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On the Evolution of the Reykjanes Ridge South of 60° N Between 40 and 12 Million Years Before Present

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Abstract. A geophysical reconnaissance survey of the western flank of the Reykjanes Ridge between 56° and 60° N resulted in locating a system of fracture zones in the area of crustal ages between 40 and 12 Ma. This system corresponds to a similar one discovered by Vogt and Avery on the eastern flank of the ridge. Rotating anomaly 13 from the east to the west using a pole of rotation of 68.4° N, 133,8° E and an opening angle of 7.78°, a satisfactory coincidence of anomalies 13 of both surveys could be attained. Accordingly the formation of this system during the seafloor spreading process seems to be proved.

Key words: Magnetic anomalies – Gravity anomalies – Seafloor spreading – Plate tectonics – Reykjanes ridge.

Introduction

Several authors, e.g., Heirtzler et al. (1968), Godby et al. (1968), Talwani et al. (1971), Herron and Talwani (1972), Fleischer et al. (1973), Meyer et al. (1972), Bott (1974), Fleischer et al. (1974),

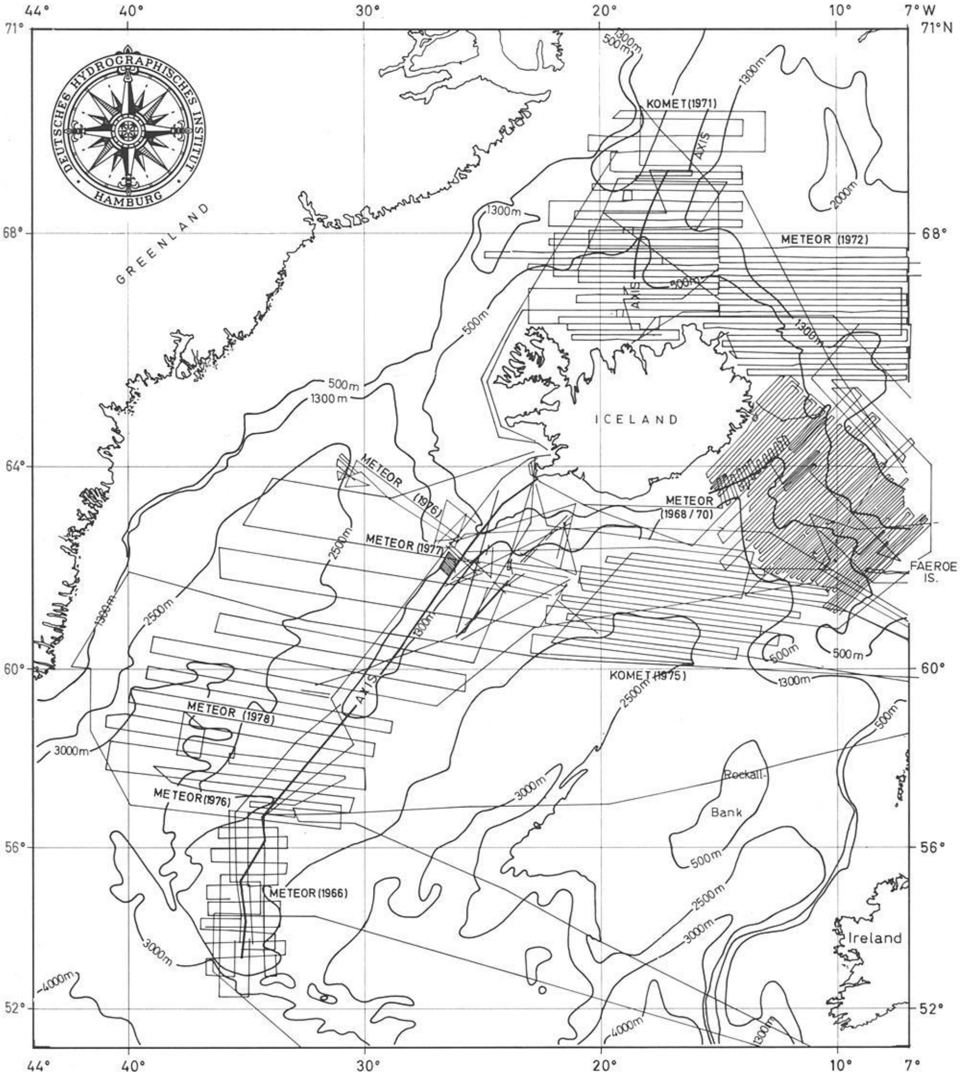

Fig. 1. Location of surveyed areas and tracks of magnetic and gravity measurements of Deutsches Hydrographisches Institut with general bathymetry

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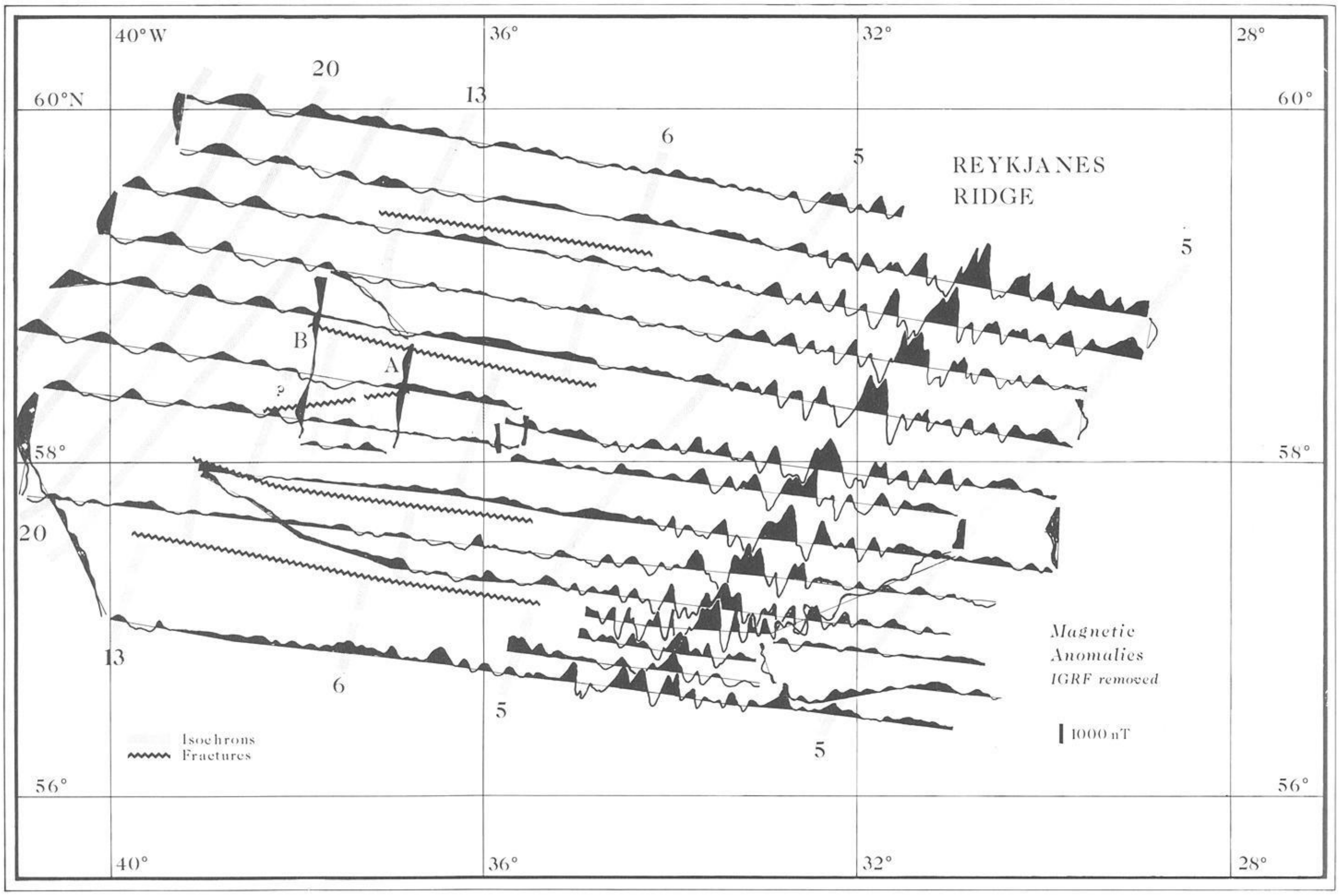

Fig. 2. Plots of profiles of magnetic anomalies. Positive anomalies black. Lineations of anomalies Nos. 5, 6, 13, 18, 20, 21, and 22 indicated. A and B are tracks where reflection seismic data are existing, too

Vogt and Avery (1974), Talwani and Eldholm (1977), contributed to the reconstruction of the main features of the evolution of the North Atlantic Ocean in the area of the Reykjanes Ridge and the Norwegian Sea. The first opening occurred about 60 Ma ago according to the time scale of Heirtzler et al. (1968) which is used in this paper. A revised time scale indicates 56 Ma (LaBrecque et al., 1977). The first positive anomaly developed was anomaly 24. Recently Srivastava (1978) assumed that opening had already started with anomaly 32 at a very slow spreading rate. Greenland was then a plate moving independently from the North American plate from which it was separated by the active ridge in the Labrador Sea (Ran Ridge). When the activity at the Ran Ridge ceased at about 40 Ma (Srivastava, 1978) the Greenland plate became fixed to the North American plate. The development of the Reykjanes Ridge was then characterized by more or less continuous and steady sea-floor spreading. In the Norwegian Sea the sea-floor spreading process terminated at the now extinct ridge axis at anomaly 7 time (28 Ma). The axis jumped to the west and separated the Jan Mayen Ridge from Greenland. A second jump to the Greenland shelf before anomaly 5 time (Talwani and Eldholm, 1977) initiated the development of the now active Iceland-Jan Mayen or Kolbeinsey Ridge (but see Vogt et al., 1979, this volume).

There are some remarkable differences between the Reykjanes Ridge and the southern part of the Mid-Atlantic Ridge. The depth of the ridge crest extends from the sea level near Iceland to 1,500 m at the southern tip north of the Charlie-Gibbs Fracture Zone; whereas south of 57° N a rift valley exists like at the more southern parts of the Mid-Atlantic Ridge, a rift valley is missing at the northern part of the Reykjanes Ridge; but here the lineations of the magnetic anomalies are more clearly developed on both sides of the axis than to the south (Fleischer, 1974).

Some features of the Reykjanes Ridge are not yet completely understood in detail, e.g., the splitting of the ridge centre on the north-south striking part of the ridge near 56° N (Fleischer et al., 1973), the initial opening stage (Srivastava, 1978), the jump of the axis at anomaly 23 time (Featherstone et al., 1977; Voppel et al., 1979), the change of magnetic pattern with approach to Iceland (Serson et al., 1968; Meyer et al., 1972) and a system of fracture zones at the eastern flank south of 60° N between anomalies 13 and 5 (38 and 10 Ma) discovered by Vogt and Avery (1974) magnetically and by Ruddiman (1972) using reflexion seismics.

The last mentioned problem will be taken up in this paper by evaluating the magnetic, gravimetric, bathymetric and reflexion seismic measurements of METEOR cruise No. 48 (May 5 – June 18, 1978). Some tracks of METEOR cruise No. 43, 1976, which was conducted by the late Dr. U. Fleischer, are included in the evaluation. METEOR cruises Nos. 43 and 48 are part of a program of Deutsches Hydrographisches Institut, 'Geophysical investigation of the North Atlantic Ocean around Iceland'. Figure 1 shows the survey areas.

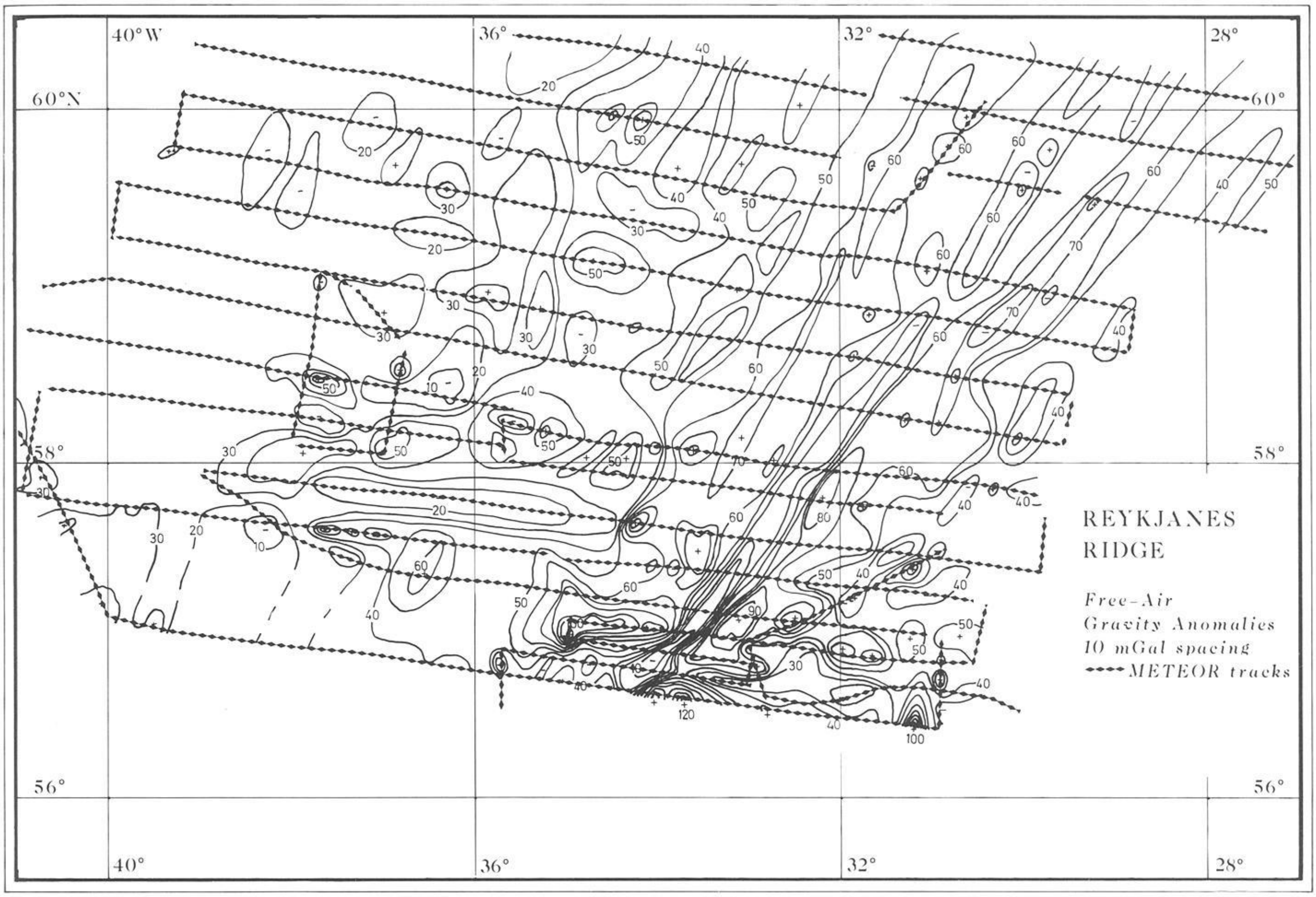

Fig. 3. Free-air gravity anomalies

Measurements

The main objective of METEOR cruise No. 48 was to gain a reconnaissance survey of the western flank of the Reykjanes Ridge area between 60° N and 57° N. This area lies west of a region investigated by Vogt and Avery (1974), south of a region surveyed by USS BARTLETT 1975 and METEOR 1977. To the south there are some lines of METEOR No. 43 (1976) and No. 4 (1966).

The survey lines run E 10° S or W 10° N according to the spreading direction since 40 Ma. These lines are separated 17 naut. miles on the average.

A preliminary rough evaluation of the magnetic lineations during the cruise gave evidence for offsets of anomalies 13 and 6. Accordingly two additional lines A and B (Fig. 2) running perpendicular to the main tracks were measured. The single channel reflection seismic measurements, carried out with a 1.2 l airgun, were expected here to indicate possible fracture zones at the offsets of the magnetic correlation lines. Positioning was performed by an integrated system of satellite and LORAN C navigation.

Magnetics

A proton gradiometer (Geometrics G801G) was used for recording the total intensity of the magnetic field. In principle the gradiometer consists of two proton magnetometers the sensors of which are towed on one cable behind the ship, the 'master' sensor at a distance of about 380 m, and the 'slave' sensor at 230 m.

The magnetic measurements are affected by time variations, especially in the vicinity of the auroral zone. The effect caused by the sun's particle radiation can be characterized by the equivalent planetary amplitude Ap derived from the three-hourly planetary index Kp. For the time of the survey (May 10–May 22, 1978) Ap was 12 on the average. That means the three-hourly range was 26 nT for moderate latitudes. The strongest disturbances occurred on 11 and 21 May with maximum Kp indices of 6 and Ap of 30 and 26, respectively. Compared with the mean Ap of 25 for the entire month of May 1978 the average disturbance during the time of measurements was about a half. Single severe events like ssc's (storm sudden commencements) could be ruled out by comparing the gradiometer (difference 'master' minus 'slave') with the magnetometer ('master' sensor) recordings, since time variations do not influence the gradiometer.

In order to obtain the local magnetic anomalies the IGRF (International Geomagnetic Reference Field) 1965 (Fabiano and Peddie, 1969) updated with the secular variation of the Leirvogur (Reykjavik) and St. Johns (Newfoundland) observatories has been subtracted from the measured values. The anomalies are plotted along the track lines in Fig. 2.

Gravity

Askania gravimeters Gss 3 No. 1 (Prototype) and No. 55 mounted to a platform controlled by an electric gyro (Anschütz), were used for gravity measurements. The instrumental drift has been computed by comparing the gravity ties in Hamburg and Reykjavik. The difference was less than 1 mGal for the average of both gravimeters. No sudden displacements were detected during the cruise. Since this type of gravimeter is free of cross coupling effects only the Eötvös effect must be corrected for. The free-air gravity anomalies with respect to the normal field represented by the International Potsdam Gravity System are presented in Fig. 3.

Bathymetry

The bathymetric measurements of the Elac 30 kHz narrow beam precision depth recorder have been corrected using the Matthews' tables. A bathymetric map is not published here. Only two profiles A and B whose locations are indicated in Fig. 2, have been plotted in Fig. 4, together with the basement depth and free-air gravity anomalies. A preliminary comparison of a bathymetric map containing only soundings of METEOR cruise No. 48, and parts of the GEBCO Plotting Sheet No. 14 is shown in a publication of Deutsches Hydrographisches Institut (Anonymous, 1979). It reveals considerable differences which are mostly due to poorer navigation aids available in previous cruises as compared to the satellite and Loran C navigation used during the new METEOR cruise.

Results and Discussion

The results of the observations are presented in Fig. 2 (profiles of the magnetic anomalies), Fig. 3 (contours of the free-air gravity anomalies), and Fig. 4 (profiles A and B with bottom and basement topography as well as free-air gravity anomalies).

The magnetic anomalies (Fig. 2) reflect the pattern expected from the knowledge of the Reykjanes Ridge as a whole (Herron and Talwani, 1972; Godby et al., 1968): typically well developed lineations of, e.g., anomalies 20, 5, and the axial anomaly. Anomalies between 5 and about 18 are poorly developed, and their lineations reveal many offsets, the identification of which is at some places difficult and only tentative since the space between profiles is for some cases too large. But anomalies 13 and partly 6 could be identified with sufficient reliability, taking into account their average distances to anomalies 5 and 20 and their parallelity with adjoining anomalies.

The pattern of the gravity anomalies (Fig. 3) is regular only for the northern crest provinces and comparable with the results of Talwani et al. (1971) who investigated the northern part of the ridge crest. The irregular pattern with large anomalies at the southern part of the ridge crest in our survey area is connected with the bend of the ridge and the so-called bight fracture zone (Vogt and Avery, 1974) which is not discussed here. As compared with the 1° × 1° average free-air gravity anomalies published by Cochran and Talwani (1978), the local anomalies over the flank provinces observed with METEOR do not show the parallelity to the strike of the ridge as a whole. Some east-west striking minima and chains of minima or maxima partly correlated with the bottom topography reflect the fracture zones expected from the magnetic anomalies. This can be recognized by comparing the magnetic and gravity maps in Figs. 2 and 3.

The system of fracture zones and the offsets of anomaly 13 (38 Ma) is now considered in detail. The following three observations led to the assumption that the crust aged between 40 and 12 Ma is highly fractured:

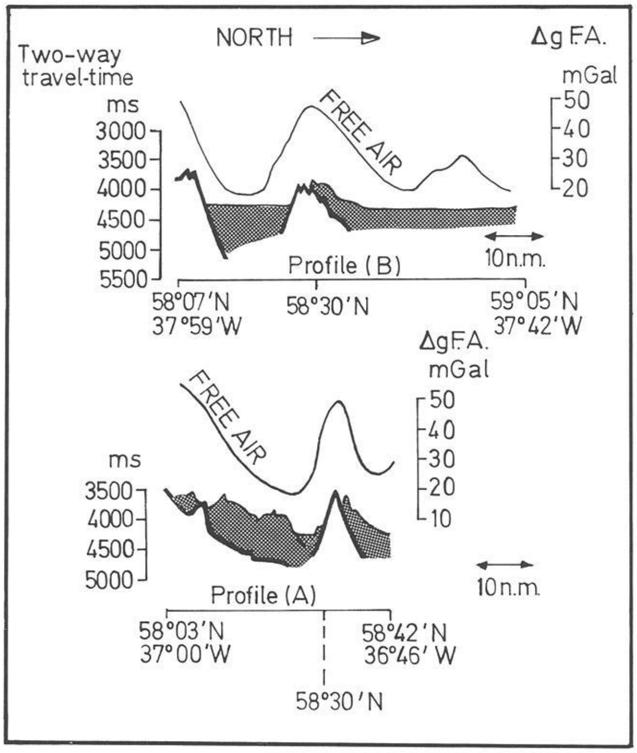

Fig. 4. Profiles of bottom and basement topography and free-air gravity anomaly for tracks A and B from Fig. 2

1. Three short magnetic anomaly strips at 58° 10′ N and between 37° and 38° W (Fig. 2) indicate a strike angle of N 5° E. This strike for 30 Ma old crust deviates considerably from the N 45° E and N 38° E strikes of anomalies generated at 50 Ma (anomaly 20) and since 10 Ma, respectively.

2. The distance between anomaly 13 and anomaly 5 (10 Ma) in the direction of spreading (N 95° E) varies from 204 to 233 km. Similar evidence is found for anomaly 6 (20 Ma) as far as it could be identified.

3. The basement on each profile A and B (Fig. 4) running perpendicular to the spreading direction, shows deep valleys possibly striking about east-west and are interpreted as fracture zones. The free-air gravity anomalies reveal minima over the topographic valleys. They are larger than expected from the water depth alone.

These observations are supported by a visual comparison with the crust of same age east of the Reykjanes Ridge where from seismic measurements a system of fracture zones has been located by Ruddiman (1972). Vogt and Avery (1974) found the magnetic pattern to be irregular with many offsets of anomalies 13 and younger. The strike of these anomalies is nearly N 10° E. The prominent fracture zones (F.Z.) are denoted by Vogt and Avery (1974) by names from the King Arthur legends. These names are inscribed in Fig. 5. It is therefore very probable that this system of F.Z. has been formed within the process of seafloor spreading. It seems justified to assume the strike of anomaly 13 to be nearly N 5° E west of the ridge. Consequently anomaly 13 generally has this strike. This is partly supported by anomalies measured on adjoining tracks, and should be considered tentative.

Each F.Z. at the eastern side must have its counterpart at the western side. In order to examine the relations between anomalies 13 east and west of the ridge axis four steps are taken:

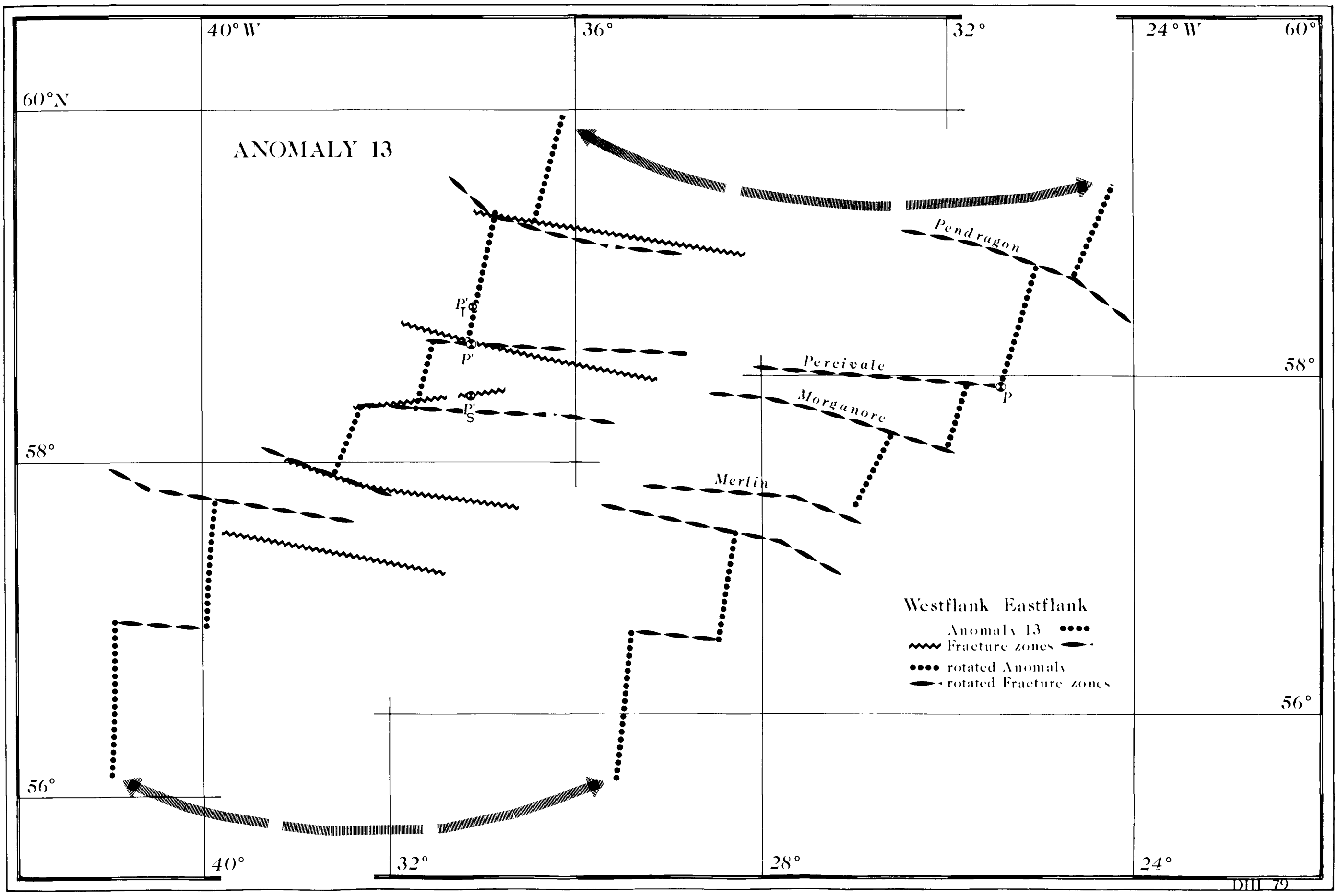

Fig. 5. Lineations of anomalies 13 and fracture zones at the flanks of the Reykjanes Ridge. *Right* At the eastern flank after Vogt and Avery (1974). *Left* At the western flank after METEOR No. 48 data and Vogt and Avery's results rotated from the eastern to the western flank using a pole of rotation at 68.4° N, 133.8° E, with total opening angle of 7.78° Note the different coordinates for the eastern and western flank. For explanation of *P*, *P*′, P'_T and P'_S see text

(a) Selection of a pair of points at the eastern and western flank where the anomalies 13 can visually be associated.

(b) Rotating the point at the eastern flank to the west applying the formulae for plate rotation on a spherical earth with the pole of rotation at 68.0° N, 129,9° E (Talwani and Eldholm, 1977) with a total opening angle of 7.78° and with the pole at 63.1° N, 142.1° E (Sclater et al., 1977) with an opening angle of 7.24°

(c) Calculation of a refined pole of rotation using the positions observed at both sides.

(d) Rotation of all offsets of anomaly 13 from the eastern to the western side.

For the first step the position of anomaly 13 at the northern edge of the fracture zone named 'Percivale' was selected since the associated position at the western side is strongly supported by the observed magnetic anomaly pattern and the fracture zone found by gravity and seismic measurements on profiles A and B (Fig. 4). In Fig. 5 these positions are denoted by the letters *P* at the eastern side and *P*′ at the western side.

Secondly the positions *P* has been rotated to the west using Talwani's and Sclater's poles of rotation and opening angles. The resulting positions are denoted with P'_T and P'_S, respectively. P'_T lies 24 km north of position *P*′ observed, P'_S lies 32 km south (to the east) of *P*′

Thirdly a new pole of rotation was calculated using the corresponding positions *P* and *P*′ observed at the eastern and western flanks of the ridge. For this the opening angle of 7.78° of Talwani was taken as a basis because P'_T and *P*′ both lie on anomaly 13. This yielded a pole position of 68.4° N, 133.8° C.

Finally, after this adjustment at one position on anomaly 13 the entire isochron of this anomaly between 56° and 60° N on the east flank of the ridge has been rotated to the west applying the new pole of rotation. The result is shown in Fig. 5.

Deviations between the rotated and observed anomaly lines and fracture zones could be due to different interpretations of anomalies. Generally the anomalies between 13 and 5 have only small amplitudes which reduces the certainty of identification. It is to be noted that the course of the fracture zones rotated from the east to the west are calculated only for the fractures between the offsets of anomalies 13. The inner and outer parts are estimated in order to facilitate their identification. This is indicated by interrupting the markings in Fig. 5.

The coincidence, however, between the anomalies rotated from the eastern to the western side and the anomalies observed or at least tentatively assumed from METEOR measurements is very good in general. The refined position of the pole of rotation (valid for the total opening of anomaly 13) seems to be supported.

The development of these fracture zones during the process of seafloor spreading has been proved by pointing out a mutual fitting system of fracture zones east and west of the Reykjanes Ridge axis. Whether this system extends to the north of 60° N or not, has yet to be determined. Voppel et al. (1979) mentioned that anomaly 13 on the east side of the ridge north of 60° N is missing on four profiles. But an offset could not be detected without doubt. So this phenomenon is assumed to be limited to the area between 56° N and 60° N immediately north of the bend of the ridge axis and the triple junction. Vogt and Avery (1974) argued that this system is a consequence of the ceasing of seafloor spreading in the Labrador Sea at about 40 Ma which was accompanied by a change of the spreading direction in the Reykjanes Ridge area. Why the anomaly strike reoriented to N 38° E at about 12 Ma has not yet been explained.

Conclusions

The result of geophysical measurements carried out with the German research vessel METEOR in 1978 is presented by maps showing magnetic anomaly profiles and free-air contours of gravity as well as by two profiles showing bottom and basement depths. The survey area covered a region on the western flank of the Reykjanes Ridge between 56° N and 60° N where the crust is highly fractured between ages of 40 and 12 Ma.

The fracture zones have been formed by the process of seafloor spreading. This interpretation is based on the comparison with a similar system located at the eastern flank by other authors. A satisfactory fit of both systems could be obtained by rotating the isochron of anomaly 13 from the eastern to the western side around a new pole of rotation located at 68.4° N, 133.8° E with an opening angle of 7.78°.

Future measurements on narrower-spaced magnetic, gravity and bathymetric tracks as well as reflection seismic profiles perpendicular to them could improve the positioning of fracture zones and lead to corrections of isochrons on both sides of the ridge axis. A better understanding of the geophysical process which induced the formation of these fracture zones and the changes of orientation of the ridge axis may then be derived.

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