Aeromagnetic measurements over Mýrdalsjökull and vicinity

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Abstract — Aeromagnetic survey results from the Mýrdalsjökull glacier region, acquired by Th. Sigurgeirsson around 1970, have been reprocessed in combination with data from a new survey. The main feature of the residual magnetic field over Mýrdalsjökull is a localized 8 x 12 km negative anomaly, of around -2000 nT amplitude relative to the regional field. Models of the crust indicate that it is caused partly by the subglacial topography and partly by a thermal anomaly associated with a possible magma chamber beneath the Katla caldera.

INTRODUCTION

Local aeromagnetic anomalies in and around Iceland are typically on the order of 1000 nT in amplitude at 1000 m altitude (Jónsson et al., 1991). They tend to be circular rather than elongated and are generally less than 20 km in size. Wide flight line spacing and gaps in data limit the resolution of magnetic-field maps based on aeromagnetic surveys. Some anomalies are observed on only one or two flight lines and their detailed shapes are, therefore, not well defined. The causes of the anomalies vary, but can sometimes be inferred from their geological setting. Some anomalies are clearly connected to central volcanoes, others are due to topography or to subaqueous eruptions which produce a complex structure of nonmagnetized tuff and breccia with inclusions of highly magnetized pillow lava (Kristjánsson, 1970).

Two, at least, of these anomalies show similar characteristics where a broad (~10 km) negative anomaly on the order of 2000 nT occurs in positive fields over an active volcano. These are Askja in Dyngjufjöll and Katla in Mýrdalsjökull. A similar, but less clear anomaly is found over Bárðarbunga in the Vatnajökull glacier. Due to the position of these volcanoes within the active spreading zones in Iceland, a fragment of reversely magnetized material can be ruled out as their source. In this paper we focus on the Katla anomaly, display the magnetic field of the Mýrdalsjökull area and interpret it.

PREVIOUS WORK

The U.S. Naval Oceanographic Office Project Magnet carried out total-field aeromagnetic surveys in the South Iceland region in Feb. 1964, at varying altitudes. Results in the form of draft contour maps were presented to the Science Institute, one of which was published as Figure 14 of Kristjánsson et al. (1989). Another map (1800 m a.s.l.) includes three flight lines which cross the central part of the Mýrdalsjökull icecap (Figure 1) and record a negative anomaly of 2000 - 2500 nT amplitude. Compared to later data, however, the positions of this survey seem to be unreliable, and it is not included in the present study.

Detailed aeromagnetic measurements over Mýrdalsjökull were made by Th. Sigurgeirsson during his 1969-72 survey of South Iceland (Figure 2). The flight lines were oriented east-west with 4 km spacing. Positioning was based on visual identification of landscape features. The nominal flight altitude was 1200 m above sea level, indicating that the plane ascended when approaching higher topography and descended again when appropriate. The icecap altitude reaches 1500 m. The magnetometer was a continuously recording proton precession instrument from which field values, averaged over 10 s (5-600 m), were obtained (Sigurgeirsson, 1970). Processing of the data included correction for diurnal and secular variation, subtraction of a regional field, and manual plott-
Figure 1. Index map of the Mýrdalsjökull glacier and the surrounding region. Glaciers are labelled. Thin lines are 200, 500 and 1000 m contours. The thick dotted line marks the topographic caldera within Mýrdalsjökull (Finnur Pálsson, personal communication, 1996) whereas the thinner dotted line denotes the inferred thermal caldera. The volcanic fissure Eldgjá is also shown.

We digitized Sigurgeirsson’s original data from the 1:100,000 maps and included them in a composite magnetic map of Iceland (Kristjánsson et al., 1989). This map represents the best available estimate of the residual field caused by crustal sources. As detailed information on flight altitudes was not preserved, no effort has been made to transform the magnetic survey to a common altitude, and no filtering other than 10 second averaging has been applied.
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Figure 2. A map of residual magnetic field on flight lines over the Mýrdalsjökull region. Negative values are indicated by bars emerging from the points of the respective measurements, southward perpendicular to the survey path. Positive deviations have double the bar density. Lines 2-14 (indicated by arrows) are from Sigurgeirsson’s survey in 1969-72 at 1200+ m altitude. Lines i-iii were measured on 25 June and 2 July 1990 at 2000-2100 m altitude. Arrows indicate the heading of each line. Four of Sigurgeirsson’s lines have been moved in order to match up with our data (#5: 0.5 km E; #7: 1.5 km E; #8: 1.0 km W and #9: 1.5 km E). — Segulfrávik mielt ùr flagvel yfr Mýrdalsjökli. Neikvett frávik er teiknað úr hverjum melipunkt hvert á fluglinu, til sudurs eða austurs, en jákvett svíð helmingi þetta í hína áttina. Linur 2-14 eru meðlar af þorþórri Sigurgeirsson 1969-72 á 1200 m heð eða herra þar sem þess þurftir. Linur i-iii voru mælir úr 2000-2100 m heð sumarið 1990. Fjórurn af linum þorbjörns þurfti að hluka til, til að þar fellu að nyrri gognum.
NEW SURVEY – JOINT PROCESSING

In 1990 the authors began an aerial survey of the magnetic field along the south coast of Iceland. As a part of that survey, two lines and a loop were flown across the Katla caldera (Jóhannesson et al., 1990) beneath Mýrdalsjökull. Positions were determined by a Loran-C navigation system with the estimated position error not exceeding 3-400 m. Total-field measurements were made at 5 or 6 s (around 300 m) intervals. The flight altitude was higher than previously, 2000-2100 m. Initial processing of data was similar to that of Sigurgeirsson (Kristjánsson and Jónsson, 1996).

Cross-over checks between Sigurgeirsson’s data and the 1990 data showed a mismatch which may be minimized by manually shifting some of his lines east or west by 0.5-1.5 km. This is reasonable because over the glacier there are few if any landmarks, and constant speed of the aircraft was apparently assumed in the plotting of Sigurgeirsson’s measurements, although ascending and descending must have affected the speed considerably. Figure 2 shows the field on Sigurgeirsson’s and our own flight lines after correction for the mismatch. Our corrections extend beyond the glacier area where they may not be appropriate.

It is obvious from Figure 2 that the field variations along flight lines are on a much shorter scale than the line spacing. Before gridding the field, standard procedure would be to filter and decimate the data along flight lines so that point spacing would be comparable with line spacing. That, however, would reduce the information in the data considerably. We have, therefore, decided to grid the original data which shows more detail, sometimes appearing as a pearl-chain structure along the flight path. This has to be kept in mind during visual inspection of the gridded representation of the magnetic field. We used the (Golden Software) Kriging method for gridding the data to a 50 by 50 km grid with 1 km node spacing. The field intensity is displayed in color in Figure 3, and as illuminated relief in Figure 4.

GEOLOGICAL SETTING AND OTHER GEOPHYSICAL DATA

The region under study lies in the southernmost part of the eastern volcanic zone of Iceland. The zone is associated with a broad magnetic high of 20 km width trending 45-50° east of north. This high, which is presumably due to basalt volcanics emplaced during the Brunhes geomagnetic chron (<0.78 Ma), disappears at the south coast. The region is characterized by fragmental rocks of the palagonite formation of subglacial or subaqueous origin. Radiometric age determinations (K. Wiese, personal communication 1994) indicate that the adjacent Eyjafjallajökull volcanic center is about 1 Ma old.

The presence of an approximately 14 km long and 11 km wide caldera, trending NW under central south Mýrdalsjökull was indicated in the geological map of South Iceland (Jóhannesson et al., 1990). Björnsson et al. (1994, 2000) have mapped the caldera in detail by radio-echo sounding. Its depth is 600 to 750 m, deepest in the north, while shallower and more rugged in the south. Björnsson et al. (1994) suggest that the variable morphology reflects different levels of volcanic activity. The highest topography occurs at the caldera rim where peaks protrude the glacier surface as nunataks.

Seismic undershooting on a NNW-SSE line through Mýrdalsjökull (Guðmundsson et al., 1994) revealed anomalously low velocity and an S-wave shadow beneath the caldera. They suggested this was caused by a shallow magma chamber in the crust, about 5 km across and reaching down to about 1.5 km below sea level. Earthquake activity in the Mýrdalsjökull area (Einarsson and Brandsdóttir, 2000) originates in two main areas, one within the topographic caldera, the other farther west, at the periphery of the glacier. It is suggested that this activity is related to two magma chambers within the volcano, the western one being younger and less developed.

A positive Bouguer gravity anomaly of up to 40 mgal is found over Mýrdalsjökull. Guðmundsson (1994a,b) suggests that the main anomaly is due to a gabbroic intrusive complex which may not reach above 2.5 km depth. A large gabbroic body should be expected to generate a positive magnetic signature.
due to its remanent and induced magnetization, unless its temperature is of the order of 500°C or above. Superimposed on this gravity high there is a horseshoe shaped high along the south, west and east rims of the caldera. It may originate in intrusions concentrated at the border of the caldera above 2.5 km depth. If these intrusions mark the lateral extent of the magma chamber it would be circular and 6 km across. Although acid rock occurs in most nunataks around the caldera, the total volume of acid rocks is probably small as it would tend to cause a negative gravity anomaly (Guðmundsson, 1994b).

**GENERAL DESCRIPTION OF THE RESIDUAL MAGNETIC FIELD**

The magnetic field over the mountainous Mýrdalsjökull and Eyjafjallajökull region appears to form a part of the Brunhes age magnetic high of the eastern volcanic zone. This is especially clear around Eyjafjallajökull and the westernmost part of Mýrdalsjökull. The high is interrupted by a wide SE-trending negative anomaly around the large Torfajökull volcanic center (no. 79 in Figure 9 of Jónsson et al., 1991), reaching the northern periphery of Mýrdalsjökull. The field is relatively smooth along the eastern edge of Mýrdalsjökull.

The most noticeable feature of the residual field is an NNW-SSE elongated depression of approximately 12 by 8 km in size, concentric to the subglacial caldera. Its amplitude at our flight altitude is -1300 nT, while the residual field surrounding it is of the order of +600 nT. We shall refer to this 2000 nT magnetic bowl and its rim as the Katla magnetic anomaly. Several localized anomalies are seen at the rim or farther away from the caldera.

A broad magnetic high extends south from the eastern part of Mýrdalsjökull, to the coast. Its N-S trend reflects the trend of the mountain ranges east of the village of Vik but it could have a deeper source. Some minor anomalies are found outside the glaciers, most of unknown origin. A small negative anomaly is clearly related to the Tindfjallajökull central volcano (Figure 2, where lines 11 and iii cross).

**THE KATLA ANOMALY**

Data from several boreholes within or near the volcanic zones in Iceland show little systematic change in magnetic susceptibility down to 2 or even 3 km (Kristjánsson and Watkins, 1977). The maximum depth of magnetic contrasts in the Icelandic crust must be greater than this and may be set by the Curie point for fairly pure magnetite (500-560°C). There is reason to believe that a thermal anomaly is present under the Katla caldera, associated with the magma chamber inferred from seismic profiling. If this is the case, a broad negative magnetic anomaly is to be expected, in particular if the Curie point isotherm reaches close to the surface (<1 km, say). However, such an anomaly would not be distinguishable from one due to the presence of non-magnetic material such as tuffs surrounded by crystalline rocks of normal magnetic properties.

The maximum depth to the sources of the field may be estimated using the half-slope depth method (e.g. Sharma, 1986). In the central northern part of the Katla anomaly (along line 8 of Figure 2) the source appears to lie below sea level. In the southern part of the anomaly the source would, on the other hand, lie close to the bedrock surface. In addition to the uncertainty of this method, the altitude of the aeroplane in the older lines was not well known.

We model the field using the magnetic pole concept (Telford et al., 1990). The generating body is split into a number of square vertical columns, all with the same uniform magnetization and their contributions to the field are summed up. We assume the columns to be sufficiently narrow to be replaced with magnetic dipoles, with monopoles at the top and bottom. The depth to the bottom monopoles is held constant across the domain of the model but the elevation of the top monopoles varies.

To model the field over Mýrdalsjökull we use for the upper poles the two dimensional topographic grid of the area provided by Björnsson et al. (2000). The depth of the bottom poles (2000 m below sea level) is not important as long as it is kept constant. In order to eliminate edge effects, the working area is extended in all directions by an 8 km wide tapering zone (not included in the figures) where the topograp-
Figure 3. A contour map of the magnetic field over Mýrdalsjökull, based on results shown in Figure 2. Contour interval is 200 nT. Because of the wide spacing of lines the original data should always be kept in mind when inspecting this map and the following figure. Dotted line: topographic caldera cf. Figure 1. Coordinates: -x,y values of the Hjörsey-datum conical projection for Iceland, in meters. – Jafnsviðsláakort af segulfrávikina á 2. mynd. Bil milli fluglina er mun meira en bil milli punkta efir fluglínunum og verður því að skoða þessa mynd og þá nástu með þau í huga.

hy is reduced down to a common depth, in this case 1000 m below sea level. Individual columns are 200 m square and the working area is 251 x 251 poles, i.e. 50 x 50 km, which matches Figures 2-4. The magnetic field is calculated at a flight altitude of 2100 m using an overall remanence intensity (Jrem) of 8 A/m, which is an estimate for Quaternary volcanics in Iceland (Kristjánsson, 1970). Figure 5 shows the vertical component of the modelled field as a shaded relief. Qualitatively its resemblance to Figure 4 is clear indicating that the topographic caldera is at least in part the cause of the magnetic bowl.

Two perpendicular cross-sections over the magnetic bowl are shown in Figure 6 along with the calculated field due to the terrain. We generate a model incorporating a vertical cylindrical structure of elliptic cross-section, elongated SE-NW beneath the caldera. For best fit to the observations, the model was set to
Figure 4. Shaded relief presentation of the contour map of Figure 3. Illumination is from the southeast. Dotted line: topographic caldera cf. Figure 1. – Hliðarþýst lágmynd af sömu gögnum og d 3. mynd. Ímyndad sölskin er úr sudanustri og drégur sérstaklega fram drettir sem stefna þvert á það. Punktaltinn synir legu öskurímans.

be 7 x 10 km in size, i.e. smaller than the topographic caldera but concentric to it. The center is at 63°38′N, 19°09′W. Within this thermal caldera anomaly we choose the upper surface of the magnetic columns at some depth below the actual topography and calculate the magnetic effect as before. In the calculated profiles, the regional field has been adjusted to agree with the observed data far away from the caldera.

As seen in Figure 6 we cannot distinguish between a shallow unmagnetized bowl in strongly magnetized material or a deeper bowl in less magnetized matter. The model, however, limits the width of the bowl, with an uncertainty on the order of 1 km.
Figure 5. Shaded relief map of the calculated field at 2100 m altitude using pole concepts (see text), assuming upper monopoles to lie in the topographic surface and lower poles at constant depth, 2000 m below sea level. Lighting from the southeast. Thick dotted line: topographic caldera cf. Figure 1. Thin line within topographic caldera: position of the inferred thermal anomaly. Dashed lines mark the location of cross-sections in Figure 6.

Figure 5 shows a shaded relief map of the calculated field at 2100 m altitude using pole concepts (see text). The upper monopoles are assumed to lie in the topographic surface, while the lower poles are at a constant depth, 2000 m below sea level. The lighting is from the southeast. The thick dotted line indicates the topographic caldera, whereas the thin line denotes the position of the inferred thermal anomaly. Dashed lines mark the location of cross-sections in Figure 6.
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Figure 6. Two cross-sections through the Katla magnetic anomaly (for location see Figure 5). Thick solid line: The observed magnetic field, derived from gridded values. Thin solid lines: topography (lower part) and topography-derived magnetic field (top), assuming Jrem = 8 A/m. Thin dashed lines represent the calculated field for a given remanence and depth of the topographic caldera. a: 1 km, Jrem = 8 A/m, b: 2 km, Jrem = 6 A/m, c: 3 km, Jrem = 6 A/m. Line patterns of topography profiles match those of the calculated magnetic field. A body 1 km thick, with bottom at 1.5 km below sea level and 5 km across is shaded. These are the limits Guðmundsson et al. (1994) set to a magma chamber inferred from their 2-D undershooting experiment. — Efri myndin sýnir segulsvið á íversniði gegnum Kótluískjúna. Sver heil lína sýnir segulsvið, dregið út á grunduðu segulgögnunum. Grennri heil lína sýnir reiknað segulsvið miðað við að allt bergr sé jafnt segulmagnað med Jrem = 8 A/m. Jafnsver lína á neðri myndinum sýnir heðarlaðið. Brotinir ferlar endurspeglu reiknað segulsvið miðað við að miðhliði öskjunaar haft sökkur um a: 1 km, b: 2 km og c: 3 km. Í tilfellum b og c er gert röð fyrir minna segulmagnaða bergr. Jrem = 6 A/m. Grá boîla sýnir kvikhöf sem níuka má út frá skjálfagögnun (Ólafur Guðmundsson o.fl. 1994)

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OTHER ANOMALIES WITHIN THE MYRĐALSJÖKULL AREA

The positive magnetic field around the caldera can, at least partly, be explained as overshoot from the deep magnetic low in the caldera, and it does indicate that the nunataks are generally not made of strongly magnetized material. There is one exception, however. Northeast of the Katla anomaly there is a strong positive anomaly (2000 nT by 5 km or so) which is presumably connected to a linear topographic depression, a gorge 150-200 m deep and 1.5 km wide (Björnsson et al., 1994) striking NE towards the Eldgjá volcanic fissure which was active around AD 930. An anomaly on flight line 10 (Figure 2) is probably related to the same structure.

CONCLUSIONS

A pronounced negative magnetic anomaly of amplitude about -2000 nT and 12 x 8 km in size is found over central Myrdalsjökull. Its location corresponds well to the position and elongated shape of the active volcanic caldera of Katla (Björnsson et al., 2000) and with the position of a magma chamber inferred from modelling of seismic refraction results by Guðmundsson et al. (1994). However, the source of the negative magnetic anomaly is smaller in size than the caldera.

Magnetic anomalies of similar dimensions are found over several volcanic centers of Quaternary and older ages in and around Iceland. These are probably caused by remanence and/or induced magnetization in caldera-filling material and in intrusions which tend to occur at caldera rims. However, much additional geological and geophysical mapping is needed to establish the source of these anomalies in individual cases. The present negative anomaly is most likely due to the relative absence of magnetization in a 7 x 10 km NW-trending region, within normally polarized basaltic material. The negative magnetic residuals within the caldera could be related to a thermal anomaly raising the temperature of much of the crust to above its Curie point. This is supported by Guðmundsson et al. (1994) who conclude that there is a shallow magma chamber in the crust under the caldera, about 5 km across.

Another possible explanation involves the partial filling of a subsided region by material of low remanence (such as palagonite tuffs), but this would be contrary to the strong positive gravity values seen in the area (Guðmundsson, 1994a,b). A third possibility is the presence of advanced geothermal alteration, as noted for some negative anomalies of smaller extent, e.g. in Námaskarð (see Kristjánsson and Watkins, 1977). The overall positive magnetic fields observed around the caldera rim also appear in our computed fields because of the vertical boundaries in the caldera model, but occasional local field peaks could be caused by strongly magnetized intrusions.

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SEGULKORT AF MYRĐALSJÖKLI

Ágrip

Í segulsvíðinu í rúmlega kilómetra háö yfir Íslandi er víða að sjá staðbundin frávik sem tengja má járðfræðilegum lýsingum fyrirbærum, meginingeldstöðum, stöpum eða möbergskollum. Vegna þess hve gisinn flugmæligögn eru hárendis koma þess frávik oft ekki fram nema á einni mællinu og er erflitt að túlka þau. Tvö sílfrávik skera sig þó úr, þau eru sviðuð á að fíta og tengjað bæði afar virkum eldstöðum, Óskju í Dynjunftöllum og Kötlú í Myrdalsjökli. Í þessari greinar er fjallad úm segulfrávikd sem tengist Kötlú.

Katla er meginingeldstöð syðst í eystra gosbeltingu sem liggur gegnum Ísland, sjálf eldstöðin er undir jökli, en jökulbottninn er vel þekktur (sjá greinn Helga Björnssonar og fl. í þessu hefti). Það sem einkennir hann öðru fremur er jarðsög eða askja sem kennir er við Kötlú og hefur rimi hennar verið teiknaður inn á myndir 1, 3, 4 og 5. Eystra gosbelting myndar um 20 km breitt jákvætt segulfrávik, tengi núverandi segulskeiði (Brunhes - síðan fyrir 780 þúsund árum) sem endar í suðri við Eyjafjallajökul - Myrdalsjökul.
Bylgjubrotsmelingar benda til mikils hita eða kvikuholfs undir öskjunni sem nær niður á 1.5 km dýpi undir sjávarmál og er um það bil 5 km í þvermál. Pyngdarmelningar hafa verið gerðar á þjókinum og benda þær til þess bergs undir niðri, gabbrostr, sem geti náð upp fyrir 2.5 km dýpi.

Í þessari glein eru sameinuð segulögðn frá Porðbírni Sigurjórsyni frá árunum 1969-72 og göngr höfunda frá 1990 (2. mynd). Við samanburð á gögunum kom í ljós að nokkrum flugilrunum úr eldri gögunum þurfti að hliðra til um allt að 1.5 km. Tölum við það röttletanlegt þar sem þorbjörn mun hafa reitt sig eingöngu á kenneiði á þöru niðri til staðsetninga.

Segulögðinn verða grindað og birt sem jafnisvöðskort (3. mynd) og sem upplýst lagiðmynd (4. mynd) en þar er búið til imýndað landslag úr segulsvöðinn og ljóst í það úr einhverri átt, venjulega undir lágrí söl, og birtast það aftir drættir en sjást í jafnisvöðsníkornum. Yfir miðjum jökklunum er djúp aftögg segulvöðgöng, NNV – SSA, 12 km lóng og 8 km breið. Í okkar flughæð er segulsvöðið á rimum þessarar legðar um 600nT, en ~1300 nT í botni hennar. Lögðö þessi er því um 2000 nT djúp. Á ríma hennar eru nokkur sterk staðhundin frávik.

Við imýndum okkur að við bryjum jörðskorðuna á sveðínun sem sýnt er á myndum 2-3 niður í lóð-réttu stuðla, 200 m á kant og líttum á hverri þeirra sem langan, grannan segul. Má þá velja stað hver sem er í grenndinni og leggja þar saman áhrif allra þessara litlu segla. Hefur það verið gert fyrir fjólda punkta í imýnduðu neti (sjá 5. mynd) og yfir því þversnið í kross yfir óskjuna (6. mynd). Líkingin á myndum 4 og 5 er augljós, en segulferlanir innan öskjunnar passa ekki. Sæ liðaninu hins vegar breytt þannig að miðjum öskjunnar, á sveði sem er sammiðja henni sjálfrí en nokkrum minna að fatarmál (sjá innri hringulaga ferli á myndum 1 og 5) er sökkta, fæst gott samræmi milli reiknuðu félanna og þeirra møðlu.

Orsakir þessarar segul-ørdeyðu gætu verið tvenns konar, þar sem útilokað er talið að neikvætt segulmagnad berg frá fjöru seguliskaðum sé þarna. Annars vegar að askjan sé full af ösegulmagnadri móbergsvöku, sem er andstætt því sem þyngdarmélningar benda til, en hins vegar að hitaðstand þessu hluta öskjunnar sé sílkt að berg sé ösegulmagnad. Þessi skýring er talin líklegri því bylgjubrotsmelingar benda til hins sama.

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