

Aeromagnetic surveys off South and West Iceland in 1990 - 1992

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Aeromagnetic surveys off South and West Iceland in 1990-1992

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Abstract - Aeromagnetic surveys by the authors in selected areas off South, Southeast and West Iceland in 1990-92 have extended the coverage of previous magnetic surveys of the insular shelf.

Southeast of Iceland, magnetic anomalies associated with the shelf edge have been mapped in detail farther east and west than in marine surveys in 1973. An inferred steep slope or edge in the basement inside the bathymetric shelf break may be followed continuously towards the west to $19^{\circ}10'W$. From there its magnetic-field signal is lost in noise, partly from Late Quaternary volcanics but a basement edge may extend to west of $20^{\circ}W$. Eastwards, the edge feature was found to continue around Southeast Iceland as far as $64^{\circ}22'N, 12^{\circ}42'W$. Model calculations confirm that it occurs in rocks (possibly pillow lava) with higher magnetization values and thicker polarity zones than Tertiary Icelandic basalts. The basement edge may be due to ocean-wave erosion of an old basalt plateau, which later subsided below sea level. Other interpretations are possible, such as an origin by faulting. The sediment lens seawards of the edge is generally

of the order of 10 km wide and its thickness may be from 0.5 to more than 1 km.

In Breiðafjörður Bay and west of Snæfellsnes, a detailed aeromagnetic survey in 1991-92 revealed the structure of several prominent WSW-ENE lineations. As these lineations are followed to the north and east in the NW-peninsula and Húnaflói, their trend turns to a northerly direction. The new survey also delineated the extent of some large volcanic centers seen in previous marine surveys. These appear to be unusually numerous along Snæfellsnes and the southernmost part of the Bay. In Faxaflói Bay, two distinct magnetic trends are seen. Magnetic anomaly lineations in both Bays can to some extent be correlated with geomagnetic chrons and polarity zones in onshore lava series. Many geometrical aspects of the anomaly can be simulated by a model which is consistent with Jóhannesson's (1980) tectonic scheme and assumed ages: in this scheme the current spreading zone took over from an older spreading zone crossing the Snæfellsnes peninsula, by a "propagating rift" mechanism.

PART 1 INTRODUCTION

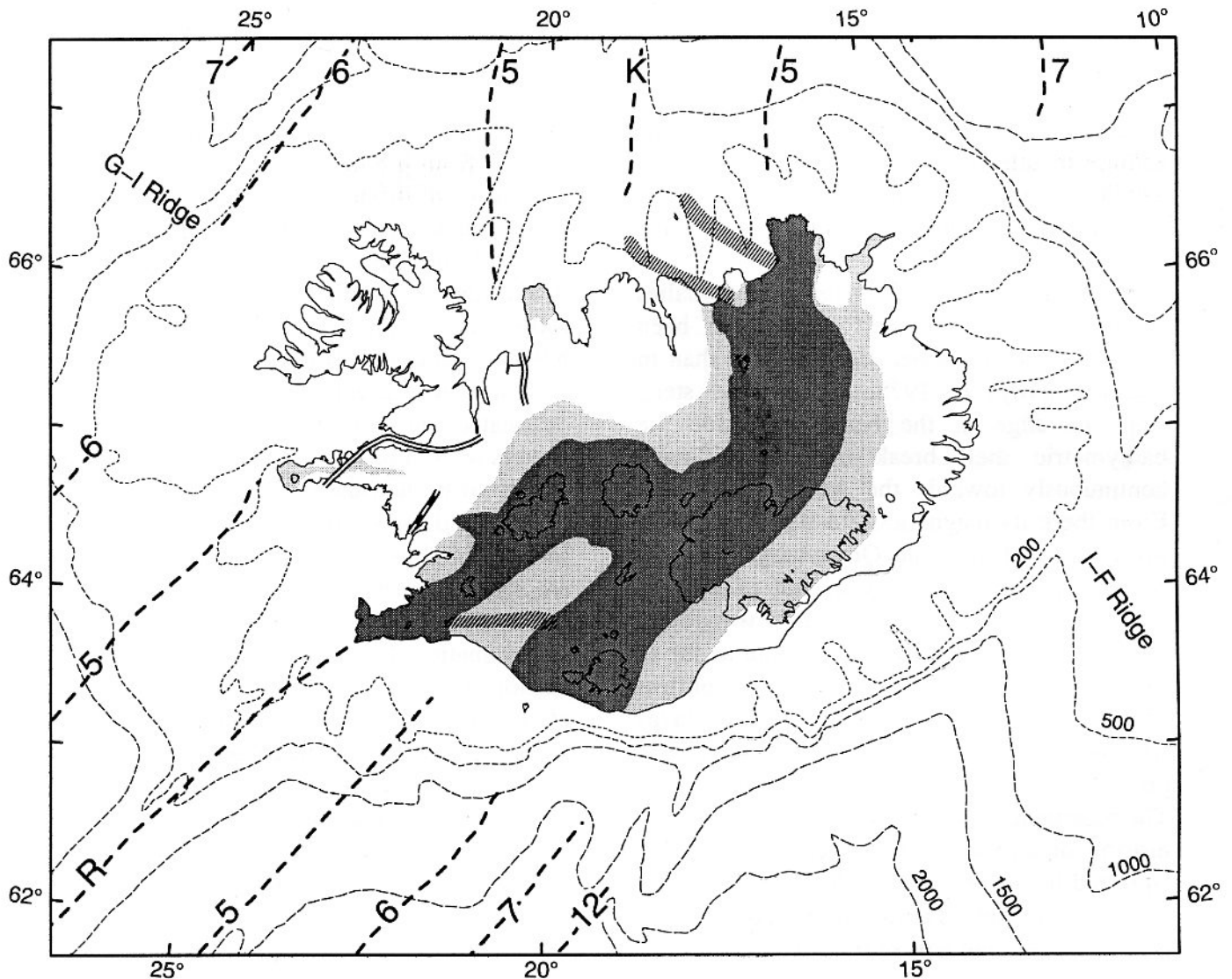


Fig. 1. Outline map of Iceland, showing the volcanic zones (adapted from Sæmundsson, 1986) and large glaciers. Light gray: Plio-Pleistocene bedrock (0.78- 3.2 Ma), dark gray: Upper Pleistocene and Holocene bedrock. Isobaths (in m) around the island are shown, and also some prominent magnetic anomaly lineations (from Nunns et al., 1983, with minor modifications based on subsequent research). R and K are the axial zones of the Reykjanes and Kolbeinsey Ridges. A syncline and an anticline in W-Iceland (Jóhannesson, 1980) are shown, as well as the South Iceland and Tjörnes transform zones.

1.1. *Geological structure and history in the Iceland region*

The Iceland region of the Northeast Atlantic is characterized by a geoid anomaly and a general

topographic high reaching 2.5 km above normal ocean depths at similar ridges. Its geological structure is also different from that of other ocean-ridge regions. The difference is expressed in relatively thick crust, and trans-

verse ridges towards Lower Tertiary volcanic areas in Greenland and the Faeroe Islands. Within Iceland, unusual features include high heat flow, the presence of two sub-parallel volcanic zones in the South (Fig. 1), an abrupt change of tectonic directions in Central Iceland, and a large number of volcanic centers producing acid and intermediate rocks (see Kristjánsson and Helgason, 1988). Rather than being composed of pillow lavas and dikes as the ocean floor on the spreading ridges, the crust is mostly a pile of lava flows down to 2 km or more below sea level. The lava pile is in general inclined towards the volcanic zones. In the fjords of East Iceland the tilt is 5-9° at sea level, increasing with depth in the pile and generally also from west to east.

Very little is known of the geological history of the transverse ridges. Bedrock samples have been obtained from the Iceland-Faeroe ridge by dredging (Noe-Nygaard, 1949; Kharin, 1976) and by coring in DSDP Leg 38. These are largely basic igneous rocks but andesites also occur. Nilsen (1978) suggested that a spot on the northern flank of the Iceland-Faeroe Ridge, now at as much as 1300 m below sea level, was dry land for some time during the Early Tertiary. The Faeroe Islands may also have subsided by at least 2 km.

The origin of high heat transport and other anomalous crustal conditions in the Iceland area has been a matter of speculation for decades. Most researchers speak of a "hot spot" in the upper mantle which in turn may be fed by a "plume" from the lower mantle (e.g., Vogt, 1983; Bott, 1976, 1988). It is generally assumed that the center of the plume or hot spot is under the northwestern part of the Vatnajökull glacier, and that the Eastern volcanic zone is moving over it towards the west, but details are far from certain.

The oldest rocks above sea level in Iceland are about 15 Ma old (McDougall et al., 1984), and there has been no fundamental change in the character of the Icelandic volcanism since then. Research on the older history, however, must primarily depend on the interpretation of sparse marine geophysical data. Nunns (1983, p. 26) suggests that the shape of magnetic anomalies is compatible with the presence of a wide accretionary zone in Iceland at Anomaly 7 time, i.e. about 27 Ma ago. Sæmundsson

(1986) quotes evidence from ocean-floor sediments for increased volcanic activity in the area about 25 Ma ago. Both these ages may be taken as an indication of the age of increased productivity of the Iceland region, and they are possibly correlated with a change in the spreading pattern in the Norwegian Sea 26 Ma ago (Bott, 1985). In contrast, it seems that in the ocean south of Iceland and the transverse ridge, no large movements of the spreading axis have occurred at least for the past 50 Ma.

In Iceland there is evidence for at least one eastward jump of the ridge axis, by over 50 km 7 Ma ago (see Section 3.5 below), and possibly other smaller jumps (Sæmundsson, 1986). It is significant that magnetic anomaly lineations south of Iceland, if continued towards the northeast, are much older than corresponding exposed rocks on shore. Thus, Anomaly 12 of approximately 35 Ma age (Nunns et al., 1983; Harland et al., 1990) is in line with the outermost promontories of East Iceland (Fig. 1) which only reach an age of 13 Ma at sea level. It is therefore possible (Kristjánsson, 1979; Bott, 1985) that Iceland is partly underlain (at > 2 km depth) by ocean crust which is 10-20 Ma older than local surface rocks. It is also possible that spreading and volcanism has commonly taken place on two volcanic zones simultaneously in the area, as is the case at present.

1.2 Aeromagnetic anomalies in Iceland

The linear magnetic anomaly pattern characteristic of the mid-ocean ridges is largely broken up over Iceland as well as the Greenland- Iceland- Faeroe ridges (Nunns et al., 1983). Only the youngest anomalies (Brunhes, Matuyama, partly Gauss and Gilbert) are seen clearly. The overall ratio of primary remanent to induced magnetization in Icelandic extrusive rocks is about 3 (Kristjánsson, 1984) or more, so that geomagnetic reversals during emplacement should be reflected in the anomaly pattern. During the period of buildup of the East Iceland lava pile in the last 13 Ma, the geomagnetic field changed its polarity at least 80 or even 100 times. Ideally, some 40-50 pairs of anomaly lineations should therefore occur through East Iceland, each pair of an estimated average width 3-4 km. However, the individual polarity-zone anomalies

will be smeared out by the rapid attenuation of short wavelengths with altitude. The thickness of a typical polarity zone in the older areas is of the order of 15 lavas, i.e. 150-200 m (Kristjánsson et al., 1995). Furthermore, the boundaries between the polarity zones in the lava pile are diffuse due to the variable tectonic dip, overlap between products of distant eruptive centers, faults and other factors. Therefore, the linear anomalies over the Tertiary areas of Iceland are replaced by very broad (> 20 -30 km) semi-linear highs and lows (Jónsson et al., 1991) and only occasionally can a thick single-polarity lava sequence on the ground be correlated with a particular anomaly. In fact the whole tilted lava pile of East Iceland generates not more than three broad lineations, of total width 140 km or so: a high over the volcanic zone and east of it, then a low, and a high reaching beyond the coast. The residual broad anomalies must be mostly due to variations in an effective or "average" polarity of the remanence vector in the basement, as seen from the airborne magnetometer. Each lineation therefore seems to be due to an integrated effect, i.e. an essentially stochastic bias in the presence of rocks of one polarity. The possibility cannot be excluded, that these wide lineations are in part also due to variations in viscous remanence in formations at elevated temperatures below sea level.

Many localized anomalies are superimposed on the broad lineations. The most noticeable of these occupy approximately circular regions of up to 10 km in extent. In Iceland and on the shelf to the west and east, they are clearly associated with central volcanoes (Kristjánsson, 1976a; Jónsson et al., 1991) and (generally positive) gravity anomalies. The same is the case west of Scotland (Hitchen and Ritchie, 1993). The source of the anomalies may be in gabbros, cone sheets, basaltic andesites or other rock types. The common coincidence of localized magnetic and gravity anomalies on the Iceland-Faeroe ridge (Fleischer et al., 1974) is also certain to be due to central volcanoes, and differentiated rocks have been dredged from such locations on the Iceland shelf (Kristjánsson et al., 1977). However, not all central volcanoes in Iceland give rise to distinct localized magnetic and gravity anomalies.

The present report extends previous research on magnetic anomalies at the insular shelf edge around the southern part of Iceland, in order to throw some light on its structure and history.

1.3 *Main previous geophysical surveys*

Existing geophysical data on the structure of Iceland and especially on the surrounding region are rather limited. To date, the largest research effort on the shelf area was a collaborative program between Icelandic institutions and the U.S. Defense Mapping Agency in 1972-73. This survey acquired accurately positioned bathymetric, gravity, magnetic and limited sediment-thickness data. Survey lines were spaced 10-12 km apart, oriented perpendicular to the coastline. In particular, magnetic data were obtained south of Iceland in three separate survey areas numbered 2, 3 and 4 in Fig. 2a. For technical reasons a zone of 5-10 km width close to the shore was left out during this survey, and an aeromagnetic survey over Iceland itself in 1968-80 (Sigurgeirsson, 1970-85; Kristjánsson et al., 1989) also did not cover this zone, thus making it difficult to correlate the onshore and offshore magnetic anomalies. No magnetic data were obtained immediately east and west of the above three marine survey areas. The gravity measurements have been published in contour maps of free-air anomalies with 10-mgal spacing (Pálmason, 1974) and Bouguer anomalies with 5-mgal spacing (Þorbergsson et al., 1990).

The German research vessel "Meteor" made various geophysical measurements over the Iceland-Faeroe ridge in 1968-70 on lines spaced 5.5 km apart. These lines reached close to the coast of Iceland, but they had a SW-NE direction, i.e. nearly parallel to the coastline and the shelf edge so that the magnetic data could not be interpreted reliably in terms of such an edge. Results were published in the form of colored contour maps (Fleischer et al., 1974). In 1973-74 the U.S. Naval Oceanographic Office collected low-altitude (160 m) aeromagnetic data around much of Iceland with position accuracy of some 2 km. Their results off North Iceland and East Iceland as far south as Gerpir have been included in maps (Nunns et al., 1983) but the data west, south and southeast of Iceland are not available to us.

PART 2

AEROMAGNETIC SURVEY OFF S- AND SE-ICELAND 1990-92

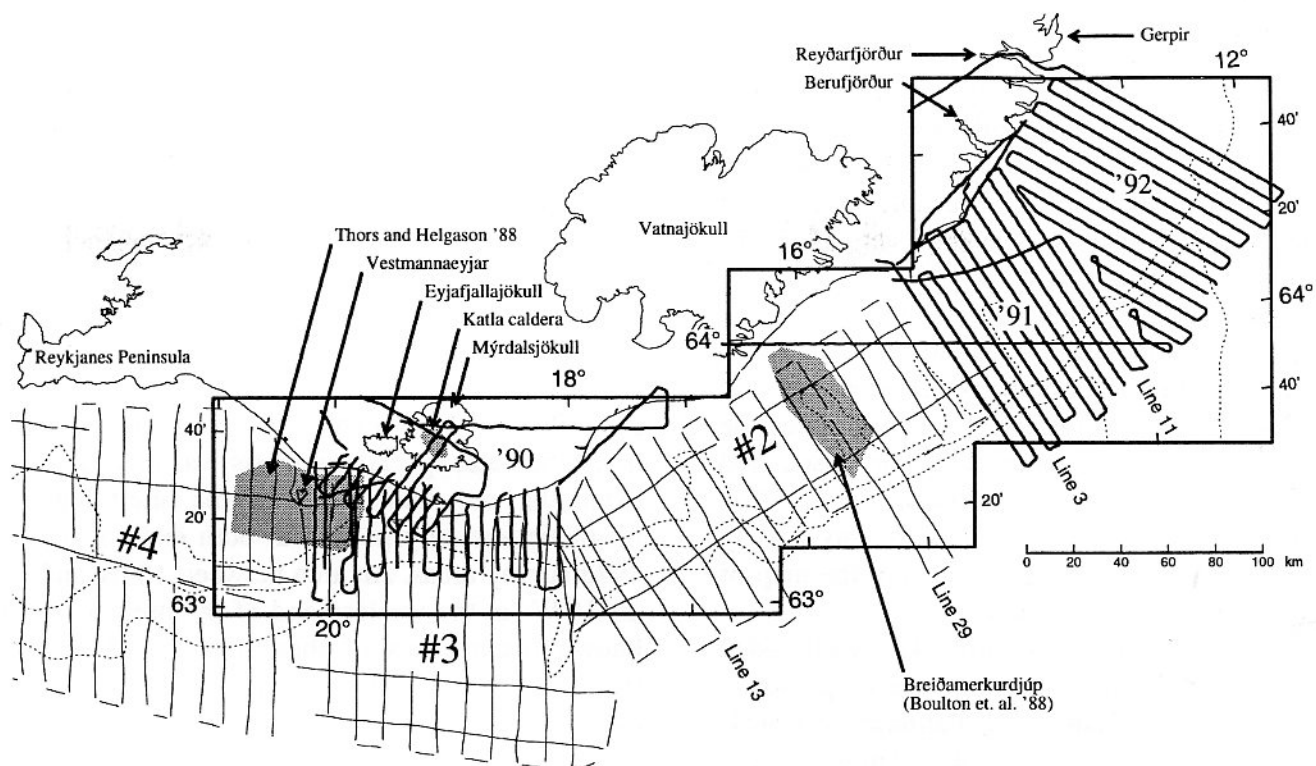


Fig. 2a. Geophysical survey lines on the insular shelf south and east of Iceland. Isobaths as in Fig. 1. Thin lines with Area numbers #2, #3 and #4: marine survey lines of 1973. Heavy lines labelled by years: aeromagnetic surveys in 1990-92. Aeromagnetic lines over the land area (Sigurgeirsson, 1970-85) are omitted here. Lines no. 13 and 29 of Area 2, mentioned in the text, are indicated, as well as lines no. 3 and 11 from our 1991 survey. Gray shading covers the sparker survey areas of Boulton et al. (1988) and Thors and Helgason (1988).

2.1 Description of the area

The shelf off South and Southeast Iceland is relatively flat ($0.2-0.3^\circ$) out to the shelf break which appears to be a very distinct and essentially continuous feature in this area. It occurs at around 200 m depth, increasing to about 300 m at the Iceland-Faeroe (I-F) ridge. From the break, the insular slope descends steeply (about 5° , locally more) down to a depth of 1000-1400 m south of Iceland, but only to 500-600 m on the I-F ridge. The distance of the shelf break from the coast is 12-15 km at the south tip of Iceland, increasing progressively towards the East, to 70-80 km off the southernmost fjords of East Iceland (Figs.

1 and 5) and 90 km towards the I-F ridge. The ridge in turn narrows towards the shelf, and a morphologically distinct east-west oriented "Iceland block" may be defined (Bott, 1976).

The steep insular slope described above is only found east of the volcanic zones off South and Southeast Iceland, between the Vestmannaeyjar (Westman Islands) archipelago and the I-F ridge (Figs. 1 and 2a). A similar but less steep slope occurs north of the Iceland-Faeroe ridge, whereas west of Vestmannaeyjar and all the way around W-Iceland to the Kolbeinsey ridge the slopes are much more gentle.

2.2 Shelf magnetic and gravity anomalies

Kristjánsson (1976b; Kristjánsson et al., 1977) described and discussed the magnetic anomalies on the shelf off South Iceland. Anomaly lineations associated with the Reykjanes Ridge disappear (Fig. 1) before they enter the shelf region; they are replaced by a pattern which is sub-parallel to the shelf edge and is mostly seen inside the shelf break. This anomaly pattern was traceable from the easternmost lines in Area 2 at 14–15°W towards the west to 18–19°W where survey coverage was insufficient. Only one large (–3000 nT) localized magnetic anomaly has been found on the South Iceland shelf, around 63°40'N, 15°W (Figs. 3b, 5). It resembles the many localized anomalies which are associated with central volcanoes (Kristjánsson, 1976a) but this one is not accompanied by any gravity anomaly as far as can be seen from the map of Þorbergsson et al. (1990).

The anomaly following the shelf edge appears likely to be due to a step-type structure, in agreement with Pálmason's (1974) conclusion from gravity observations that a step of 1 km or more in the basaltic basement occurs under the South Iceland shelf. The magnetic anomaly is complex in shape on many of the survey profiles, but it usually has both a main peak and a trough. Sometimes the peak is closer to the shore, and sometimes not, but the line spacing is generally too large to allow connections of details between lines. Kristjánsson (1976b) suggested on the basis of simple model calculations that the width of a basement step causing the anomaly was of the order of 3–4 km. The upper edge of the step was estimated to occur 5–15 km from the shelf break, increasing towards the east. The nature of this sediment-covered step is still uncertain, but it is undoubtedly a major feature of the structure of the Iceland margin. The sediments were possibly deposited by a glacier which reached to the shelf break, or by sediments carried out by glacial rivers. Five valleys of less than 200 m relief have been eroded into the southern shelf between 18°W and the Iceland-Faeroe Ridge; their presence does not seem to have an effect on the magnetic anomaly pattern.

The steepest gradients in the free-air gravity anomaly seen in satellite sea-level measure-

ments (D.T. Sandwell, pers. comm., 1994) essentially coincide with the 200–500 m depth interval off South and SE-Iceland. Neither these data nor the published gravity maps already referred to have sufficient resolution to provide constraints on the detailed structure of the shelf.

2.3 Aeromagnetic survey off S- and SE-Iceland in 1990–92

In 1990–92 we carried out an aeromagnetic survey of selected areas off the south coast and southern part of the east coast of Iceland. While the main purpose was to extend the general magnetic field coverage and connect the 1973 marine survey to overland geomagnetic data, special emphasis was placed on extending our knowledge of the shelf-edge magnetic anomaly pattern at both ends of the 1973 survey areas. An area between 18°W and 20°10'W (at the western end of the previously known occurrences of these anomalies) was flown in 1990, in order to connect the northern part of Area 3 with a 1969–72 overland survey (Sigurgeirsson, 1980–85). A larger area, continuing eastward from Area 2 of the 1973 survey, was flown in 1991–92.

The flights proceeded as follows (Fig. 2a):
June 26, 1990: Eighteen north-south lines running from the south coast between 18°W and 20°W, at 6 km spacing. The intended flight altitude was 900 m above sea level, sufficient to clear coastal mountains. However, due to weather conditions the altitude was reduced to 300 m so lines had to be shortened and many did not reach the coast. One line was flown over Mýrdalsjökull at 2000 m (Jónsson and Kristjánsson, 1996).

July 2, 1990: Ten short lines perpendicular to the coast between 19°W and 20°W at 900 m altitude. This survey also included flights over Mýrdalsjökull at 2100 m.

May 6, 1991: Extension of the marine survey area 2 from 1973 towards northeast. Twelve lines stretching 100 km SSE from the coast with 6 km spacing, at altitude 300 m.

July 14, 1992: Further extension towards NNE, up to the Reyðarfjörður fjord in East Iceland. Ten lines stretching 100 km ESE from the coast and a few short ones to fill a wedge formed against the 1991 flights. Same spacing and altitude as in 1991.

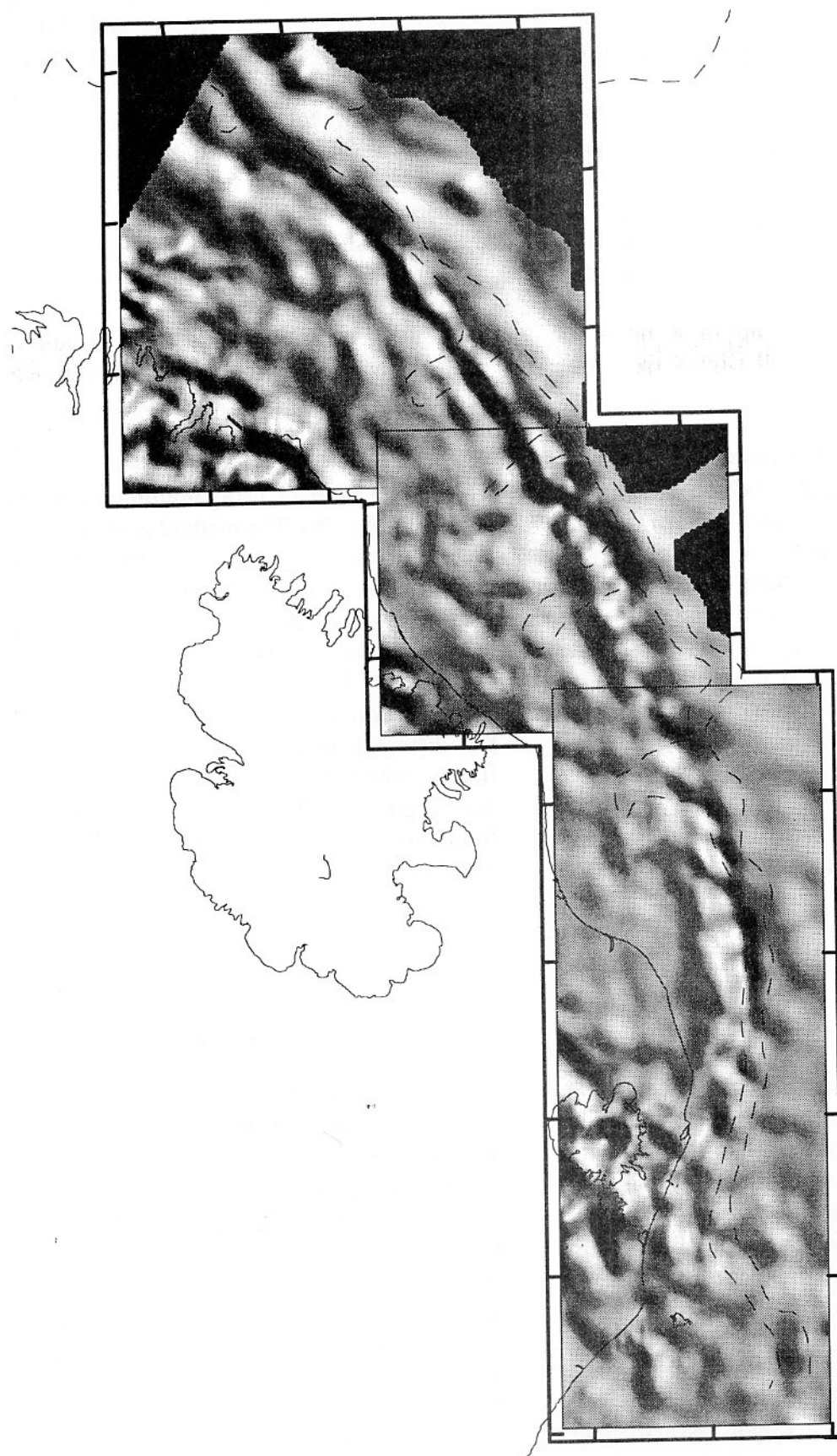


Fig. 2b. Composite shaded-relief map of magnetic anomalies in the region of Fig. 2a, after filtering with a distance weighted window with active length of around 3 km. ($p_r = 1/r^{1/2}$, $p_0 = 1$) The map is based on widely spaced survey lines, so that a smaller window would generate a pearl-string appearance along these lines.

2.4 Data acquisition

For the surveys we hired TF-BMX, a Cessna Skymaster II aircraft, the pilot of which also assisted in the collection of data. This type of plane has one engine in the front and one in the rear, flanked by two large tail fins. Our magnetometer is a Geometrics G-856X proton precession meter, recording the total field intensity digitally at a pre-set interval of 5 seconds (approx. 310 meters ; 6 seconds on 2 July 1990). It can store up to 8 hours of measurements. In the 1990 flights the probe was fitted under the left wing of the plane which turned out to give an unsatisfactory signal quality. Later, the probe was mounted on a non-magnetic bracket behind the left tail fin (Jónsson and Kristjánsson, 1991).

In 1990 an aviation Loran-C receiver was used for navigation. There were repeated problems due to i) a relatively long (30 sec) and variable processing time within the receiver, ii) spatial offsets presumably caused by ground/sea/glacier conductivity variations, and iii) occasional temporary loss of signal. In 1991-92 the pilot navigated by a ProNav GPS-100 receiver, resulting in very straight flight lines. Positions were recorded at 4-sec (approx. 250 m) intervals by an onboard computer, and we estimate them to be accurate to within 200 m.

2.5 Data processing and presentation of results

The raw data consists of two independent computer files, one with total magnetic field measurements and time, the other with positions and time. The uncertainty in the field measurement relative to the position is ± 1 sec. Short gaps in position or field values were filled manually by extrapolation. The two independent data sets were merged and the following corrections done on the magnetic field values:

- i A direction-dependent effect due to the aircraft was corrected for, to an estimated accuracy of 10 nT which is small in comparison with the observed anomalies.
- ii Diurnal variations were subtracted, using records of the Leirvogur Geomagnetic Observatory near Reykjavík.
- iii Secular variation of the total field was

corrected for by means of Leirvogur records, to a 1967 reference level also used by Þ. Sigurgeirsson in his 1968-80 aeromagnetic surveys of Iceland.

- iv The mean geomagnetic field intensity was subtracted from the data, using a third degree polynomial derived from Canadian measurements at 3-4 km altitude over Iceland in 1965 (see Kristjánsson et al., 1989, p. 37). This field is very similar to the IGRF.

As the geomagnetic field around South Iceland has a high inclination ($+75^\circ$) our scalar residual values will be a good approximation to anomalies in the vertical field component.

A shaded-relief map of the field was made by gridding the data, using minimum-curvature gridding (Fig. 2b). The method gives a realistic picture of the field only if the line spacing is similar to or smaller than the height above the magnetic source. This is obviously not the case in survey area 2 at the center of Fig. 2a which should be kept in mind during further interpretation. No attempt was made to correct for different recording altitude in different flights when the data sets were combined during gridding. The results are plotted along flight lines in Fig. 3a,b,c which show several distinct anomaly features.

2.6 Description of nearshore anomalies, 18-20° W

Volcanic activity in the Eastern volcanic zone of South Iceland seems to largely peter out before reaching the coast, with east-west oriented structures and tectonics being apparent at its southern end (Sæmundsson, 1986). Here we find the Katla-Eyjafjöll complex with two volcanic centers. The Katla center (Jónsson and Kristjánsson, 1996) has a large negative magnetic anomaly (Fig. 3a). The volcanically active Vestmannaeyjar are evidence that this zone continues offshore. Little was known of the extent of volcanic activity on the shelf until the sparker survey by Thors and Helgason (1988), see Fig. 2a. This revealed the presence of various small volcanic structures of presumed Early Holocene age on the sea floor around the Vestmannaeyjar islands, reaching at least as far east as $20^\circ 00' W$.

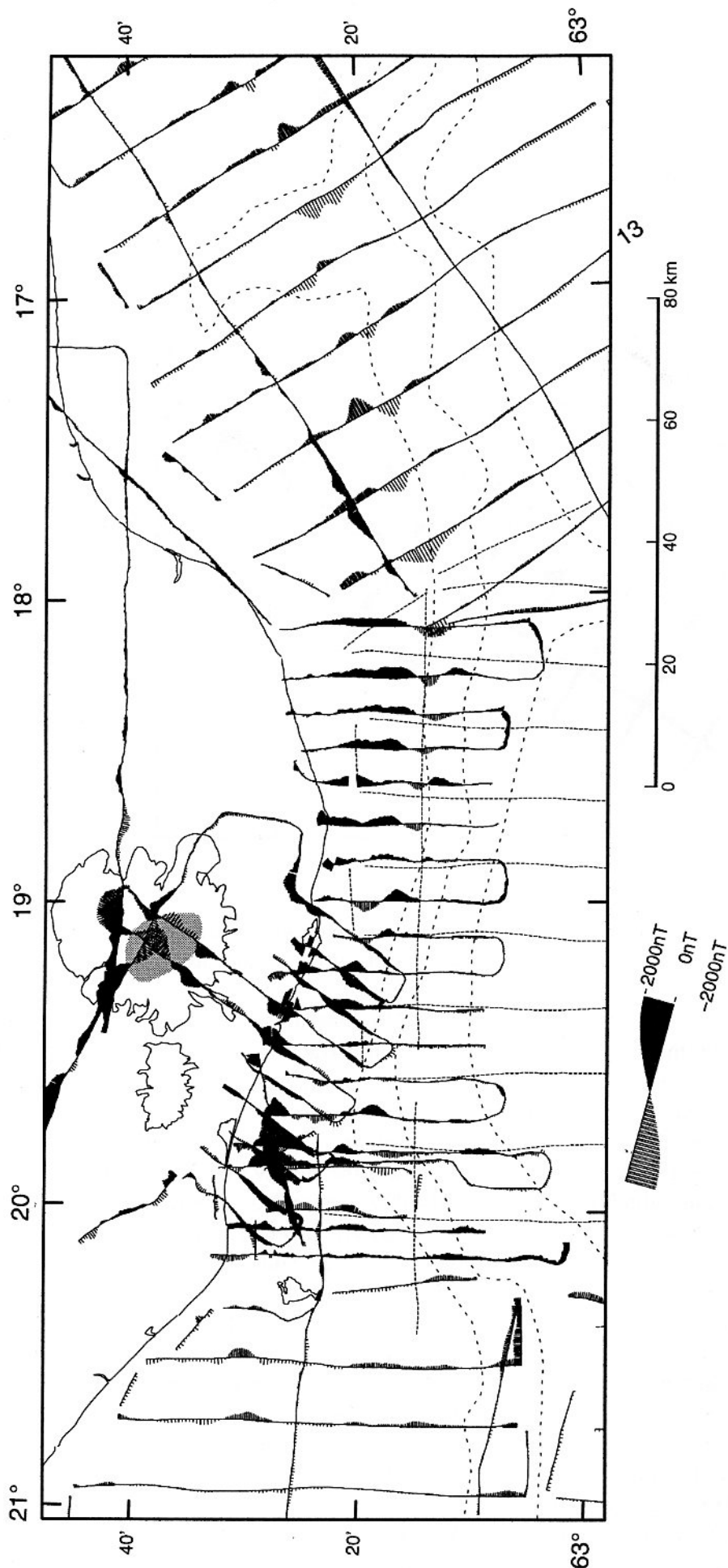


Fig. 3a. A plot of magnetic field residuals on survey lines south of Iceland. Parts of Areas 2 and 3 from 1973 (low-pass filtered with a filter of 4.3 km width along marine survey lines) and 1990 flights (unfiltered data). The residual field is represented by bars emerging from the measurement points perpendicular to the survey path. The positive deviations have double the bar density of negative ones. The "positive" side is generally north or east of the flight track which may cause ambiguity in lines oriented around NE. Line 13 of Area #2 (Fig. 4a) is indicated.

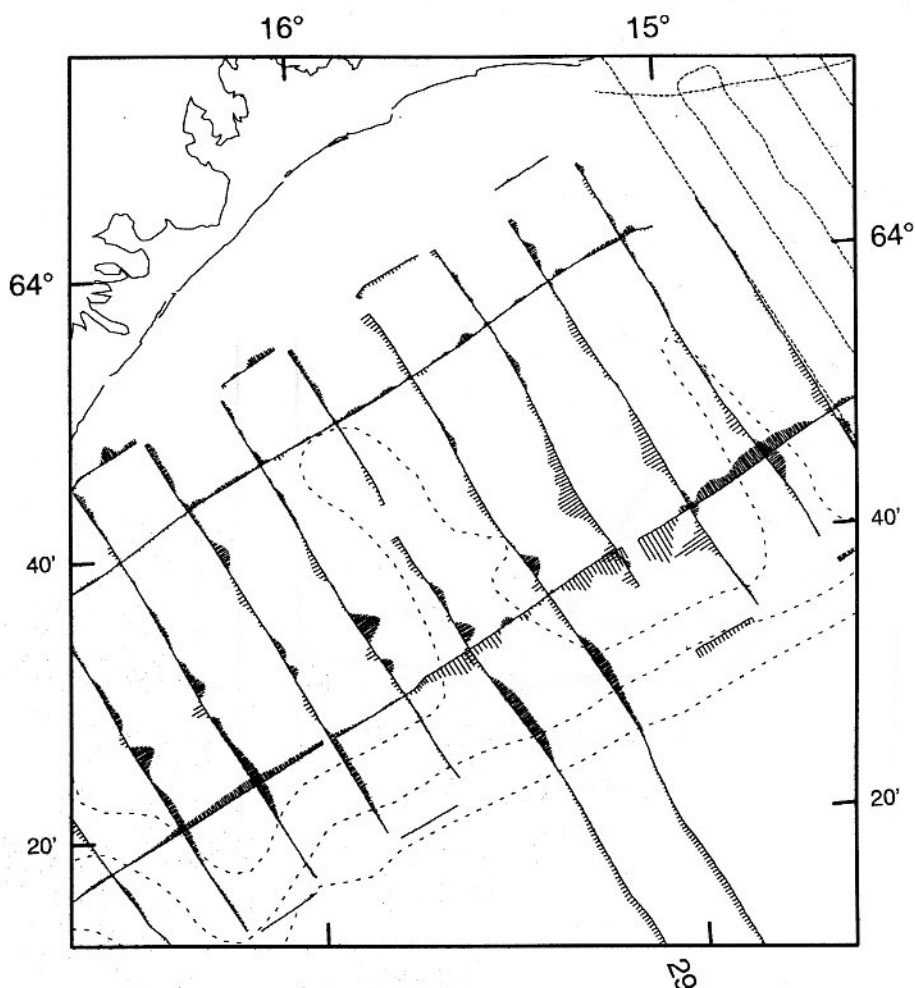


Fig. 3b. Same as Fig. 3a, part of Area 2 from 1973 around the Breiðamerkurdjúp submarine valley. Line 29 of Area 2 (Fig. 4b) is indicated. Same scale as in figures 3a and 3c.

Our aeromagnetic measurements (Fig. 3a) clearly show the shelf-edge anomaly continuing west, at least to $19^{\circ}10'W$. The basement edge is then 8-10 km offshore. The disappearance of a definite edge anomaly may be connected with the presence of a localized E-W oriented gravity low of 30-50 km extent, which reaches from $19^{\circ}10'W$ to about $20^{\circ}00'W$ just outside the shelf (Þorbergsson et al., 1990). The westernmost part of the gravity low, from $19^{\circ}50'W$, coincides with a partially sediment-filled valley (Háfadjúp) mapped by Thors and Helgason (1988). Still farther west, between Vestmannaeyjar and the mainland, the presence of an edge anomaly is uncertain, probably due to noise from small volcanic structures (Fig. 3a and Kristjánsson et al., 1989, Fig. 14). Thors and Helgason (1988) have however identified a basement step in their sparker results here, at $20^{\circ}20'W$; they suggest that this is where the

depth to "basement" increases, from 250 m as found in refraction measurements at the coast to a lava horizon at 820 m in a drill hole in Vestmannaeyjar.

Positive magnetic anomalies occurring in 1973 marine survey lines at $63^{\circ}30'N$, $20^{\circ}30'W$ - $20^{\circ}40'W$ (second and third line from left in Fig. 3a) are probably due to late Quaternary volcanics (see Thors and Helgason, 1988, Fig. 21).

West of $20^{\circ}W$ the shelf (Selvogsbanki) increases in width to more than 50 km. The magnetic field over it is very flat most of the way to the Reykjanes Ridge (Kristjánsson, 1976b, Fig. 2). Even immediately south of the Reykjanes peninsula the field only exhibits a broad and featureless low (Kristjánsson, 1978; Kristjánsson et al., 1989, Fig. 4a). The steep mountainsides at the south coast of the peninsula (from $22^{\circ}40'W$ to $23^{\circ}W$) may represent

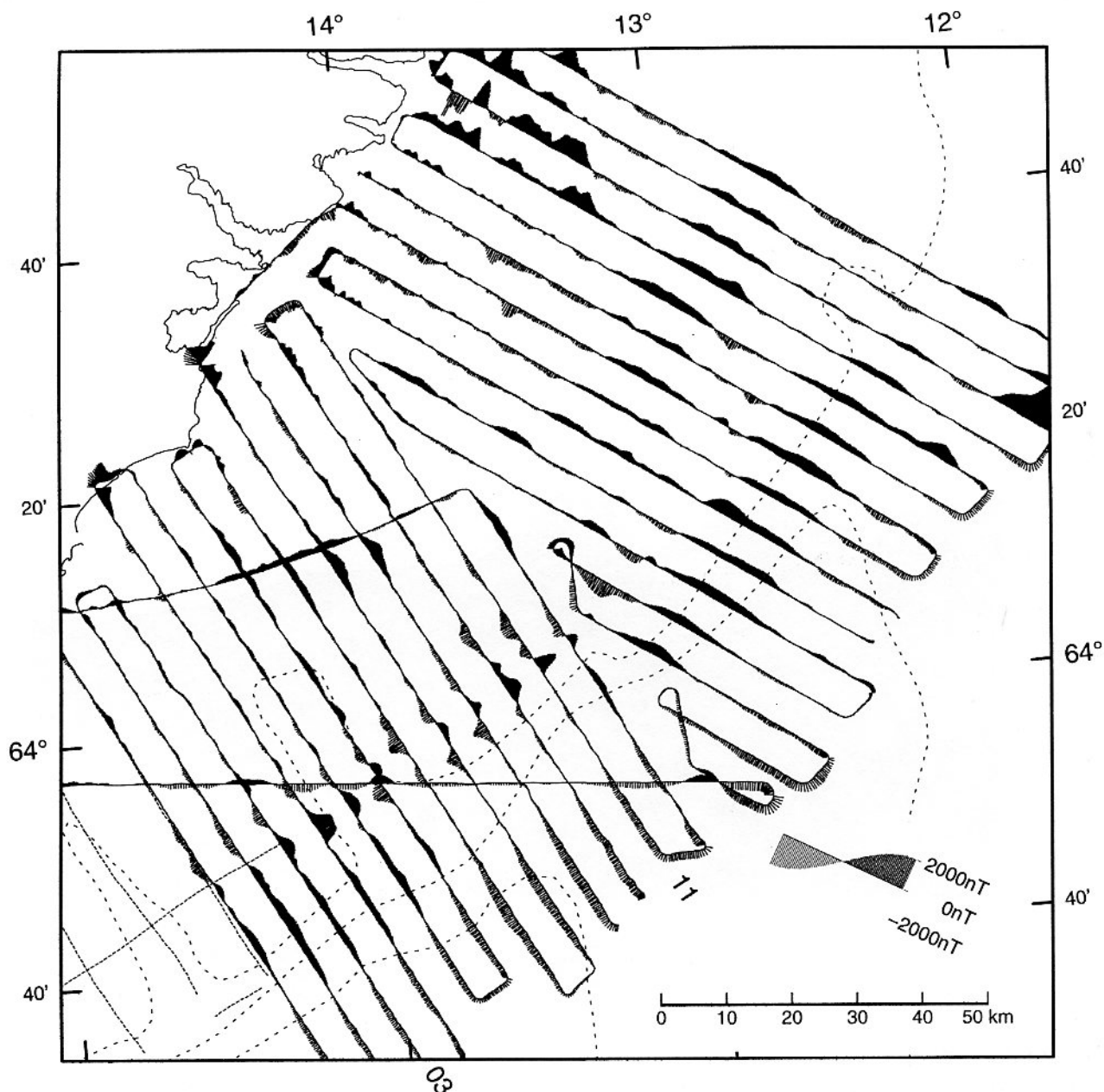


Fig 3c. Same as Figs. 3a,b. Flight lines from 1991-92 southeast of Iceland. The lines interpreted in Fig. 6 are indicated.

a scaled-down version of the submarine basement step off SE-Iceland. Egloff and Johnson (1978, Profiles 11,13) have confirmed the presence of sediments in the southernmost part of Selvogsbanki, but their seismic soundings only penetrate of the order of 500 m below the sea floor.

2.7 Anomaly modelling

It must be kept in mind that an infinity of possible source configurations can be proposed to explain any magnetic anomalies. In the

present case, not much other data is available to constrain our models, but we have endeavored to keep these models as simple as possible. They give an indication of the size of the structures and of the magnetic contrasts needed to explain the observed anomalies, but cannot be expected to be correct in detail. The software used is the 2 1/2 dimensional package "Gravmag".

Line 13 of Area #2, 1973 (Fig. 4a)

The basement-edge magnetic anomalies found by us and by Kristjánsson (1976b) are variable

in shape. One which is unusually large and regular is found in marine survey line no. 13 in Area 2 of 1973 (cf. Fig. 3a). Its peak-to-peak amplitude is 2500 nT. We have attempted to

required magnetization intensities a little but more complicated models would increase it considerably. Our conclusions from the model of Fig. 4a include:

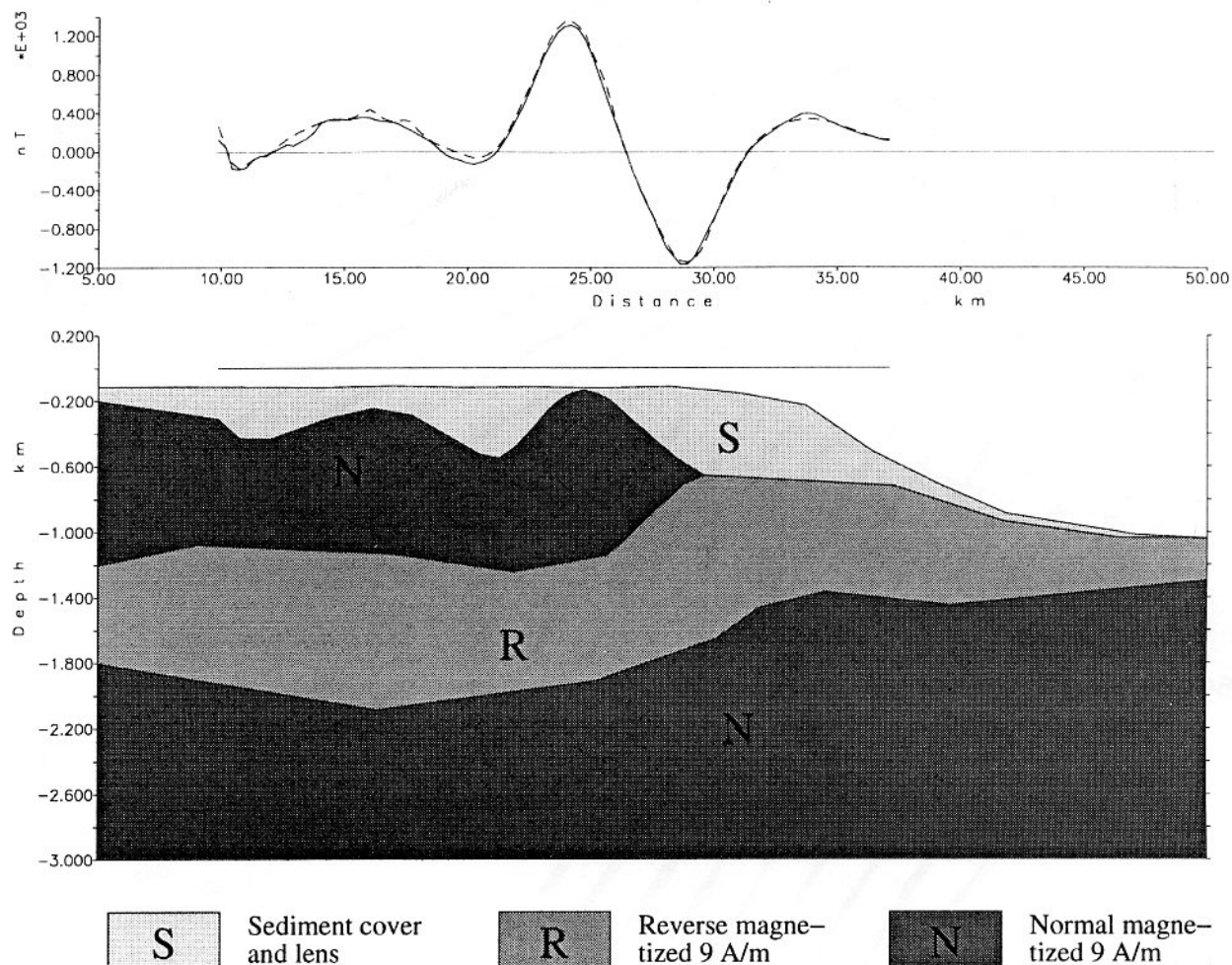


Fig. 4a. Modelling of sources for the marine survey line 13 from Area 2, 1973 (hatched curve). No filtering has been applied to the observed magnetic data (solid curve). The shape of the anomaly on this line is relatively simple compared to that on other lines of our surveys. Vertical exaggeration in Figs. 4 and 6 is approximately 6.7 : 1.

model the source for it in terms of a sandwich of three layers (Fig. 4a), with alternating magnetic polarity. A very good fit can be obtained if the top normal layer ends 7-8 km within the shelf break and the magnetization is 9 A/m. (The magnetic inclination is assumed 75°, and the susceptibility is 0.03 emu for magnetized layers and 0.01 emu for sediments). These values are quite high, as the averages found in Upper Miocene to Lower Quaternary lavas during paleomagnetic sampling (Kristjánsson, 1984; Kristjánsson et al., 1995) are always around 4 A/m. Structures with steeper boundaries could reduce the

- > There is a step-like structure in the basement 7-8 km within the shelf break.
- > Magnetization of the bulk of the material is high, not less than 6-8 A/m.
- > Due to an anomaly seaward of the break, a sediment lens under and in front of the break cannot be more than 1 km thick unless it contains magnetic materials.
- > Bedrock material which rises close to the surface at ~25 km coincides approximately with a positive gravity anomaly (G. Þorbergsson et al. 1990, D.T. Sandwell pers. comm. 1994) which is seen within the shelf edge around much of Iceland.

Line 29 of Area #2, 1973 (Fig. 4b)

The long marine survey line no. 29 from 1973 runs along the shallow submarine valley of Breiðamerkurdjúp (Figs. 2a, 3b). The valley is offshore from the Breiðamerkurjökull glacier outlet, and the shelf here was intensely studied in 1979-85 by Boulton et al. (1988), using sparker profiles. They mapped a "till" unit and muddy sediment infill lying unconformably on "bedrock", but their data did not differentiate between the various possible types of bedrock. One of their survey lines (L1, possibly also L2a; Boulton et al., 1988, p. 196) reaches beyond the shelf break, but its results are not interpreted in the paper. The sparker measurements showed a very strong reflector,

mostly buried under relatively thin (0-100 m) sediments. The sediments do not show any evidence of thickening towards the shelf break, rather the opposite. Little seismic energy was reflected from deeper interfaces. On side-scan sonar images in areas without sediment cover the reflector was identified as "bedrock".

Laughton et al. (1972) have found at 59°N a strong reflector which turned out to be indurated hyaloclastite of Quaternary age originating from Iceland, and similar sedimentary reflectors were identified by Egloff and Johnson (1978) off SW-Iceland. The reflector on the Breiðamerkurdjúp shelf therefore need not consist of crystalline basalt such as lava flows.

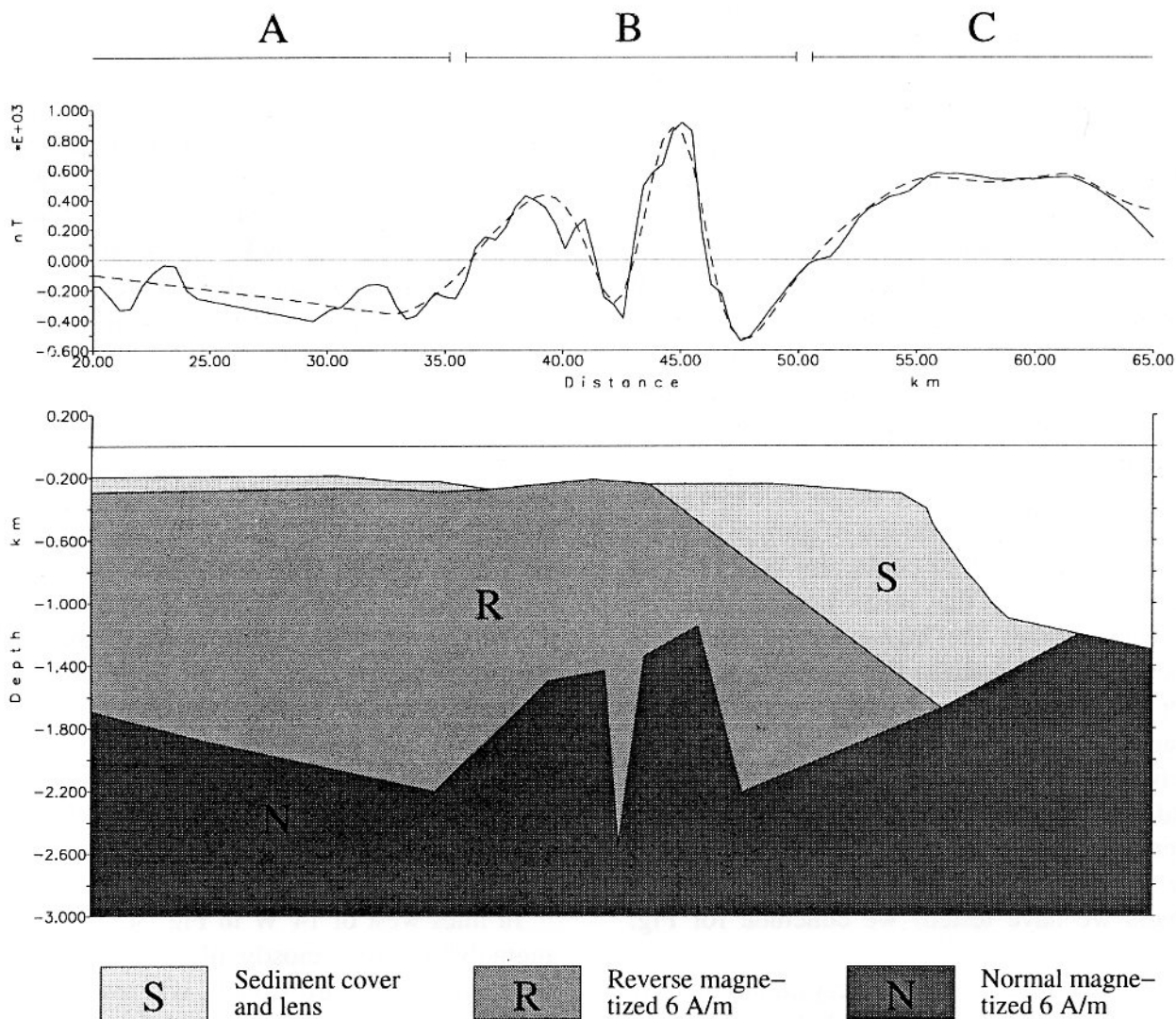


Fig. 4b. Modelling of sources for marine survey line 29 from Area 2, 1973. Bathymetry and configuration is based on Boulton et al. (1988) where possible.

Older seismic profiles (Johnson and Tanner, 1971) approaching the coast southeast of Iceland indicate a sediment lens in front of the insular slope. The thickness of the sediments may exceed 1 km. Dr. Y. Kristoffersen of the University of Bergen kindly ran a multichannel seismic line along the 1973 survey line no. 29 in 1989 on the Norwegian research vessel "Hakon Mosby". The seismic section has been very difficult to interpret, due to bad weather during acquisition. Still, some outward-dipping reflectors can be seen under the outermost part of the shelf, reaching down to 1.2 sec two-way travel time (twtt) in the shelf material. The dip is of the order of 0.5 sec twtt per 4 km, i.e. several degrees. The bedrock in front of the insular margin appears to be buried by 1400 m (1.4 sec twtt) of sediments (K. Gunnarsson, pers. comm. 1993).

We have used the bathymetry and sediment thickness on the shelf to simulate the observed magnetic anomaly on line no. 29. One possible geometry of the source is shown in Fig. 4b. We expect the outermost 10 km or so to be built up of sediments contributing little to the magnetic field. The inner part of the shelf (labelled A) requires a large reversely magnetized body which we assume to lie on top of a normal layer. Assuming bodies with magnetic contrast 12 A/m (i.e. plus and minus 6 A/m) we need vertical structures in the interface of at least 1 km height to explain the anomalies B. Smaller bodies of normal polarity closer to the sea floor could also be a feasible explanation, but the more complicated the model becomes the higher magnetization is needed for the bodies. The anomaly at B can not be caused by an interface between non-magnetic sediments and a magnetized body only (unless it has very high magnetization) and it is impossible to use magnetic measurements to predict how much of the shelf is built up by sediments. Based on this model (and others we have tested) we conclude for Fig. 4b:

- > Net magnetization of the crystalline rock is not less than ± 6 A/m, and there are large step structures in the material
- > It is difficult to estimate the amount of sediments at the shelf edge
- > As in line 13 above, the presence of a seaward anomaly (C) precludes the presence of thick sediments in front of the shelf.

2.8 Area off Southeast and East Iceland

The anomaly correlated with a buried basement edge by Kristjánsson (1976b) clearly continues towards the northeast (Fig. 3c) until it disappears near $64^{\circ}22'N$, $12^{\circ}42'W$, approximately where the Iceland block is joining the Iceland-Faeroe Ridge. As in the 1973 surveys, the anomaly varies considerably in shape (see below) but the peak-to-trough amplitude of these anomalies is of the order of 1200 - 2000 nT at 300 m altitude.

There are also three distinct positive magnetic anomaly lineations in the area, both of 10 - 20 km width. One of these (H in Fig. 5) follows the insular slope in most of the area, but it is broken near $15^{\circ}W$ by a major negative anomaly of central-volcano type (see below). Less extensive positive lineations (H' and H'' in Fig. 5) are closer to shore. A low occurs outside the insular shelf south of $64^{\circ}N$ in all flight lines in Fig. 3c; its width is of the order of 20 km and it possibly extends to $17^{\circ}W$ or even $19^{\circ}W$. The basement edge from $12^{\circ}W$ to $15^{\circ}W$ is found in rocks of predominantly reverse polarity, as the edge anomaly mostly occurs in the minor low between the two positive anomalies H and H'. It definitely seems that these lineations curve around Southeast Iceland, although they may make a slight angle with the edge anomaly. This would be consistent with the SE-Iceland margin being largely composed of extrusive sequences. It does not appear that the lineations are a continuation of NE-trending anomalies from the Reykjanes ridge. Those rocks of the edge which contribute most to the edge anomaly (polarity zones of perhaps 400-1000 m thickness each) may clearly be of either normal or reverse magnetization. The seismic results described in the previous section show that the sequences do not necessarily dip inwards or westwards.

In lines west of $14^{\circ}W$ in Fig. 3c, the "edge anomaly" consists mostly of a seaward main peak and a landward trough, whereas in lines farther east we see a main peak between two troughs, and still farther east a main trough between two peaks. In those lines farthest to the northeast which show the edge anomaly, there is a seaward trough and a landward peak. There are also smaller peaks and troughs superimposed on these. We have attempted to

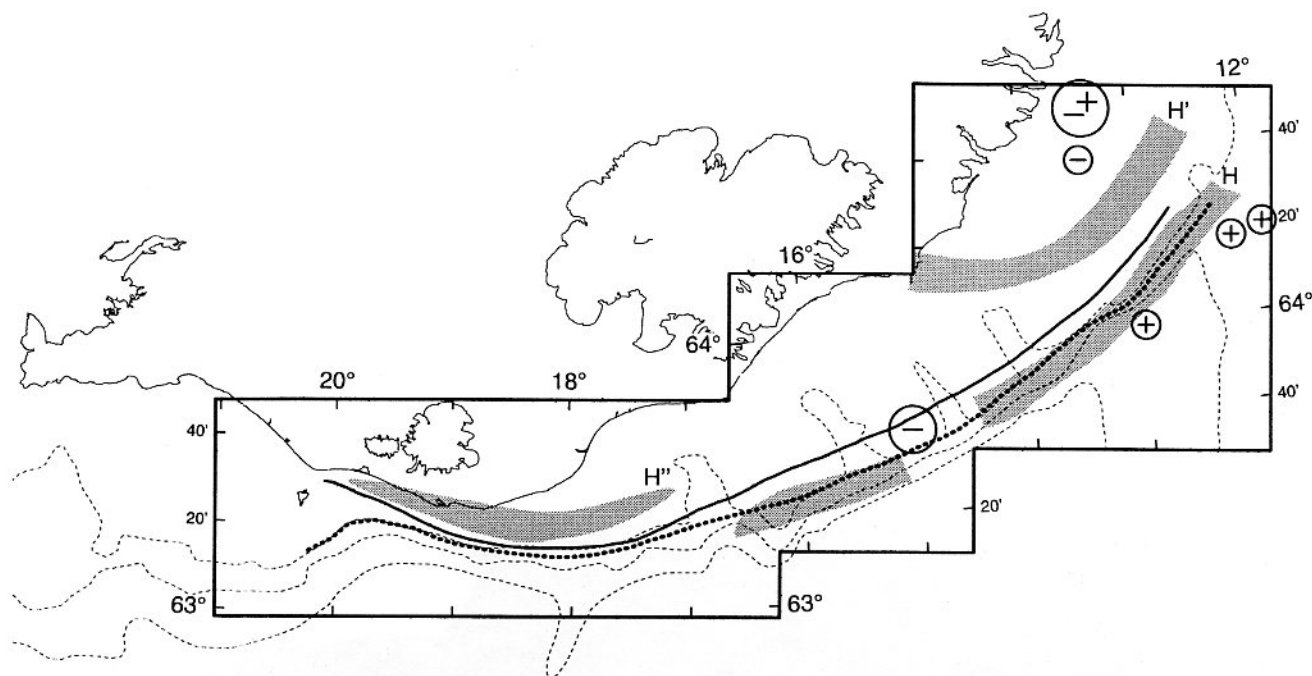


Fig. 5. Some main features inferred from the magnetic anomaly field south and southeast of Iceland. *Thick dotted line*: bathymetric shelf edge. *Solid line*: estimated boundary between magnetic and non-magnetic formations at the sea floor. *Gray*: elongated positive anomalies H, H', H'' following the coastline trend. *Circles*: Localized magnetic anomalies (polarity shown) possibly due to central volcanoes.

model the field on two of the survey lines indicated in Fig. 3c. The results are shown in Fig. 6a,b.

Line 03 from 1991 survey (Fig. 6a)

The peak to peak anomaly is around 1200 nT which is not among the highest in our survey. The main anomaly (A-B-C of Fig. 6a) is difficult to explain in terms of a simple model of a sediment lens in front of magnetized basement. Peak C requires magnetized material close to the surface so we assume a steep landward limit of the sediment lens. Anomaly A-B, however, must be a result of relief of 1 km occurring in the boundary between reversely and normally magnetized rocks, if the magnetization in these is assumed ± 4 A/m. A positive anomaly around the shelf break (D) rules out the possibility for a basin of non-magnetized sediment there.

Line 11 from 1991 survey (Fig. 6b)

The peak to peak anomaly is 2000 nT (note different scales for the magnetic field between figures). A good fit can be obtained with a sandwich of three layers, R-N-R. We interpret the anomaly A as 2-300 m steps in the upper

interface. Anomaly B can be very difficult to model in terms of a tilting interface between a reversely magnetized layer and sediment only, and we assume the model in Fig. 4d to give an upper limit to the landward extent of the sediment. Unlike other lines which we have modelled, there seem to be no restrictions on the thickness of the sediment under and in front of the insular slope.

2.9 Extent and position of the basement edge

In Fig. 7 we plot the distance of peaks and troughs of the presumed basement edge anomaly from the bathymetric shelf edge, as a function of distance along the shelf, from 19°W. The bathymetric shelf edge (interpolated across submarine valleys) closely follows the 200 m contour except at the extreme eastern end of Fig. 5. Some of the local troughs marked on this graph may be in part due to the elongated regional lows mentioned above. Due to time constraints we have only modelled the anomalies on four survey lines. Broadly speaking however, our model calculations indicate that the upper edge of the basement step may be found anywhere under that major anomaly

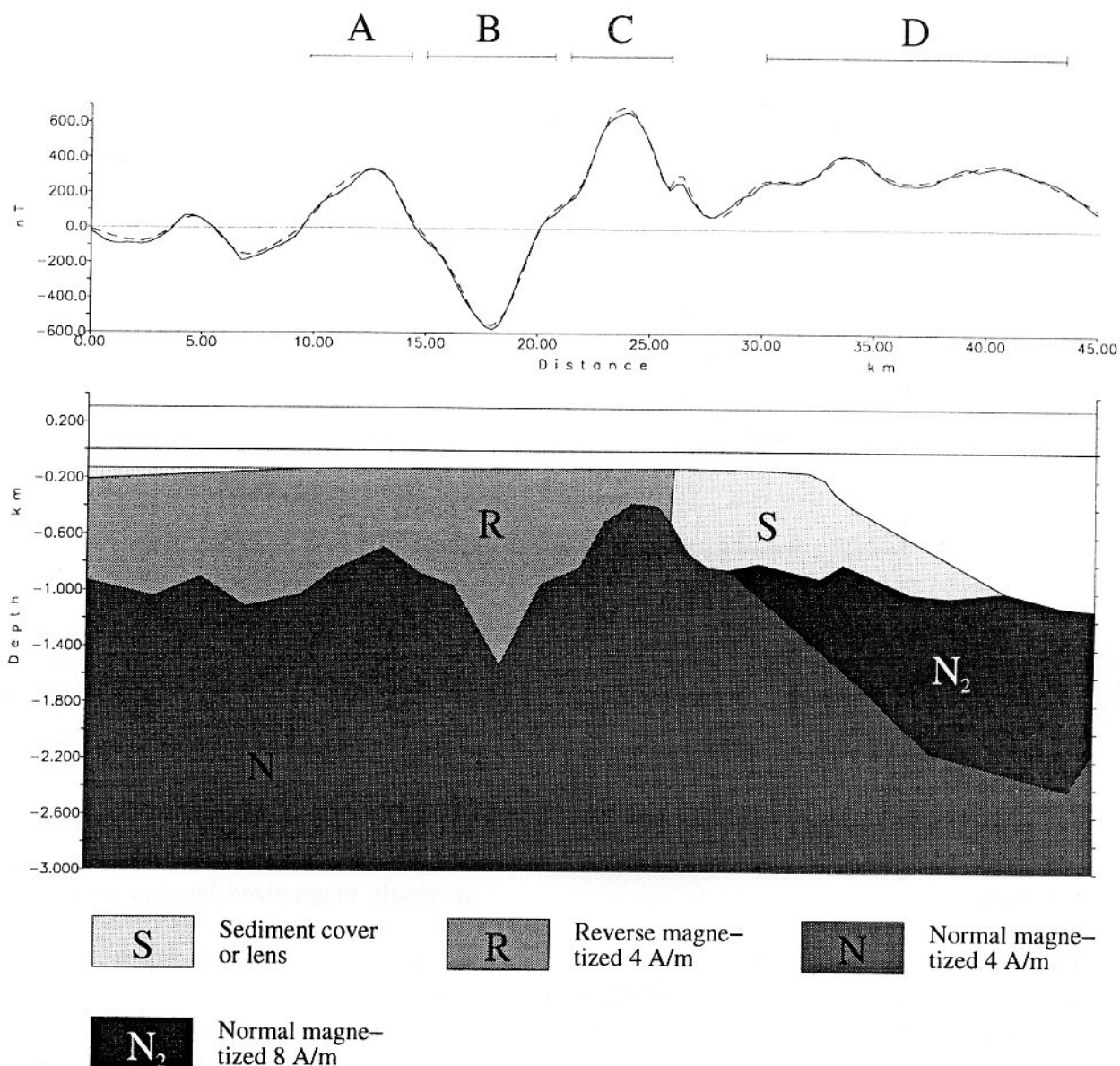


Fig. 6a. Modelling of sources for the magnetic anomalies found in flight line 3 from 1991. See text, and Fig. 3 for location.

which is farthest from shore.

The estimated position of the upper edge of the basement step south and southeast of Iceland by Kristjánsson (1976b), based on the 1973 marine magnetics is shown as gray circles in Fig. 7. The present calculations indicate that the width of the sediment wedge is probably somewhat less than the earlier estimate, of the order of 4-6 km from 19°20'W to 18°W, 6-8 km from 18°W to 17°W and 8-10 km most of the way between 17°W and 12°30'W where it peters out. The inferred position of the upper edge of the basement step south and southeast of Iceland, based on the

1973 marine magnetics and our 1990-92 surveys, is shown in Fig. 5. Off East Iceland, the edge thus does not reach as far north as was tentatively concluded by Kristjánsson et al. (1977) from "Meteor" data.

It is likely that the production of sediment from the Vatnajökull glacier region has been much larger than can be accounted for on the South Iceland margin. Much has been transported downslope to the south as turbidite (Laughton et al., 1972; Boulton et al., 1988) and laterally (mainly westwards?) with ocean currents.

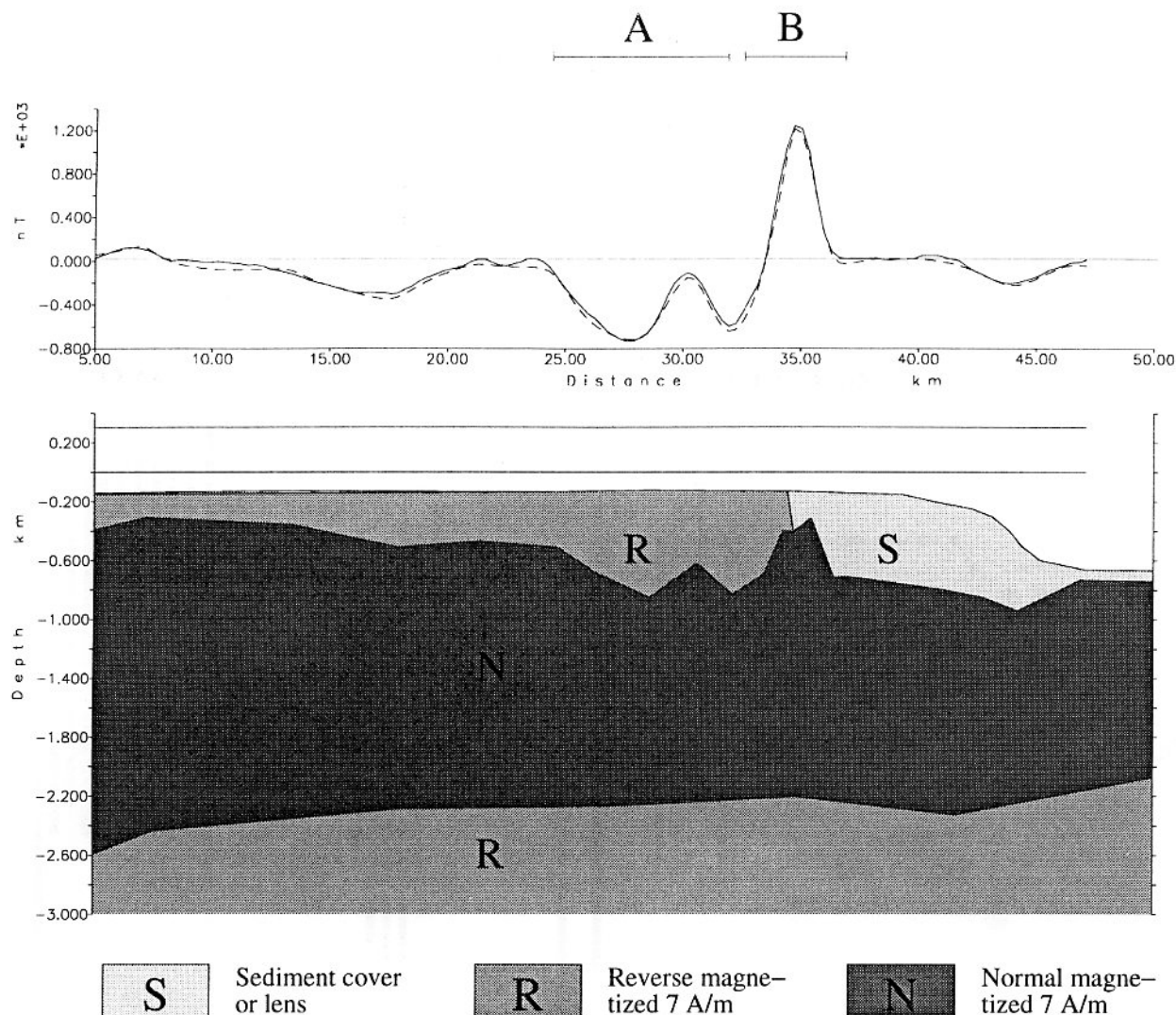


Fig 6b. Modelling of sources for the anomalies in flight line no 11. from 1991, Fig. 3c. See text.

2.10 Central volcanoes

In Figures 3b and c some localized magnetic anomalies, marked with circles in Fig. 5, are likely to be due to central volcanoes. The largest one is a complex set of anomalies, some 10 km from the coastline southeast of Reyðarfjörður. They are accompanied by gravity anomalies, seen in the maps of Fleischer et al. (1974). Acid rocks which are found on the island of Skríður 3 km from the coast (Gibson et al., 1966) may belong to this large volcanic center. Shallows occurring at 15-25 km offshore in a number of places between the Gerpir promontory (easternmost point of Iceland) and Berufjörður may also contain intrusions connected with this center and with the Dfönuboði center 15 km due east

of Gerpir (Kristjánsson et al., 1977).

Farther to the southeast at around 64°20'N on both sides of 12°W there are positive anomalies which also coincide with gravity anomalies (Figs. 5 and 9 of Fleischer et al., 1972). There is a 3000 nT negative anomaly at Breiðamerkjúpur, already mentioned. The three remaining localized anomalies of Fig. 5 are smaller and it is less certain whether they relate to central volcanoes.

2.11 Origin of the basement shelf and edge off S- and SE-Iceland

If we assume a linear increase in age of 1 cm/yr with distance from the spreading zone and a rate of vertical buildup of 1000 m/Ma (Kristjánsson et al., 1995), we can estimate that

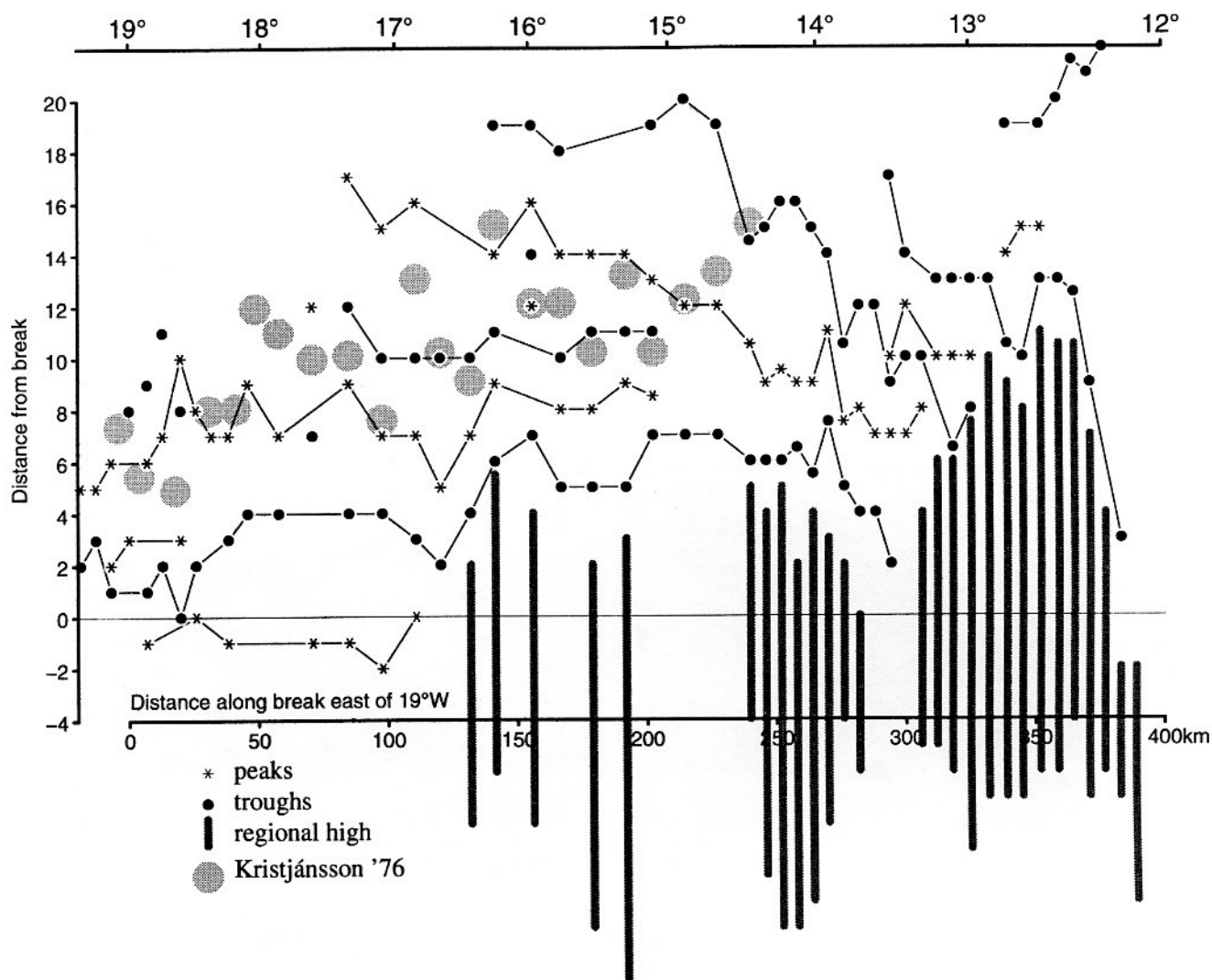


Fig. 7. Position of anomalies relative to the bathymetrically defined shelf break south and southeast of Iceland. Horizontal scale shows distances along the shelf edge from 19°W (see Fig. 1) towards east and northeast. The magnetic field around the shelf edge is rather irregular. Definite peaks (stars) and troughs (black dots) in marine and airborne survey lines are shown. An attempt is made to link adjacent features: the diagram shows 6 chains of peaks and 5 of troughs. Gray dots: mean position of basement edge under the shelf as estimated by Kristjánsson (1976). Over the eastern part of the shelf there is a wide positive anomaly (H of Fig. 5) interrupted by a localized negative anomaly near 15°W. This anomaly is indicated by vertical lines.

the age of the crust at normal ocean depth (> 2000 m below sea level) under the insular slope at the outer limit of the "Iceland block" 90 km east of Iceland is about 25 Ma. A similar maximum age is found by this method northwest of Iceland, in good agreement with two age estimates for the Iceland block mentioned in Section 1.1 above. It is quite possible that the age around 25 Ma represents renewed activity at the hot spot after a hiatus of 10 Ma or more. This would be in keeping with the "double flood basalts" volcanism

recently suggested for other large igneous provinces of the world (Bercovici and Mahoney, 1994).

Excessive volcanic production since 25 Ma ago on a segment of the Mid-Atlantic Ridge of the order of 500 km in length, must be connected to the presence of the hot spot or plume. Judging from the geochemistry of postglacial extrusives, the center of the hot spot currently seems to lie in the northern part of the Vatnajökull glacier, on the eastern edge of the volcanic zone. The insular slope is much

steeper east of Iceland than to the west; it may be tentatively suggested that this is related to a long-term offset of the hot spot to the east from the plate boundary. The basalt plateau in the past reached to about 1500 m above the present sea level in East Iceland (Gibson et al., 1966), and possibly to 2000 m in Southeast Iceland (Walker, 1975) while that in Northwest Iceland only reached to less than 1000 m (Einarsson, 1963): this pronounced east-west asymmetry could also be due to an asymmetrically placed hot spot.

At the current state of knowledge it is difficult to postulate any single course of events to generate the observed geological structures in the Iceland area: the magnitude, location and timing of these events are all of critical importance. The available seismic data (Thors and Helgason, 1988; Boulton et al., 1988) indicate that the structure of the shelf is often complex, but the possible mechanisms for the shaping of the shelf edge are basically three: constructional, erosional and tectonic.

By "constructional" mechanisms one implies that the ridge segment producing excessive volcanics had sharply defined ends. If it was a single segment, its length has been growing with time. If there were two, the eastern one was presumably more productive than the other. "Erosional" mechanisms might chiefly involve wave erosion (Thors and Helgason, 1988, p. 36) possibly of a pillow-lava substrate, during a period of maximum uplift more than 15 Ma ago, and then levelling of the shelf in the Quaternary after subsidence of a large region. It seems most likely to us that the shape of the basement edge around South and Southeast Iceland is due to some combination of these two causes.

The simplest "tectonic" mechanism which one can visualize to generate the shelf edge by faulting is large-scale subsidence of the sea floor outside the Iceland block. This might be accompanied by uplift of the Iceland block relative to sea level, greater in East Iceland than in West Iceland. The sporadic occurrence of small earthquakes at the shelf edge (P. Einarsson, pers. comm., 1994) may signify the presence of such faults but the earthquakes might also be caused by stress from present-day differential loading of the upper crust. It is, however, difficult to explain why faulting should only take place along one curved line

rather than, say, on a set of concentric curves around the hot spot.

2.12 Magnetization

It seems likely from our modelling (Figs. 4,6) that magnetic polarity zones on the shelf are much thicker than those observed in outcrops on shore which are typically 150-200 m. This could be due to more vigorous extrusive activity than on shore, and/or a slower rate of geomagnetic reversals than in the last 15 Ma.

The magnetization intensity inferred for the basement step in our modelling also needs to be considerably higher than that in Neogene basalt lavas in Iceland. This is supported by the fact that step-type magnetic anomalies of comparable dimensions (>1000 nT peak-to-peak, several km) rarely occur in results of aeromagnetic surveys over the fjord regions of NW-, N- and E-Iceland (Sigurgeirsson, 1980-85; Kristjánsson et al., 1989), even where the local relief is 1000 m or more and the survey lines lie only 200 m above the plateau remnants. If the shelf is older than the onshore lavas as seems inevitable and of similar material, this is a surprising result, because one would normally expect magnetization to decay with increasing age. However, it is possible that the shelf material consists of more magnetite-rich or more highly oxidized lavas than those found on shore. Finally, the intensity of the geomagnetic field might have been stronger at that time.

Other possibilities for the material in the shelf include fresh rapidly cooled basalt such as pillow lava. Pillows, as well as lumps in brecciated and tuffaceous material, are strongly magnetized, but their remanence is carried by relatively unoxidized titanomagnetite which is sensitive to alteration and in that case is not likely to generate large anomalies of both signs. Dikes in Iceland have also been found to have a primary magnetization of similar or less intensity than lavas (Kristjánsson, 1984, 1985) and it is difficult to visualise dike intrusion in the regular pattern exhibited by the anomalies of Fig. 3. Gabbros, and highly altered basalts containing secondary magnetite, are still more distant possibilities.

2.13 *General conclusions and discussion of Part 2*

The primary use of magnetic field surveys over an area is to find directional trends and unusual features, and to estimate the lateral dimensions associated with both. More definite interpretation in terms of geological structures is often possible, but in order for it to be of much practical use it is necessary to have access to other relevant geological and geophysical data. In the present case of our studies on the insular margin south of Iceland, such data is most limited. The resolution of available gravity maps is insufficient for study of those features which are highlighted in the magnetic signal, and the only multichannel seismic measurements in the area so far were unsuccessful. Our interpretation is therefore very qualitative.

Just inside the bathymetric shelf edge south and southeast of Iceland, a remarkable zone of strong magnetic anomalies occurs. The shape of these anomalies suggests that they are due to sediment-covered steep edges or polarity boundaries in the crystalline basement. By using simple single-polarity models for a scarp its thickness was estimated by Kristjánsson (1976) to reach 1 km or more in agreement with previous conclusions from gravity data (Pálmason, 1974). However, more complex models of the shelf margin with two or three layers (presented in Figs. 4, 6) would allow the thickness of the sediments to be in the range 0.5-1 km. The only seismic reflection data in the area, while very limited, do not contradict this conclusion.

The length of the edge feature is at least 350 km from 19°10'W to 12°42'W, i.e. from

the South Iceland volcanic zone to the Iceland-Faeroe ridge. At its western end it is very close to shore but there its magnetic signal is almost lost in noise from near-surface Quaternary volcanics. It is possible that some structures related to the edge may continue on shore under the sands south of Mýrdalsjökull. On much of the shelf west of Vestmannaeyjar, magnetic anomalies are very subdued, presumably due to sediment cover.

Anomaly lineations following the Reykjanes Ridge on its eastern side generally peter out before they enter the shelf area; however, they correspond to much higher ages (by up to 20 Ma) than the exposed rocks on shore in their direct continuation. One reason for their disappearance may be major eastward jumps of the rift axis, to be discussed in Part 3.

The dimensions of this basement edge makes it one of the major continuous structural features of the Iceland region. Similar but less conspicuous features are seen from satellite gravity maps to occur between the Iceland-Faeroe ridge and the Kolbeinsey ridge, as well as off West Iceland. The structure of the edge south of Iceland seems to be complex and variable. There is some evidence that it may cut inclined lava sequences containing thick polarity zones. The magnetization of the rocks in the basement edge is higher than that of typical Tertiary basalt lavas in Iceland, by a factor of two in the simplest possible models but more if complex layering/stepping is assumed. The material is probably a pile of subaerial or pillow basalt lavas. The origin of the edge feature is still uncertain.

PART 3

AEROMAGNETIC SURVEYS IN BREIÐAFJÖRÐUR AND FAXAFLÓI 1991-92

3.1 1972 survey of the Breiðafjörður area - interpretation problems

In 1972, a marine magnetic survey was carried out by Icelandic and U.S. scientists in Breiðafjörður Bay, W-Iceland (Area 9) and west of the bay (Area 7). The results were published by Kristjánsson (1976a,c). They indicated two elongated magnetic anomalies running along the Bay from southwest to northeast, a positive one near the tip of the Snæfellsnes peninsula and a negative one farther north. However, the interpretation of the results in terms of distinct ridge-generated lineations as attempted by Nunns et al. (1983) was not entirely satisfactory, for the following reasons:

- i The distance between survey lines was 10 km, and they did not approach the coast, due partly to limitations of the Raydist positioning technique and partly to the presence of numerous shoals and skerries.
- ii There were enormous short-wavelength variations in the magnetic data, caused by bedrock topography in the shallow waters within the bay, and also by submarine Quaternary volcanic structures as well as remnants of older central volcanoes present.
- iii During the time of the survey in Areas 7 and 9 considerable ionospheric disturbances occurred, including one of the largest magnetic storms on record (4 - 6 Aug '72).

These problems made it difficult to ascertain the continuity of the two major anomaly lineations in Breiðafjörður Bay. It is also difficult to connect them definitely with anomalies on shore or with lineations to the southwest.

Only a few papers have been written about the overall age distribution, structure and tectonics of West and Northwest Iceland since 1976 (e.g., Jóhannesson, 1980; McDougall et al., 1984) and some of their conclusions have been revised (Kristjánsson and Jóhannesson, 1996; H. Jóhannesson, pers. comm. 1996). For instance, it is not entirely clear how the active

zone of rifting and volcanism lay through the western part of Iceland in the period 6 -15 Ma ago.

3.2 Methods in the new survey of Breiðafjörður and Faxaflói in 1991-92

The present authors decided to carry out an aeromagnetic survey of Breiðafjörður Bay in 1991-92 in order to improve our knowledge of the structure of this area. Additionally, some survey lines were flown in the outer parts of Faxaflói Bay, in order to extend aeromagnetic coverage towards the SW. (Note that a mismatch in regional field values is evident between 1985-86 flights and older (DNAG) gridded data in the maps of Kristjánsson et al. (1989) and Jónsson et al. (1991)). The flight altitude was generally 600 m. Navigation was by GPS as described above, minor gaps being bridged by interpolation. Magnetic measurements were made at 5 sec intervals.

The flights proceeded as follows (Fig. 8):

4 June 1991: Two short lines in Breiðafjörður and 7 short lines west of Snæfellsnes were flown at 3 km spacing. In Faxaflói, 4 long lines were added at 6 km spacing, as well as a loop to check the accuracy of results from some 1985-86 flight lines where Loran positions had not been quite reliable. During the last part of these flights, one of the largest magnetic storm disturbances of the year began suddenly, affecting total-field measurements significantly from 4:40 p.m. We have made efforts to compensate for the effects of this storm using Leirvogur Magnetic Observatory records and cross-checks, but the two central long lines in Faxaflói remain of somewhat less reliability than the others.

30 June 1992: Fifteen long E-W lines were surveyed in Breiðafjörður with 3 km spacing, as well as some shorter ones. One line was flown west of Faxaflói, between the two lines affected by the magnetic storm of the previous year.

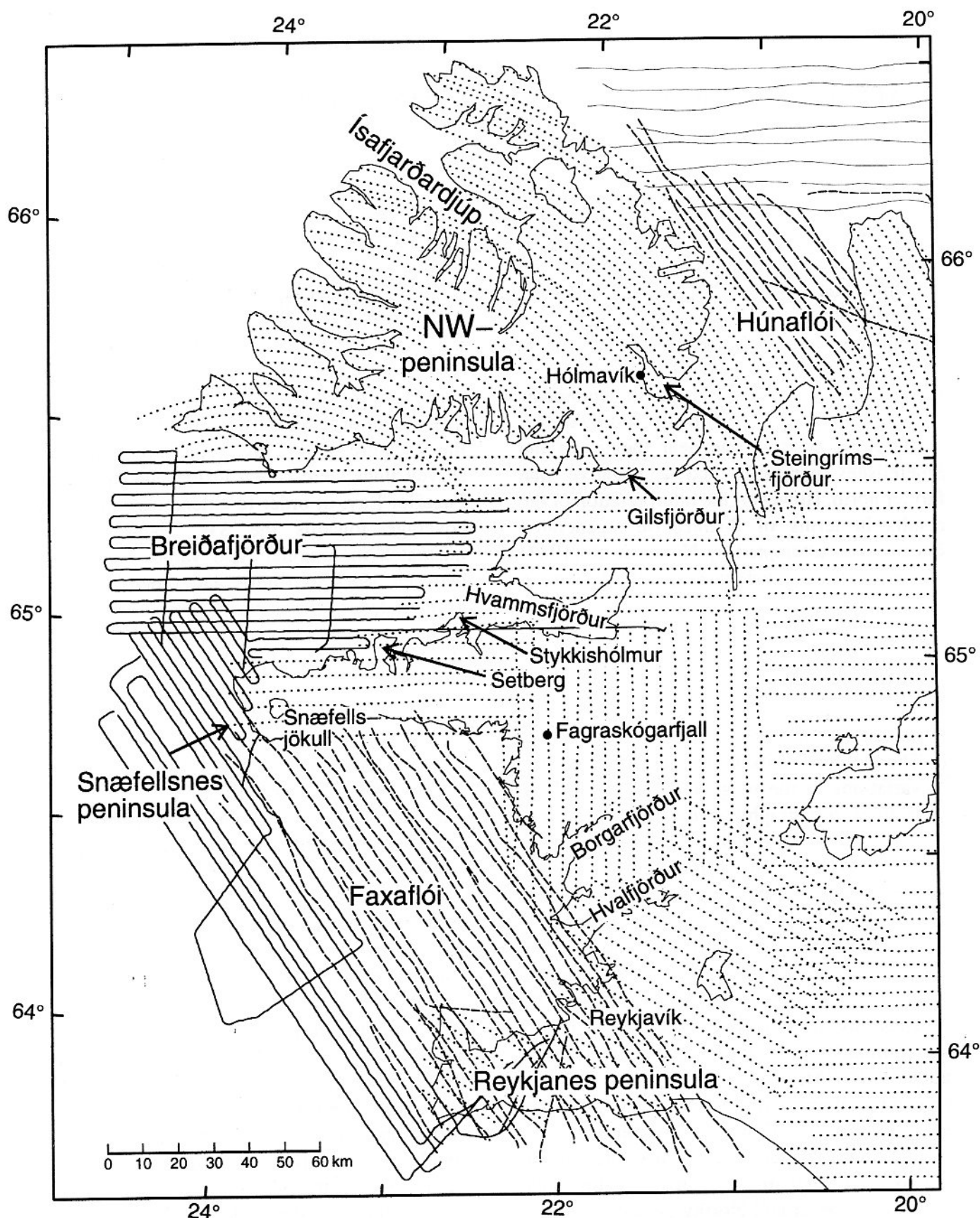


Fig. 8. Index map of West Iceland. 1985-86 aeromagnetic survey lines in Húnaflói, Breiðafjörður and Faxaflói, flown at 900 m altitude with Loran-C positioning, are shown as broken lines. 1991-92 tracks which were flown at 600 m altitude using GPS positioning are shown as solid lines. The land and coastal area was covered by Þ. Sigurgeirsson in 1968-74 at 900 m altitude and similar spacing, shown as dotted lines. Line spacing is generally 3 km. Thin lines north of Húnaflói bay: Project Magnet 1973-74 survey at 160 m altitude.

The results were processed at the Science Institute in a similar way as described above. To the west, the flights in Breiðafjörður reach close to 25°W. On the other three sides they overlap slightly with the flight lines of Sigurgeirsson (1979) at 900 m altitude. The agreement between the two sets of data is very good so they have been combined in the figures referred to below. The 1972 marine measurements are not used here. In Faxaflói, the magnetic measurements on the transverse legs of the loop of Fig. 8 agreed well with 1985-86 data.

3.3 Description of the magnetic field

In Fig. 9 the residual magnetic field of the West Iceland is drawn in a similar fashion as in Fig. 3.

In Colour-Plate 1 we have attempted to interpret various parts of the field as having predominantly positive or negative magnetic signature, as done in two contour maps of Sigurgeirsson (1970, 1979) for W-Iceland.

The following characteristics are most noticeable:

a. The mountainous Snæfellsnes peninsula exhibits a strongly fluctuating magnetic field. These fluctuations are no doubt due partly to Quaternary subglacial basalt volcanism and partly to larger volcanic centers, both active ones such as Snæfellsjökull and older eroded centers such as Setberg (see Jóhannesson 1980). Offshore southwest of Snæfellsjökull a small (500 nT) positive lineation of limited extent is seen but we have not continued it onto shore in Plate 1 as we presume that its source rocks are much older than the formations exposed around Snæfellsjökull.

b. A negative anomaly lineation with generally ENE trend occurs at the north coast of the peninsula. It is rather faint and of irregular shape, about 10 km in width, from the tip of the Snæfellsnes peninsula to Setberg. There it is offset to the south, becomes more distinct and widens to 15-20 km before ending abruptly at the mountainous area north of Hvammsfjörður. Its amplitude is of the order of 1000-1500 nT here. The volcanic center at the mouth of Hvammsfjörður does not seem to generate a distinct localized anomaly. Irregularities in the anomaly lineations farther west (north or northwest of Stykkishólmur) may be

associated with a localized gravity high seen in the map of Þorbergsson et al. (1990). A north-trending lobe of the negative anomaly lineation north of Fróðá (Anomaly M of Kristjánsson, 1976a,c) is related to a gravity low.

c. A prominent positive anomaly lineation runs through the southern part of Breiðafjörður Bay. In Fig. 9 and Plate 1 its continuity along the shelf from a location 35 km WSW of Snæfellsnes and to shore at the west coast of the Reykjanes promontory west of Gilsfjörður is demonstrated for the first time. This is the anomaly which Nunns et al. (1983, Fig. 3) and other authors correlate with "Anomaly 5" on the Reykjanes Ridge. This correlation seems fairly certain although it must be noted that west of the Faxaflói Bay (near 25°W) the data coverage is sparse, with the presence of the anomaly being inferred across gaps of up to 40 km in the map of Nunns et al. (1983). The magnetic anomalies F and H of Kristjánsson (1976a,c) are now seen as belonging to this lineation, rather than being localized anomalies.

A definite kink or offset of the positive anomaly (similar to that mentioned for the negative anomaly above) occurs near 23°30'W. West of this kink there are irregular but strong local anomalies, both within and outside the lineation. One of these, about 10 km in extent near 65°N, 24°15'W (A of Kristjánsson, 1976a,c) reaches 3000 nT at 600 m altitude a.s.l. It is thus one of the most prominent localized anomalies known to occur over Iceland and the shelf.

West of Gilsfjörður, the positive anomaly of Plate 1 is at least 12 km wide and 1000-1500 nT in amplitude. A less distinct region of generally positive field extends from the main anomaly towards the east, over Gilsfjörður and the peninsula south of it. The course of this positive anomaly lineation north of our Plate 1 is not clear (see Kristjánsson et al., 1989). One possibility is that it is offset a little to the west at the coast of the Northwestern peninsula and continues through the peninsula in a north-northeasterly direction. However, this correlation does not seem to agree with what is known of the age and remanence polarity of lava formations on the peninsula (McDougall et al., 1984; Kristjánsson and Jóhannesson, 1996).

d. West-northwest of the "Anomaly 5" lineation there is a very noticeable negative

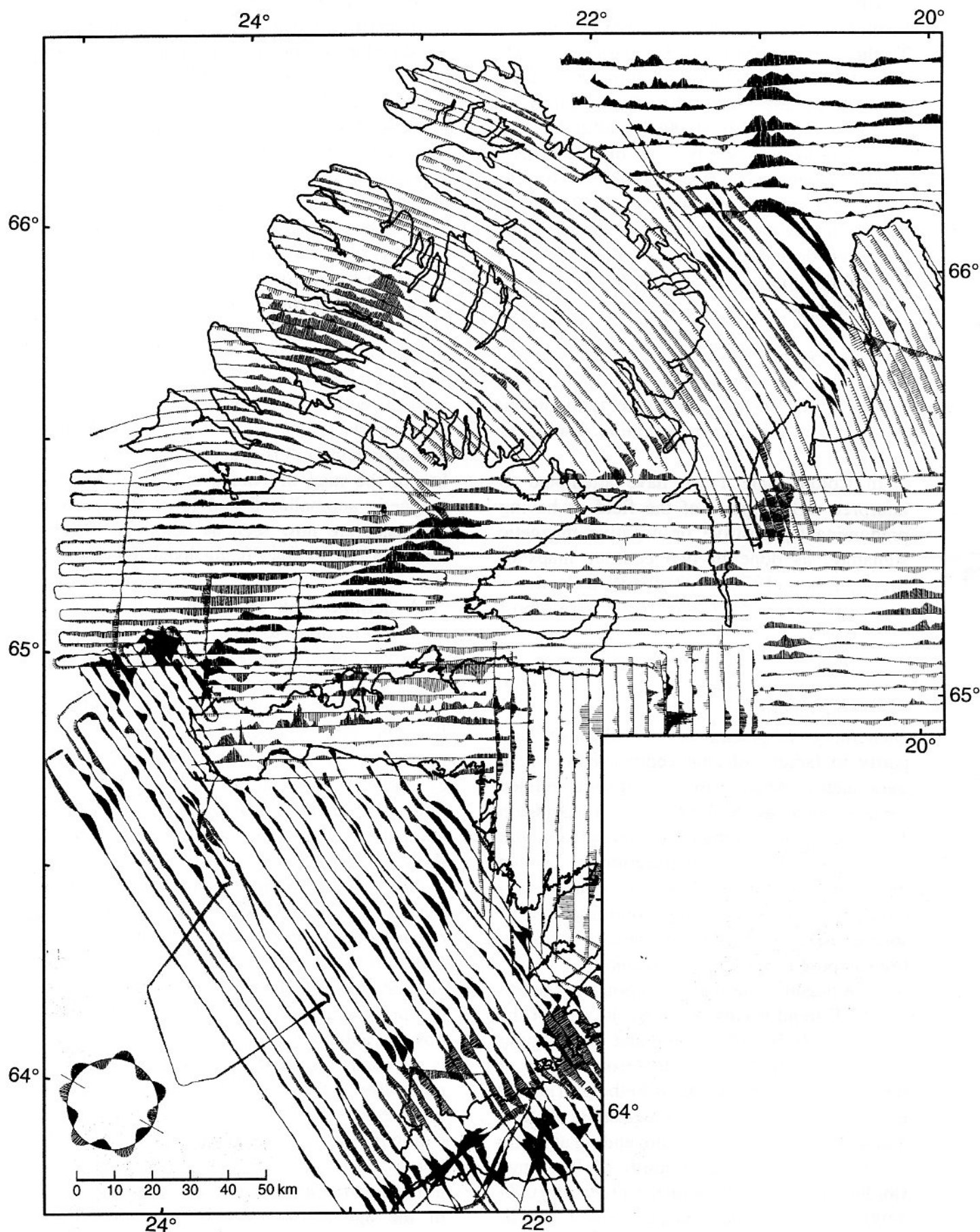


Fig. 9. Residual magnetic field in West Iceland. Plotting convention, which is similar as in figure 3, is illustrated in an imaginary circular flight at the bottom left of the figure. The maximum field variations on the circle are ± 1000 nT. See Fig. 8 for survey dates and altitudes.

magnetic lineation, of the order of 25 km in width and 1000-1500 nT in amplitude. Within this lineation occurs the +3000 nT anomaly mentioned above, as well as another positive localized anomaly of about 1500 nT amplitude and 15 km size. The anomaly G1 of Kristjánsson (1976a) probably belongs to this relatively large region of localized anomalies. It does not seem possible to continue the negative lineation with any confidence west of 25°W, due to the presence of additional localized anomalies (Kristjánsson, 1976c).

e. In the north-western corner of Plate 1 we see further positive, negative and positive lineations, with amplitudes of up to 6-800 nT. In the color map of Nunns et al. (1983) Anomalies 5A and 5B west of the Reykjanes Ridge seem to break up into irregular fragments after they reach the shelf.

Fig. 9b also shows magnetic anomalies in Breiðafjörður bay, the NW-peninsula and Húnaflói bay. The positive lineation near 24°W in Breiðafjörður is seen to become more pronounced over the western fjords of the NW-peninsula, but it has not been connected to a particular single polarity zone in the lava pile (Kristjánsson and Helgason, 1988). Otherwise, lineations over the peninsula and the western part of Húnaflói are not very distinct. This may be partly due to the fact that the dip of the lava pile is small in most parts of the peninsula, and irregular in other parts such as around Steingrímsfjörður.

3.4 *Qualitative interpretation of the anomalies in Breiðafjörður and NW-Iceland*

The most straightforward interpretation of the Breiðafjörður anomaly lineations is to assume that they are due to magnetic remanence in lava sequences which have been tilted towards an extinct volcanic zone coincident with a synclinal structure in Snæfellsnes (Jóhannesson, 1980). The upper edge of each lava sequence where one polarity dominates will produce most of the anomaly but feeder dykes may also contribute to it.

A tentative interpretation of the anomalies is given in Plate 2. The figure is a geometrical description of the main discernible trends of the anomalies which may be caused by a variety of geological processes. The most prominent anomalies seem to cover elongated

regions of the order of 15 km in width with a crude en echelon structure. This structure is superficially similar to that seen in magnetic anomalies over fissure swarms in the western active volcanic zone. However, it must be stressed that in Breiðafjörður the anomalies are more probably due to the upper edge of lava series lying to the north-west of the fissures generating the lavas. The lifetime of any fissure system also may or may not have coincided with a period where one polarity dominated.

The number of distinct anomaly regions falls off towards the northwest. One or two such regions occur in the Arnarfjörður-Álftafjörður area but the presence of central volcanoes makes their trend uncertain. Small anomalies which can be traced between flight tracks have been indicated by lines in Plate 2. They are possibly caused to some extent by topography (e.g., the N-S running fjords on the south side of Ísafjarðardjúp).

As remarked by Kristjánsson and Jóhannesson (1996), the trend of anomaly lineations turns as they pass through the NW-peninsula, from a northeasterly direction characteristic of the Reykjanes Ridge and Breiðafjörður to a northerly one in Húnaflói and farther off shore. However, this trend is not clear-cut in Plate 2 and in its SE-corner there is also some evidence for a N-S trend.

On comparison with the geomagnetic polarity time scale of Cande and Kent (1995) it seems likely that the negative lineation at the north coast of the Snæfellsnes peninsula is due to lavas dating from a period of reverse polarity 8.1-9.7 Ma ago. The "Anomaly 5" lineations in Breiðafjörður and the eastern part of Húnaflói would similarly date from 9.7 or 9.9 to 10.9 Ma ago (C5n). The wide negative anomalies in mid-Breiðafjörður and the eastern part of the NW-peninsula would be caused by lavas of 10.9-11.9 Ma age, and the two positive anomaly lineations in the north-western corner of Plate 1 would date from 11.9-12.4 Ma ago (C5An). These age estimates agree approximately with the age of lava flows in the Northwestern peninsula as determined by McDougall et al. (1984). A spreading rate for the North American plate may be estimated from K-Ar dates at the NW- and SE- sides of the peninsula, and seems to be somewhat in excess of 1 cm/year in the period 9-15 Ma ago.

A thick series of normally magnetized lavas, expected to represent the long normal "Anomaly 5" interval, runs NE from Gilsfjörður (Jóhannesson, 1980) and crosses the Steingrímsfjörður fjord east of the village Hólmavík (see McDougall et al., 1984). It lies a little west of a positive magnetic anomaly which occurs in the area; this offset could be due to the large local variations in tectonic tilt evident around Steingrímsfjörður. Much field work is needed to establish the geological structure and ages of lava formations around Húnaflói bay before more quantitative modelling and correlations can be attempted.

The magnetic data now available in the Breiðafjörður area supports earlier suggestions (Kristjánsson, 1976a,c; Kristjánsson et al., 1977) that central volcanoes are unusually common on an east-west zone of 40-50 km width along the Snæfellsnes peninsula (coincident with the Quaternary to Recent volcanic area) and immediately north of it. This zone continues to the west or west-northwest across the shelf beyond the limits of the present survey, probably to 27°W or even farther.

3.5 *Description and qualitative interpretation of magnetic results in Faxaflói Bay*

Magnetic field residuals in Faxaflói and nearby land areas are shown in Fig. 9 and Plate 1. Our 1991-92 measurements match well with those from 1968-71 and 1985-86. The ENE-trending magnetic lineations of the Brunhes, Matuyama, Gauss and Gilbert chrons are seen in the southern and western parts of the Bay and on the Reykjanes peninsula. In contrast, north-eastern part of the Bay is dominated by NNE-trends. In accordance with the earlier work by Jóhannesson (1980) we assume that the main positive lineation is contemporaneous with "Anomaly 5". This correlation is supported by mapping results (H. Jóhannesson and L. Kristjánsson, unpublished data) showing the presence of thick NW-dipping lava sequences of normal polarity in Mt. Fagráskógarfjall and nearby mountains.

If the synclinal structure of the Tertiary lava pile of Snæfellsnes continues into Faxaflói Bay, the negative lineation in the Bay to the northwest of the "Anomaly 5" lineation is younger and the NNE-trending part of the bent negative anomaly is older. The outer (WSW-

trending) part of that negative anomaly is presumed to be of Gilbert chron age (approx. 3.6-5.9 Ma), continuing on shore north of Hvalfjörður. This interpretation is in good agreement with what is known of the geology and age of that region.

In the northwestern part of Faxaflói the residual field is mostly of negative polarity but "flat", i.e. it is difficult to see a definite pattern in the anomalies. This is possibly due to a thick sedimentary cover. The positive anomalies just offshore south of Snæfellsjökull in Fig. 9 (previously seen as anomaly S by Kristjánsson, 1976c) may be caused by a buried volcanic center. A positive gravity anomaly of 10-15 km extent is indicated here in the map of Þorbergsson et al. (1990) but it is based on very limited observations. The isolated positive magnetic anomaly at 64°30'N, 24°W may also be due to a volcanic center. Otherwise, the only central-volcano type anomalies we are aware of in the marine area of Faxaflói are at Reykjavík and in shallow waters north of Reykjavík (G. Jónsson and L. Kristjánsson, unpublished report, 1994).

The sharp change in trends in Faxaflói Bay is most likely related to the major lateral (eastwards) shift in the active volcanic zone which took place gradually several Ma ago (Jóhannesson, 1980). This shift is manifested among other things by a syncline in the Snæfellsnes peninsula (Fig. 1) as well as an anticline and an unconformity in the Borgarfjörður area. In Plate 3 we have attempted to make a simple model accounting for the change in trend in Faxaflói. It is envisaged that the new volcanic zone grew from the north at a rate of around 2.5 cm/year while the older one waned. The new zone began $36/\cos 40^\circ = 47$ km west of the old one. The model explains also why the Anomaly 5 magnetic lineation west of the Reykjanes Ridge (Fig. 1; see also Nunns et al., 1983) is farther away from the ridge crest than the Anomaly 5 lineation east of the Ridge.

3.6 *Main conclusions and discussion of Part 3*

The results of Þ. Sigurgeirsson's aeromagnetic surveys and other work showed that the magnetic anomaly structure of Iceland is highly complex and much less linear than that

over the Mid-Atlantic ridge in general. The reasons for this complexity probably include the thick crust of Iceland, topographic effects, central volcanoes, the presence of multiple and wide volcanic zones, large lateral movements of the axis of spreading, long-distance flow of lavas, and so on. It has proved largely futile to try correlating the linear anomaly features seen over the older (>3-5 Ma) parts of Iceland with particular magnetic chrons.

With this in mind, the attempt by the present authors to interpret anomaly lineations in the Breiðafjörður and Faxaflói areas must be viewed as somewhat tentative. The interpretation suggests that the Breiðafjörður area consists of regularly dipping lava series generated on an echelon fissure swarms (Plate 2). As we move eastwards from the mouth of Breiðafjörður towards Húnaflói, the trend of anomaly lineations, dikes and strike directions in the lava pile tends to become more and more northerly; a similar trend change is currently observed in the fissure swarms and magnetic anomalies of the active volcanic zones.

The main positive anomalies in Breiðafjörður are most likely a direct continuation of the "Anomaly 5" lineation on the Reykjanes Ridge. They seem therefore caused by rocks of 9-10 Ma age, a conclusion which agrees fairly well with results of radiometric dating in the NW-peninsula. A positive lineation in eastern Húnaflói lies a little to the east of the "Anomaly 5" lineation on the Kolbeinsey Ridge, and west of lavas dated at 7-8 Ma (Kristjánsson et al., 1993). It is therefore possibly due to lavas of Chron C4A, of 8.7-9.0 Ma age. Spreading on the Snæfellsnes zone in the Breiðafjörður and Húnaflói areas may have slowed down after this time. Much additional dating in western and central northern Iceland is required for finding out the precise history of rifting in the region, including the role of the Tjörnes transform zone.

In Faxaflói, an abrupt change in trend of anomaly lineations (Fig. 9 and Plate 3) is consistent with the processes suggested by Jóhannesson (1980). The SW-NE volcanic zone through Snæfellsnes retreated after 7-8 Ma ago as a new volcanic zone farther south-east progressed through W-Iceland and the

shelf from the north-east at a rate of about 2.5 cm/year. A simple model of magnetic anomaly lineations in the Faxaflói and Reykjanes area based on this propagating-rift concept explains many aspects of the magnetic anomalies and ages in this area.

The Snæfellsnes peninsula and southernmost part of the Breiðafjörður Bay have a unusual multiple role in the geological history of Iceland, as an active off-axis volcanic zone (petering out in the lowlands north of Borgarfjörður), as a zone of high central-volcano concentration (reaching far west of Snæfellsjökull), and as a region of tectonic movements (probably connected with the change in trend of the ridge axis). In the period 6-12 Ma ago, the tectonic role of the Snæfellsnes area may have been similar to that of the Reykjanes peninsula of to-day. All these processes probably have a common underlying cause. However, our knowledge of the geology of Snæfellsnes is still too limited to speculate on details. In particular, the relation between individual central volcanoes and the surrounding lava pile has not been investigated.

A condensed version of Part 3 emphasising various conclusions from our work will appear separately in a paper (Kristjánsson and Jónsson, 1996).

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Color plates:

Plate 1 Interpretation of magnetic field anomalies in the Faxaflói - Breiðafjörður area. Red: areas with predominantly positive anomalies. Blue: areas with predominantly negative anomalies. Green: a clear regional polarity signature cannot be determined due to low amplitudes and/or irregular localized anomalies (Quaternary volcanics, landscape effects, etc.).

Plate 2 Geometrical interpretation of anomaly lineations in NW-Iceland and the Breiðafjörður-Húnaflói area. Main anomaly areas are shown as red (positive) or blue elongated regions. Minor lineations are shown as lines (solid for positive anomalies, broken for negative ones). Central volcanoes (H. Jóhannesson, pers. comm. 1995) are indicated by asterisks. Distinct localized magnetic anomalies which are probably caused by central volcanoes, are indicated by colored circles. Geomagnetic polarity time scale (Cande and Kent, 1995) is to the right.

Plate 3 A simple model illustrating the generation of magnetic anomaly lineations with two different trends in W-Iceland and offshore, during the last 11 Ma or so. It is assumed that periods of normal and reverse polarity are of equal length, of the order of 1 Ma each. Crust generated during these periods gives rise to respectively positive (red) and negative (blue) magnetic anomaly lineations. The violet negative lineation corresponds approximately to the Gilbert chron, and the positive lineation of yellow color corresponds approximately to Anomaly 5.

- a-f) The sequence 1 to 6 illustrates the progression of the presently active rift zone (upper arrow) towards the southwest, concurrent with the dying out of an older rift zone (lower arrow) farther west.
- g) The pattern no. 6 from Fig. 11a, fitted to the anomaly structure of W- Iceland (Figs. 1 and 9, and Jónsson et al., 1991). This pattern is consistent with the new zone appearing some 2 Ma after the end of Anomaly 5, and being 36 km offset to the SE (i.e. splitting crust which was 4 Ma old at the time).

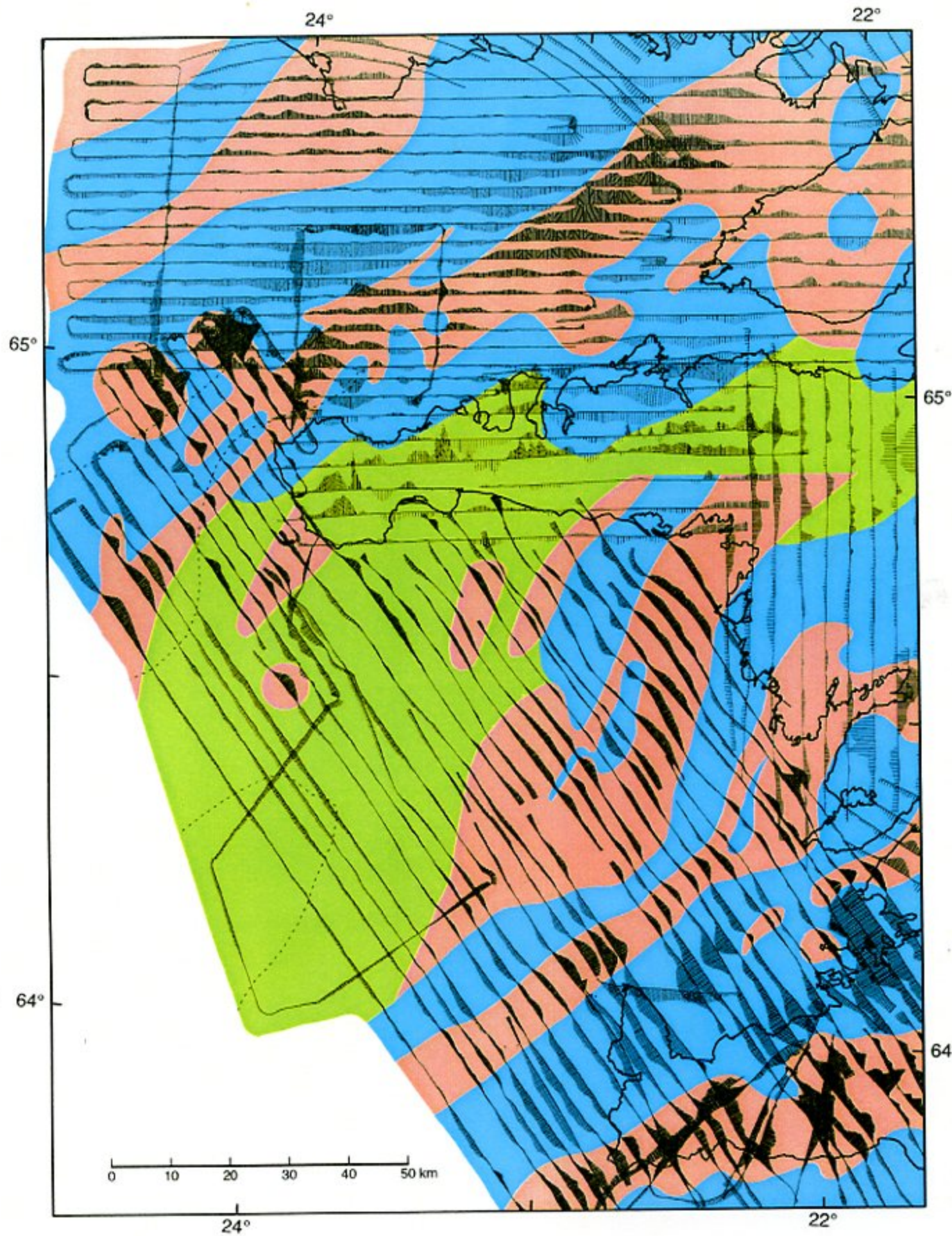


Plate 1

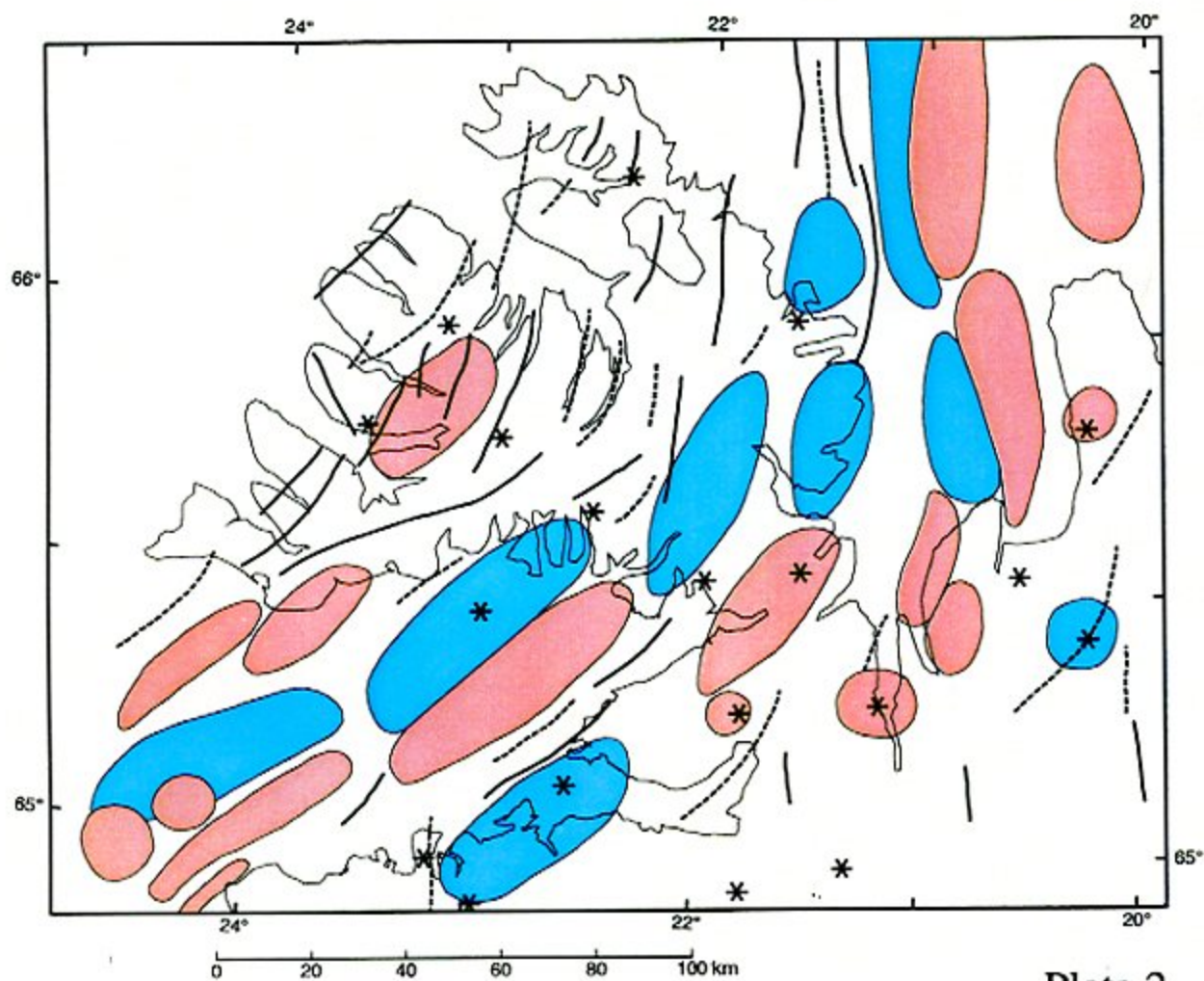


Plate 2

