turbidite layers present. On the other hand, the pelagic sediments appear to dominate from the Oligocene on. Turbidites are no longer present. The biogenic component increases; muds and clays are present, but they appear to have been deposited as suspensoids in quiet water conditions. This later phase appears to be associated with the sediment deposition at post anomaly 13 time at an elevation that was higher than that of the surrounding sea floor.

The age of the basement determined radiometrically is 27 ±3 m.y. (Kharin et al., this volume). This age is younger than that obtained from faunal evidence in the overlying sediments. Faunal evidence suggests early Oligocene or late Eocene. If the late Eocene data are in error and there are no Eocene sediments present, this would not invalidate the arguments regarding initial deposition in in deep water and subsequent elevation, but simply pushes the whole sequence of events to a somewhat later time. If the above considerations are correct, they have an important implication about the geochemistry and petrology of the basalt. Although the

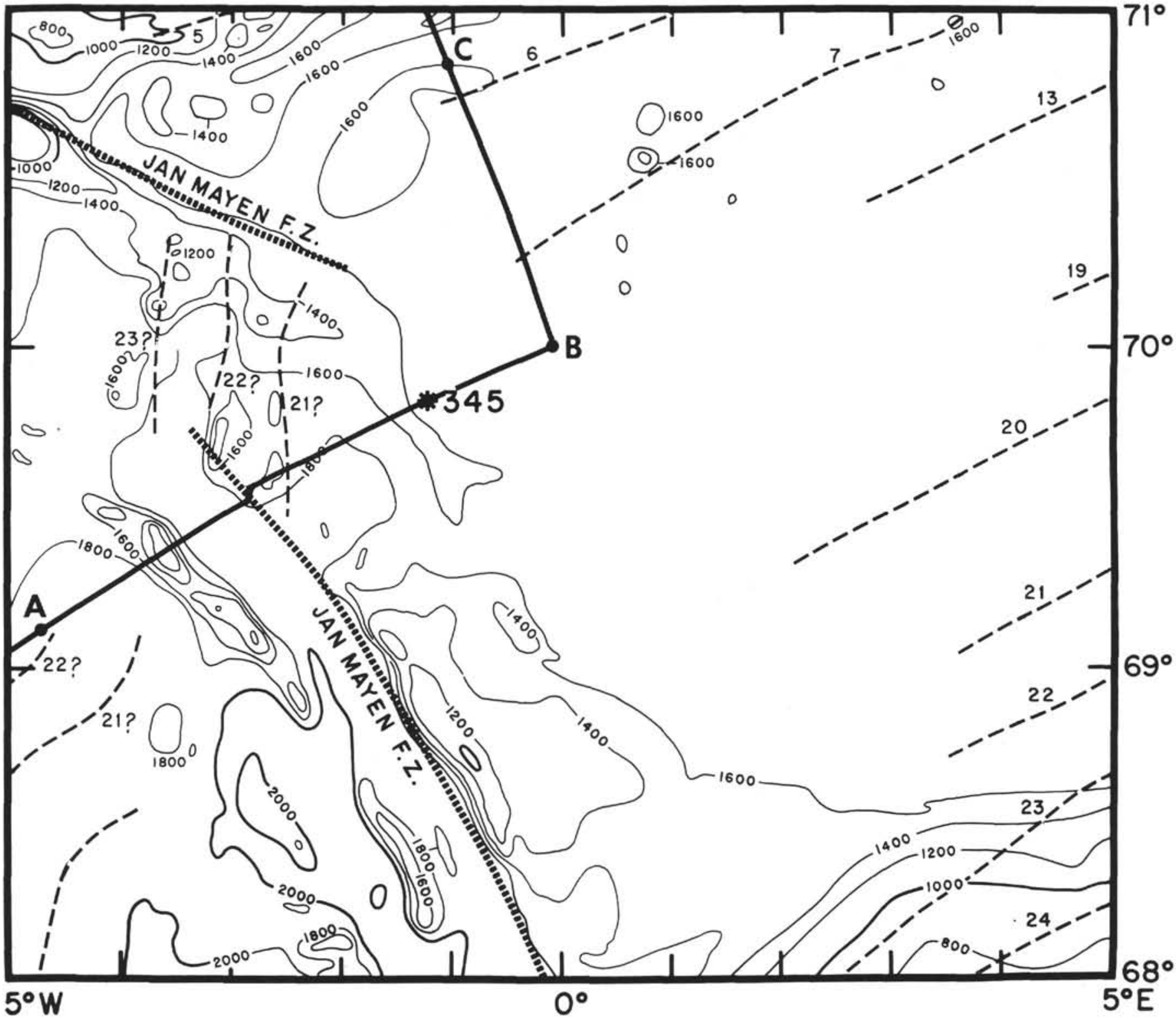

Figure 21. *Location of Site 345, the magnetic lineation bathymetric contours in the neighboring area (Grønlie and Talwani, in preparation; Talwani and Eldholm, in press).*

site is close to a fracture zone, the geochemistry and petrology should be associated with normal ocean crust rather than the fracture zone.

Knipovich Ridge

The continuation of the rift at the crest of the Mohns Ridge is shown to continue into the Knipovich Ridge (Figure 1). However, other than the presence of a positive magnetic anomaly in most crossings over the Knipovich Ridge, no identifiable magnetic lineation pattern has been found for this ridge and therefore none has been shown in Figure 2. Figure 23 shows magnetic anomalies plotted on track in the vicinity of Site 344. The Knipovich Rift is also shown in this figure as are topographic peaks rising above 2000 meters. The drill site was located on the east flank of a topographic high—a "rift mountain." The location of Site 344 can also be seen on the profiler record in Figure 24.

Igneous rocks cored at this site were coarse-grained diabases and gabbros. The radiometric age of 3 m.y. is younger than the age of the overlying sediments which contain fauna of Pliocene or late Miocene age. The intensity of the igneous magnetized rocks is very small. All of these observations indicate that the igneous rocks drilled form a sill that has been intruded into the sediments. The age of the information of the ocean floor at this site was therefore not determined.

CONCLUSIONS

Verification of Sea-Floor Spreading Model of Opening of the Norwegian Sea

Since igneous rocks reached by drilling in the Norwegian Sea were invariably basalt and the ages determined for the basalt were generally in accord with

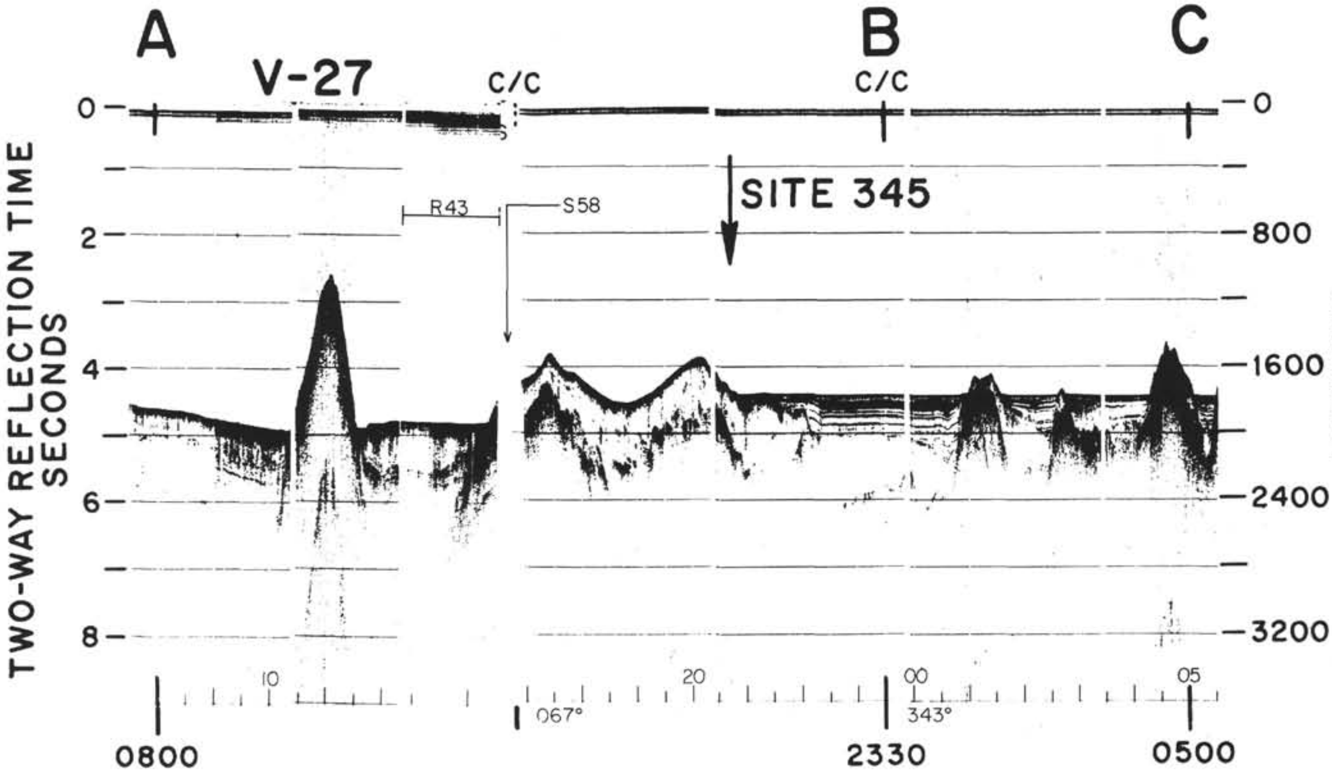

Figure 22. *Reflection profiles along track ABC passing through Site 345. Location of profiles shown in Figure 21.*

the model proposed by Talwani and Eldholm (in press), lend support to their model for the tectonic evolution of the Norwegian Sea. It should be pointed out, however, that an argument can be made that in some cases that "true basement" was not reached, but that basalt flows much younger than "true basement" were reached. In particular, at Sites 338 and 342 on the Vøring Plateau from multichannel seismic profiling, there is evidence, of reflectors below the basaltic layer. At Sites 348 and 350 the layer penetrated had been termed an "opaque" layer; drilling demonstrated that it was basalt. An argument can be made, therefore, that at some of the sites the basalt that was drilled into does not represent the original sea floor but, rather, represents basalt flows subsequent to the time of formation of a "true basement." However, the ages determined generally agree so well with the proposed model that in most cases it seems that, if basement was not sampled, the material actually sampled was not too different in age from the underlying basement.

We recognize, of course, that especially in marginal areas such as the Vøring Plateau it is difficult to absolutely refute the argument, in view of subbasement reflectors, that the basalt flows reflect volcanic activity over continental basement at the time of early rifting, rather than the age of the sea floor itself. Because anomaly 24 is present on the Vøring Plateau, the presumed continental area could lie between anomaly 24 and the Vøring Plateau Escarpment. We believe that the preponderance of the geophysical data argue against such a hypothesis, but it cannot be absolutely refuted.

Time of Opening of the Norwegian Sea

The oldest anomaly found in the Norwegian Sea is anomaly 24. Anomaly 25 has not been seen in the Norwegian Sea. The corresponding ages by the Heirtzler time scale are 60 and 63 m.y., but if the Heirtzler time scale is too old by 5-7 m.y. the age of the opening would perhaps lie between 53 and 58 m.y. The oldest sediments recovered in the Norwegian Sea are early Eocene. It would seem then that an age of about 55 m.y. represents the best estimate of the time of the initiation of opening of the Norwegian Sea.

Land Bridges

After the opening of the Norwegian-Greenland Sea started, two topographic barriers existed between the Arctic and the Atlantic. One of these barriers was due to the high elevation of the Iceland-Faeroe Ridge which was created above sea level, but gradually subsided. The model of Talwani and Eldholm (in press) suggests an age of 55-25 m.y. for the formation of the Iceland-Faeroe Ridge. This age is not contradicted by the age of the basalt found at Site 336. Best estimate of the time when the oldest parts of this ridge started subsiding below sea level is about 25 m.y. ago. We note that many assumptions have gone into arriving at this figure. However, we also note that this date is substantiated by faunal evidence from Sites 336 and 352 which lie, respectively, on the north and south side of the Iceland-Faeroe Ridge. Fauna at least as young as late middle Oligocene differed at the two sites, conforming the existence of a land bridge at least up to this time.

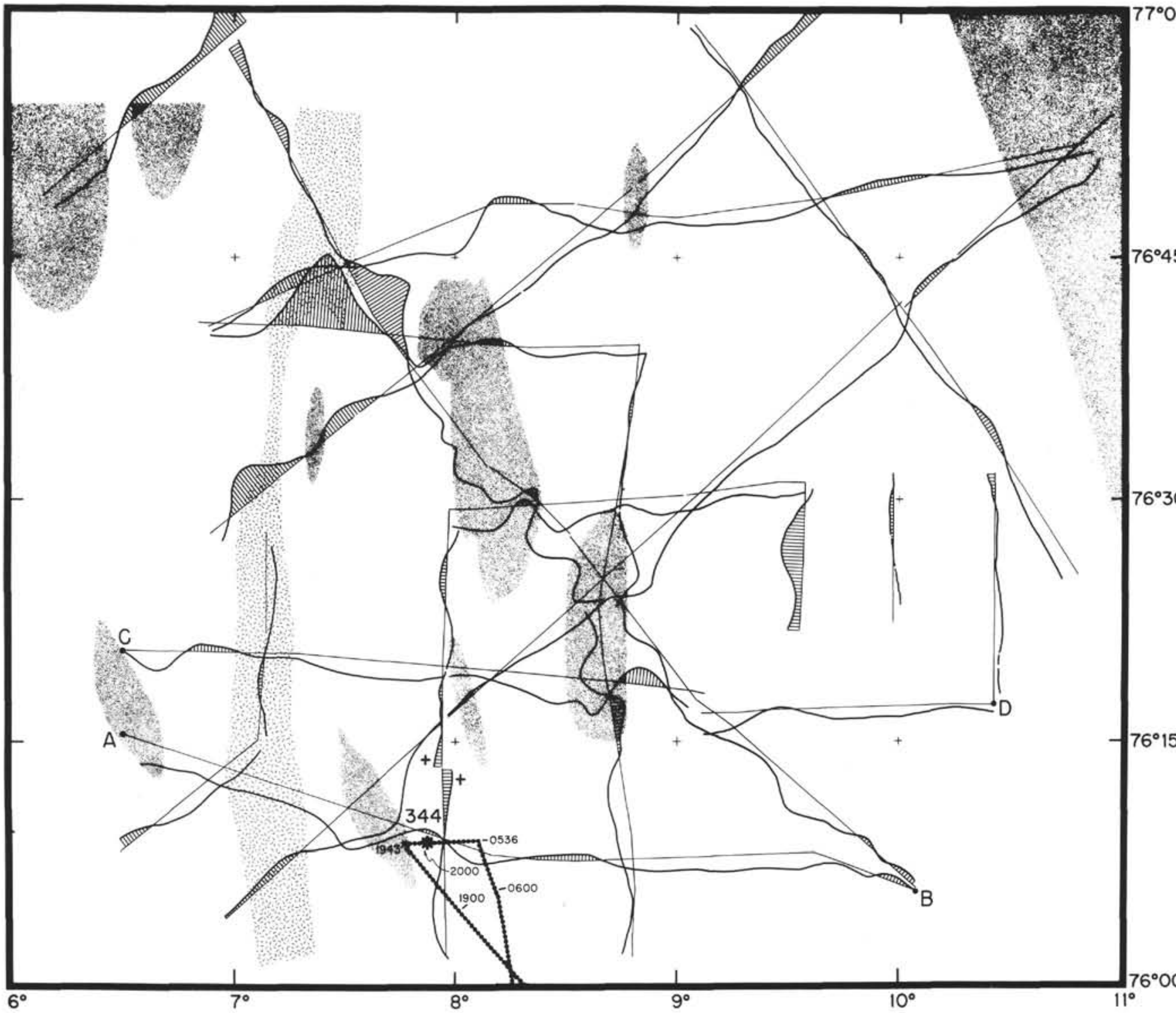

Figure 23. *Magnetic anomalies plotted along Vema tracks in vicinity of Site 344 on the east flank of Knipovich Ridge. The light shading corresponds to the Knipovich Rift floor (depths greater than 3200 m). Darker shading corresponds to peaks in the area rising above 2000 meters.*

The second land bridge in this area persisted because, in the Greenland Sea, the motion during the first phase of opening, that is between the time of opening to about 38 m.y. ago, was a shearing motion. Greenland slid past Svalbard and the Barents Shelf without there being any opening in the Greenland Sea. This opening started, according to the model of Talwani and Eldholm (in press), at 38 m.y. after which time the connection was established between the Arctic Sea and the Norwegian Sea. The results of the drilling do not bear on the problem of this second land bridge.

We also point out that the faunal evidence suggests that soon after the early opening of the Norwegian Sea, especially the Eocene, faunal similarities of the fauna existed with northern Europe. The sea connection must have been through the North Sea and the shallow sea extending over the Norwegian margin and the Inner Vøring Plateau. Continuous sedimentation appears to have taken place in this area throughout the Tertiary.

Opaque Layer

Eldholm and Windisch (1974) have described an opaque layer in the area north of Iceland and the southern part of the Jan Mayen Ridge; it is generally smooth. Also, in some areas, the opaque layer is suddenly interrupted, leaving "holes." These factors led to the supposition that the opaque layer was perhaps an ash layer, but whereas it might cover basement in some areas, it could not because its lack of relief represents oceanic basement. However, drilling at Sites 348 and 350 showed that this opaque layer represents basalt flows. Age determined for the basalt, especially at Site 348, agrees so well with the age predicted for a sea-floor spreading type model, that it seems reasonable to suggest that the basalt layer, if not representing the sea floor at the time of its original formation, was emplaced very soon thereafter. It is not easy to give a simple explanation for the "holes" but it is possible as Talwani

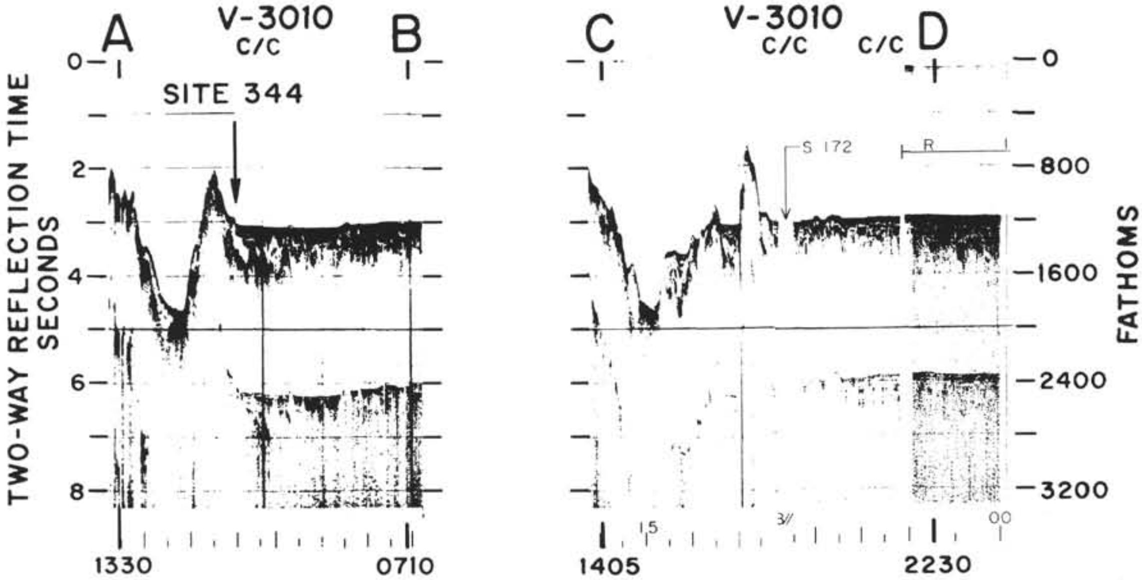

Figure 24. *Seismic reflection profiles obtained in the vicinity of the Knipovich Ridge for Vema Cruise 30.*

and Eldholm (in press) have suggested that the holes represent subsided continental crust lying between areas in which new ocean floor has been created by sea-floor spreading.

Hot Spots and Mantle Plumes

Several areas in the Norwegian Sea can be considered to be areas of unusual elevation when considered in the light of "age versus depth" curves for mid-ocean ridges. These areas include the Iceland-Faeroe and Iceland-Greenland ridges, Iceland, the Iceland-Jan Mayen Ridge (Kolbeinsey Ridge), and the area lying between the Jan Mayen Ridge and the Iceland-Jan Mayen Ridge, the latter is the area where spreading took place between the time of spreading in the Norway Basin and in the Iceland-Jan Mayen Ridge. The extinct spreading axis in this area has been called the extinct spreading axis of the Icelandic Plateau. The area towards the southwest of Norway Basin, which contains Site 350, can also be considered an area of unusual elevation, if it is accepted that it was formed by sea-floor spreading. The Outer Vøring Plateau is also an area of unusual high elevation.

An important objective of the drilling program was to determine if the chemistry of the basement associated with sites at unusual elevation was anomalous. Areas of unusual elevation have been ascribed to hot spots and mantle plumes. Adopting the model of Schilling (this volume) for the Faeroe-Iceland region, Raschka and Eckhardt (this volume) have divided the basalts at the various sites as either "plume derived" or normal "ocean-ridge magma" types. According to Raschka and Eckhardt, hot mantle plume-type basalts occur at Sites 342 and 343 on the Outer Vøring Plateau, Site 345 in the Lofoten Basin, and Site 350 in the area southwest of the Norway Basin, which lies on the southern morphological extension of the Jan Mayen Ridge.

Elsewhere, normal ridge-type basalts are associated with Site 336 on the Iceland-Faeroe Ridge, Site 337 on the extinct axis in the Norway Basin, Site 338 on the Outer Vøring Plateau, Site 344 on the Knipovich Ridge, and Site 348 near the intermediate extinct axis on the Icelandic Plateau. Schilling's (this volume) results parallel those of Raschka and Eckhardt (this volume).

At Sites 342, 343, 345, and 350 light rare earch enriched patterns. which he believes to be characteristic of plume activity, exist. At Sites 337 and 348 light rare earch depleted pattern is observed. At Site 336 the pattern shows light rare earth depletion for samples from two flows whereas in a sample from a third flow, light rare earth enrichment is shown. At Sites 338 and 344 the results can be perhaps considered intermediate showing relative patterns of rare earch enrichment but an overall low level of RE enrichment exists..

One result is immediately apparent. There is no simple correlation between areas of unusual elevation and basement geochemistry. For example, Site 348 which lies in an area of unusual elevation possesses a very characteristic rare earth depleted pattern associated with normal mid-ocean ridge segments, but the basement at Site 350 which, as we have discussed earlier, was formed at normal sea-floor depth and subsequently elevated, has a light rare earth enriched pattern.

The models that Schilling has proposed for the Faeroes invoke a variation in time of the mantle plume activity to explain the variation of light rare earth patterns. He has attempted to explain his rare earth analysis of the samples obtained in the Norwegian Sea in a similar fashion. However, it is perhaps fair to say that the pattern of variation in time and space of mantle plume activity tends to get quite complicated in order to explain all the observations. For example, on the Vøring Plateau the basalts at Sites 342 and 343 which are presumably somewhat younger than the basalts drilled at Site 338 show a greater light rare earth enrichment. The opposite is true for the sequence of basalts on the Faeroe platform. If the ages of the Vøring Plateau basalts are, as a whole, somewhat younger than the Faeroe basalts then, in order to explain the results in terms of the Schilling model, one has to assume that the mantle plume activity in the Faeroes decreased in time and very shortly afterwards it increased on the Vøring Plateau. Thereafter it decreased again on the Iceland-Faeroe Ridge but it must have resumed again in order to explain the light rare earth enrichment of the sample from the youngest flow. Either such rapid change in activity of the mantle plumes actually did take place or some other explanation for the chemistry of the basalts has to be invoked.

ACKNOWLEDGMENTS

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