MAGNETIC SURVEYS SOUTH AND SOUTHEAST OF ICELAND

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Abstract—Aeromagnetic surveys were carried out in 1990–92 over parts of the insular shelf south and southeast of Iceland, to extend the coverage provided by a 1973 marine survey. Prominent magnetic anomalies associated with the shelf edge over a distance of some 400 km, are interpreted in terms of a continuous basement edge in this region. This edge lies several kilometres landward of the shelf edge as defined from bathymetry, indicating the presence of a sediment lens of the order of 1 km in thickness. The formations making up the shelf seem to form thicker polarity zones and have a higher intensity of remanence than Neogene basalt lava flows and dikes in Iceland, but their age is unknown. Other geophysical information from the shelf area is too limited to constrain modelling of the anomaly sources. © 1998 Published by Elsevier Science Ltd. All rights reserved

INTRODUCTION—PREVIOUS WORK

General
The shelf surrounding Iceland is divided into four segments by the Mid-Atlantic Ridge and the Greenland–Iceland–Faeroe transverse ridge (Fig. 1). The shelf width is of the order of 80–150 km, except the segment south and southeast of Iceland. There the width is generally 50–70 km but less than 20 km in the vicinity of 19°W. The shelf edge in the region south and southeast of Iceland is essentially a continuous feature following closely the 200-m isobath, except for the occurrence of a few shallow submarine valleys. The insular slope is also steepest where the shelf is narrowest, up to about 14° near 19°W.

The insular margin is an important transition region between the ocean floor and the largely subaerial extrusive basaltic volcanism in Iceland, but little is known of its geological history or structure. Dredging of crystalline volcanic rock has been carried out on the Mid-Atlantic Ridge and in a few localities on the shelf where volcanic centers are thought to occur, but not south of Iceland. The only deep drill hole on the shelf is in the Vestmannaeyjar (Westman Islands) archipelago. It reached 1565 m, penetrating mostly clastic sediments to 820 m depth and then a sequence of lava flows (Tómasson, 1967).

Magnetic field surveys furnish valuable information on the age and structure of the shelf. Previous magnetic surveys off south and east Iceland were all carried out around 1970.
Fig. 1. Outline map of Iceland, showing the volcanic zones, glaciers and lakes. Bedrock ages generally increase away from the volcanic zones, reaching 13 Ma at the east coast and 15 Ma in the northwest. Light hatching: Pliocene–Pleistocene bedrock (0.78–3.2 Ma), heavier hatching: Upper Pleistocene and Holocene bedrock. Isobaths (in m) around the island are shown, and also some prominent anomaly lineations (modified from Nunns et al., 1983). R and K are the axial zones of the Reykjanes and Kolbeinsey Ridges. Stippling: active transform zones.

Although they do not provide complete coverage of the area and some were made on rather widely spaced lines, the general characteristics of the residual field are known.

Magnetic anomalies over Iceland show less of a linear pattern than those over the ocean ridges. This difference may be due to several factors such as a greater width of the volcanic zone in Iceland and a more complex structure of the crust (Kristjánsson and Helgason, 1988). The aeromagnetic anomaly lineations over the ocean ridges occur more or less vertically above their volcanic source rocks whose age may be found from the geomagnetic polarity time scale. Direct extrapolation of the magnetic anomaly lineations east of the Reykjanes Ridge (Fig. 1) onto shore would however encounter exposed volcanic formations which are much younger (by 10–20 Ma). Field lineations onshore may in most cases be correlated confidently with the latter. This large mismatch in ages across the shelf is not due to the presence of any obvious transform fault offshore; Kristjánsson and Jónsson (1998, Fig. 6) suggest that it is caused by eastwards movement of the main spreading zone in the southern part of Iceland since 6–8 Ma ago (Jóhannesson, 1980).
Previous magnetic results

Aeromagnetic measurements were made at 900–1200 m altitude and 3–4 km line spacing over southern Iceland by T. Sigurgeirsson in 1969–72 (see maps in Kristjánsson et al., 1989, and Jónsson et al., 1991). The paper by Fleischer et al. (1974) contained maps of marine magnetic survey results on the Iceland–Faeroe Ridge, reaching to approximately 15°W on the shelf. The U.S. Naval Oceanographic Office ‘Project Magnet’ made airborne measurements east and southeast of Iceland around 1973 (see map of Nunns et al., 1983). We have not been able to obtain the survey data of Fleischer et al. or of ‘Project Magnet’ in a format suitable for detailed interpretation.

Kristjánsson (1976) published the results of a 1973 shipborne total-field magnetic survey south of Iceland between 15° and 23°W. It covered the area from about 5–15 km offshore to 60–120 km offshore. Eysteinsson and Gunnarsson (1995) published a contour map of magnetic anomalies around Iceland incorporating some of the above data.

Kristjánsson (1976) and Kristjánsson et al. (1977) pointed out the presence of large magnetic anomalies landward of the shelf edge, occurring over a distance of 250 km or more. Peak-to-trough amplitudes were typically 700–1200 nT, and their width was 2–6 km. These authors interpreted the main characteristics of the anomalies in terms of a simple single-polarity step model. The step was estimated to be of the order of 3 km in width, lying several kilometres within the shelf break. The step was assumed to be at least 1 km high for consistency with gravity results mentioned below and in order to account for the amplitude of the anomalies if a net magnetization of 6.5 A/m was assumed. This value is similar to the average intensity of natural remanence found in Upper Quaternary basalts in Iceland (Kristjánsson, 1970). The average remanence intensity in older Neogene basalts is lower, around 4 A/m (Kristjánsson, 1984). Most of the remanent magnetization is thermo-remanence of primary origin. Induced magnetization values in Icelandic rocks are of the order of 1 A/m or less. The polarity of the remanence was positive (normal, N) in some lines and negative (reverse, R) in others.

Seismics

Judging from sparse reflection seismic data mostly obtained before 1975, the shelf has a thin (0–100 m) cover of unconsolidated sediments. The most detailed sparker surveys have been published from two small regions south of Iceland, shown by stippling in Fig. 2 (Thors and Helgason, 1988; Boulton et al., 1988). We are aware of only one attempt to investigate the shelf off southeastern Iceland by multichannel seismic reflection, approximately along the line marked ‘line 29’ in Fig. 2. Unfortunately this attempt was not successful due to bad weather conditions (K. Gunnarsson, pers. comm., 1993).

Gravity

The gravity field around Iceland has been measured during various marine surveys (Thorbergsson et al., 1990) and more recently by satellite altimetry (D. Sandwell, pers. comm., 1994). The available gravity data base has recently been used by Eysteinsson and Gunnarsson (1995) in plotting free-air and Bouguer gravity maps of the Iceland area. The free-air gravity anomalies over the shelf south of Iceland indicate that the density of shelf rocks is 2700–3100 kg/m³ (Pálmason, 1974). The shelf is therefore most likely to be composed of basalts of at least 1 km thickness. The published offshore gravity values represent averages of the actual field, probably over distances of the order of 10–20 km. This resolution is not sufficient to constrain models of the internal structure of the shelf.
SURVEY WORK AND DATA PROCESSING IN 1990-92

Our airborne surveys in 1990–92 were aimed at extending the coverage provided by the 1973 marine survey in two areas (Fig. 2). In the survey flown in 1990, we attempted to follow the shelf-edge anomalies farther west than had been feasible with the results of the marine survey. In 1991–92 we flew a number of lines northeast of the area of the marine survey. Details of the survey procedures and data reduction are described in a report (Kristjánsson and Jónsson, 1996). This report and all data are available on request.

Field measurements were made at 5-s (about 300 m) intervals and position measurements at 4-s intervals (using Loran-C in 1990 and GPS in 1991–92). Crossover checks and comparison with geographic features onshore indicate that the accuracy of each position is better than 200 m. The separation of adjacent lines was 6 km. Field measurements are accurate to about 10 nT. Total-field residuals were computed by subtracting a ‘regional’ field estimated from the results of a Canadian survey at 3–4 km altitude in 1965 (Sigrurgeirsson, 1970). The regional field has been updated using measurements at the Leirvogur magnetic observatory in SW-Iceland (T. Sæmundsson, pers. comm., 1994).

MAIN RESULTS, 1990–92 FLIGHTS

General description

Figure 3 shows the total-field residuals on our 1990 survey lines east of the Vestmannaeyjar archipelago. The flight altitude is 900 m on the short NE–SW lines and 250 m on most of the N–S lines. The signature of a simple step-type anomaly, i.e. a pair of positive and negative anomalies, is clearly seen at or inside the 200-m isobath, especially east of
Magnetic surveys south and southeast of Iceland

![Magnetic survey map of Iceland](image)

Fig. 3. A plot of unfiltered magnetic field residuals on the aeromagnetic survey lines south of Iceland, also including flights over the Mýrdalsjökull glacier at 2000 m altitude. The residual field is represented by bars emerging from the measurement points, perpendicular to the survey path. Field plotting convention is illustrated in the upper right corner, amplitude ±1000 nT. Positive deviations have double the bar density of negative ones; 200-, 500- and 1000-m isobaths are shown. Results on line 8 are modelled in Fig. 6a.

19°00'W. The main peak of the anomalies may, however, be either on the landward or seaward side.

On the shelf west of 19°W, the irregularity of magnetic anomalies increases. It is most probable that this is due to late Quaternary volcanism on fissures south and southwest of the Katla central volcano (Figs 2 and 3). Thors and Helgason (1988) found a number of small hills of presumed volcanic origin occurring within the sediments on the shelf around Vestmannaeyjar, between 20°W and 20°40'W.

Figure 4 shows field residuals on our 1991–92 survey lines off southeast Iceland at 900 m altitude. As in the flights of Fig. 3 and in marine profiles in the intervening area of the shelf (Kristjánsson, 1976) there is a sequence of elongated edge anomalies landwards of the 200-m isobath west of 13°W. On approaching the Iceland–Faeroe Ridge (IFR), this pattern tends to be replaced by wider bands. They remain parallel or subparallel to the coastline, and appear to some extent to continue into the IFR.

Figure 5 is a shaded-relief map of magnetic data, spatially filtered to illustrate the main anomaly features. It also includes sparse marine magnetic data from 1973 (Kristjánsson, 1976). The filtering compensates for the different survey altitudes of the data sets. Viewing the entire area, the most noticeable aspect of the map is the strong anomaly which follows the shelf edge. The easternmost part of Fig. 5 displays a rather simple pattern. Between 15° and 17°W the anomaly is more complex and includes a large negative anomaly probably due to a central volcano (see below). From 17°30' to 19°W the anomaly pattern again becomes simple, stepping en echelon landward into an area of the shelf affected by recent volcanism.
Fig. 4. Magnetic field residuals in 1991–92 survey flights southeast of Iceland. See Fig. 3 for explanation. Results on line 11 are modelled in Fig. 6b.

Models—Introduction

We have attempted to model the anomalies from some of our flight lines with 2½-dimensional sources having a structure consistent with the bathymetry and, where available, sparker evidence. We use the models to restrict or to rule out certain possibilities in the structure of the shelf, and as a basis for further discussion. At this stage they cannot give any precise idea about the genesis of the shelf region. In making the models we have kept in mind that the structure of volcanic formations in Iceland is dominated by subhorizontal layering. Each model is composed of as few layers as possible, to avoid excessively high magnetization values. The lines no. 8 at 19°00’W and no. 11 at 13°30’W (see Fig. 3 and Fig. 4 for locations) which are discussed as examples below, were chosen because of their relatively simple appearance.

Model—Line 8

A model to account for results on flight line 8 from 1990 is shown in Fig. 6a. A non-magnetic lens of sedimentary material, of about 5 km width on the sea-floor, lies in front
of a sandwich of normal-reverse-normal polarity (N-R-N) rocks, where the bottom two layers are each 1 km or more in thickness. The intensity of magnetization required is of the order of 4 A/m. The slope of part of the contact between the sediment and reversely magnetized bedrock in the model of Fig. 6a exceeds 50° which may not be realistic.

It seems necessary to include in the model a large body of rock with reverse magnetization, unless we are prepared to use models with higher magnetization values and very distinct lateral contrasts between normal and reverse units. The thickness of the reverse layer in Fig. 6a is much greater than the 200 m average thickness of polarity zones in the lava pile in Iceland (Kristjánsson and McDougall, 1982), but alternating layers of the latter thickness would obviously require very high remanence intensity to produce the observed anomalies. The shelf break itself is not reflected in the magnetic field, strongly suggesting that it is made of sediments reaching at least down to the level of the abyssal plain. Another source of lateral magnetic contrasts which might account for our observations, could be normal-polarity intrusions within the reverse block. Such intrusions onshore often carry strong remanence, especially if rapid cooling occurred.

Model—Line 11

The flight line 11 from 1991 is shown in Fig. 6b. It has large anomalies, reaching a peak-to-peak value of 2000 nT. As in the line discussed above, the peak is farther offshore than the trough. The main characteristic of both models is a layer of normal-polarity rocks overlain by a reverse-polarity layer with a thick non-magnetic sediment in front. A good fit can be obtained with a sandwich of three R-N-R layers, of rather strong magnetization (± 7 A/m). In this kind of model the anomaly labelled B can be very difficult to model in terms of only a single tilting interface between the reversely magnetized layer and sediment, and therefore a ridge in the underlying normal-polarity zone has been added. The ridge
Fig. 6. (a) Modelling of sources for the anomalies in flight line no. 8 from 1990. The shore is at 0 km. Vertical exaggeration is 6.7:1. The observed residual magnetic field (solid curve) has been smoothed with a window of about 1 km half-power width. Broken curve: field calculated from model. (b) Modelling of sources for the anomalies in flight line no. 11 from 1991. The observed field (solid curve) has not been filtered. The shore is far to the left of the diagram. Vertical exaggeration 6.7:1.
may also be represented by intrusions. We assume the model to give an upper limit to the landward extent of the sediment. The anomaly A is interpreted as 200–300 m undulations in the upper interface.

**Interpretation**

Models of the anomaly sources from two other flight lines and one of the 1973 marine survey lines are presented by Kristjánsson and Jónsson (1996). Broadly speaking, our results from this modelling suggest that the outermost part of the shelf is built up from essentially non-magnetic sediments, of 1 km or more in thickness. The model calculations indicate that under the anomaly which is farthest from shore, there is the edge of a magnetized body, sometimes of normal and sometimes of reverse polarity. We interpret this body as a sequence of lava flows, possibly with intrusions occurring at its boundary with the sediment lens. In order to produce the observed anomalies, the thickness of polarity zones in our models is 600–1200 m and the magnetization intensity of the material of the shelf is 4–9 A/m. As stated above, both values are greater than what is typically observed in Icelandic Neogene lava sequences, i.e. 200 m (Kristjánsson and McDougall, 1982) and 4 A/m (Kristjánsson, 1984) respectively. This is consistent with the fact that anomalies of comparable size are not found to be associated with landscape features in Iceland, even at steep 600–800 m plateau scarps.

In Fig. 7, we have estimated the position of the boundary between crystalline rocks and sediments along the coast, using constraints gained from our models. This boundary is far within the shelf break as we have defined it (around the 200-m isobath in most of the area of Fig. 7, deeper towards the IFR). However, the model calculations indicate that the width of the sediment wedge is somewhat less than that estimated by Kristjánsson (1976, Figs. 5
and 6) from his simple one-layer model of the basement edge. This width (Kristjánsson and Jónsson, 1996, Fig. 7) is on average of the order of 4–6 km between 19°20'W and 18°W, increasing to 8–10 km between 17°W and 64°30'N, 12°30'W (just west of the Litlajúp submarine valley, Fig. 2) where the edge anomaly becomes indistinct.

The surface area of the sediments between 13°W to 19°W, is estimated to be about 2400 km² and assuming an average thickness of 1 km, they amount to 2400 km³. Such a volume, if removed from the drainage area of rivers flowing south in southeastern Iceland, corresponds to erosion of a 150-m layer from that area.

Farther northeast along the shelf and on the Iceland–Faeroe Ridge Kristjánsson et al. (1977, Fig. 1) tentatively concluded from sparse marine records that magnetic anomalies could be used to follow a basement edge to 65°N. However, the present data set demonstrates that in addition to the distinct edge-type anomalies there are both central-volcano anomalies and broad positive anomaly bands such as that marked H° in Fig. 7. It is possible that each of the latter is caused by a thick lava series of uniform polarity, tilting towards shore. In Fig. 4 we have therefore not been able to trace the basement edge itself farther northeast than 64°30'N.

Central volcanoes

Onshore in Iceland, large local magnetic anomalies are commonly found at active and extinct central-volcano complexes. Typical dimensions are 1000–2000 nT by 6–10 km; an example of these which occurs over the Katla caldera in Myrdalsjökull glacier in central southern Iceland, is included in Fig. 3 (Jónsson and Kristjánsson, 1998). They tend to be associated with caldera structures and are not significantly elongated along the dike swarms that pass through these centers (Jónsson et al., 1991). These magnetic anomalies are more often positive than negative, and are sometimes accompanied by positive gravity anomalies with amplitudes of the order of 10 mgal. Similar anomalies have been noted on the shelf east and west of Iceland as well as on the transverse ridges (Fleischer et al., 1974; Kristjánsson et al., 1977).

Offshore in our western survey area (Fig. 3) no anomaly of this kind is apparent, but in the vicinity of the IFR several such anomalies occur (Fig. 7). In the intervening area, Kristjánsson (1976, Fig. 4) only recorded a single localized anomaly (near the shelf edge at 15°W, see Fig. 5) probably related to a central volcano structure. The relative paucity of localized anomalies on the shelf south of Iceland may be a result of it being too far removed from the influence of the mantle plume under Iceland to generate conditions for the development of large central volcanoes.

CONCLUSIONS AND DISCUSSION

New modelling of our results from 1990–92 aeromagnetic surveys generally confirm previous conclusions from a more simple modelling of marine magnetic surveys (Kristjánsson, 1976):

1. Within the insular shelf off south and southeast Iceland a continuous edge- or step-structure in crystalline basement occurs several km inside the shelf edge. In order to keep the intensity of magnetization in the basement material reasonably low, it must be assumed to form thick zones of uniform polarity.
2. The thickness of the sediment wedge is of the order of 1 km.
3. The basement edge extends for at least 400 km which makes it one of the larger structural features in the Iceland region.

We were not able to ascertain whether magnetic anomalies associated with the edge structure continue onshore somewhere west of 19°W, or to what extent they can be followed through the IFR. These possibilities need checking further, preferably by a survey also employing seismic reflection methods. A free-air gravity high which follows this basement edge off the south coast east of 19°W seems to continue westwards, reaching a local maximum on the coast south of the Eyjafjallajökull glacier (Eysteinsson and Gunnarsson, 1995). Similar but broader elongated gravity highs extend around most of eastern and northeastern Iceland to 16°W, as well as around western Iceland.

Hypotheses of the genesis and history of the ‘Iceland block’ must be able to explain the presence of the continuous extensive steep edge of the basement south and southeast of Iceland. The only other geophysical data available (gravity and shallow reflection seismics) do not yet provide much constraints on its detailed composition. The edge in the basement may mark the outer limits of excessive volcanic production in Iceland, modified to some extent by erosion during subsidence and to a lesser extent by faulting.

The relatively high magnetization in the basement material may be due to a high content of magnetic minerals, small effective grain size (rapidly cooled intrusives or submarine extrusives?) or other factors. Its age is unknown. The large thickness of polarity zones points to a high productivity of volcanism, possibly during a pulse of activity of the Iceland mantle plume. The sediment lens may be mostly of Quaternary (even Late Quaternary) age, in which case its generation may to some degree have been determined by changes in sea level and isostatic movements.

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REFERENCES


