Reviewed research article

The Stardalur magnetic anomaly, SW-Iceland: a review of research in 1968–2012

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Abstract — *Prominent geophysical anomalies of several km extent were noted in the vicinity of the farm Stardalur in southwestern Iceland in a gravity survey published in 1954, as well as in a 1968 total-field aeromagnetic survey published in 1970, and a seismic refraction study of the crust published in 1971. Further low-altitude and ground magnetic surveys were conducted around Stardalur in 1969–1973, and an exploratory hole was drilled to 200 m depth in 1969–1970 at the site of a very distinct peak in the ground anomaly. Various studies were carried out on a core (to 143 m depth) and on cuttings recovered by the drilling. From 41 m depth down, this material consisted of altered olivine tholeiite lava flows, with a mean remanent magnetization intensity of the order of 15 times the average for Icelandic Tertiary lavas. Modelling of the anomaly peak, which was found to reach at least 27 μT above the main geomagnetic field intensity of 52 μT, indicated that the lava flows formed a body of dimensions about 200 by 600 m striking NE to NNE, inside a caldera structure. This structure probably dates from a normal-polarity subchron around 2 m.y. ago during the Matuyama geomagnetic chron. Further studies on samples from the Stardalur drill core revealed the presence of quite pure and slightly cation-deficient magnetite, whose percentage in the lavas is more than twice the average for Tertiary basalts in Iceland. The magnetite has largely been formed by exsolution from titanomagnetite, but it is also present in small grains which have separated from olivine. A very minor proportion of the magnetite may be of single-domain size, and it appears not to be a decisive factor in the bulk magnetic properties of the lavas. For instance, the natural remanence is much less resistant to alternating-field demagnetization than could be expected for single-domain grains. It is not certain whether it is a primary thermal remanence or of secondary origin, although the former seems more plausible. In agreement with the conclusions of previous researchers, it appears likely that the strong magnetization is due to a chance combination of circumstances (such as high magnetite content, high oxidation state, and strong ambient field) rather than to some unique phenomenon. In this paper, a new ground magnetic survey at Stardalur is presented, along with a simple model of the source of the main anomaly peak. The geological reasons for the creation of that source remain unknown, but comparisons are made with a magnetic anomaly at Hvanneyri in western Iceland which has similarities with the Stardalur anomaly.*

GEOPHYSICAL AND GEOLOGICAL RESEARCH RELATED TO THE STARDALUR ANOMALY, TO 1973

Surface exposures in Iceland consist mostly of lavas and other extrusives of basaltic composition. They resemble the Early Tertiary volcanics in the U.K. (western Scotland and northern Ireland), the Faeroes and Greenland. On the basis of this resemblance and other evidence, the oldest rocks in Iceland were for decades considered to be of Eocene age and to belong to the same volcanic province as the other localities. However, it was established by Moorbath *et al.* (1968) that the age of exposures in Iceland does not greatly exceed 15 million years (m.y.). Occurrences of gabbro, andesitic and rhyolitic rocks are common in Iceland; Walker (1959) showed that these as well as dike swarms are associated with central-volcano complexes of a similar kind as those in the U.K. The volcanic centers in Iceland are however smaller in size, often 5–10 km across as compared to 15–20 km for some Scottish centers.

Early geophysical studies

In the early 1950s, T. Einarsson (1954) carried out a gravity survey of Iceland. Where his stations were sufficiently dense, several localized anomalies were noted, one being the Stardalur gravity anomaly near a farm of that name 20 km northeast of Reykjavik. In Einarsson's maps this anomaly is assumed to be of about 8 km size and +10 milligal (mgal) amplitude, but its northern part could not be measured due to mountainous terrain.

An aeromagnetic survey of total-field intensity at 900 m altitude above sea level (a.s.l.) over southwestern Iceland, made in 1968–1969 by Þ. Sigurgeirsson (1970a,b,c), revealed several elongated or roughly circular positive or negative magnetic anomalies of typical amplitudes 0.5–2 micro-Tesla (μT). However, three prominent positive anomalies stood out in the map, see Figure 1. One of these (at St in Figure 1) coincided with the above-mentioned gravity anomaly. As the flight-line spacing was 4 km, the dimensions of the magnetic anomaly are not known with certainty. They may be estimated from Sigurgeirsson's maps as being 8–10 km (Friðleifsson and Kristjánsson, 1972). The Stardalur positive magnetic anomaly lies inside a negative anomaly lineation of 20 km width and -1.5 μT amplitude (relative to the local International Geomagnetic Reference Field intensity F which was 51.75 μT in 1968; it has increased by about 0.65 μT since then), striking ENE to NE. The amplitude of the Stardalur anomaly at this survey altitude may reach 4.5 μT above the expected regional field value within the negative lineation.

The two other prominent positive anomalies were at mt. Skálafell in Hellisheiði (Sk in Figure 1) and at Ferstikla (F in Figure 1). The former was later surveyed in detail by Þ. Sigurgeirsson at 800 m altitude, and a contour map of his results was published by Pálmason (1987). The Skálafell anomaly which is elongated in a direction 30° east of north, is associated with Late Quaternary volcanics erupted subglacially (Sæmundsson *et al.*, 2010). The Ferstikla anomaly is clearly related to a volcanic center (Jóhannesson and Sæmundsson, 2009; Kristinsson, 2009), active 3.3–2.6 m.y. ago during the Gauss geomagnetic chron. No detailed magnetic results are available on this anomaly which has its peak within a 2–4 km wide fjord. Apart from negative magnetic lineations running sub-parallel to the volcanic zones, the main negative anomalies in Sigurgeirsson's (1970a) map occur just east of Reykjavík (R in Figure 1).

Sigurgeirsson's discovery of the Stardalur anomaly sparked considerable additional research at that locality. He carried out a total-field aeromagnetic survey in 1969 on six short lines at altitudes of 300–350 m a.s.l., intersecting over the Stardalur farm buildings at 64°12.7'N, 21°29.0'W, alt. 190 m a.s.l. Judging from a contour map of his results (Kristjánsson, 1987) the maximum intensity exceeded 59 μT. Field measurements made on the ground in the Stardalur area in 1969 indicated that the magnetic anomaly was composed of two parts: a wide anomaly of mean dimensions 7 km and amplitude 5 μT, and a few peaks superimposed on the wider anomaly. In the most prominent of these peaks, field values of up to 79 μT were found. From the ground survey data, Kristjánsson (1970) provisionally estimated that the cause of this peak could be a single body of 200×600 m size striking NE, with an upper surface at a depth of 50–70 m, and a total magnetization intensity of 50–60 Amperes per meter (Am^{-1}). Analysis of more detailed ground-survey data (Búason, 1971) yielded a magnetization estimate of 80 Am^{-1} and slightly different dimensions.

General information on rock magnetism in Iceland

Magnetization (i.e., dipole moment per unit volume) of a material is a sum of two vector quantities. One of these vectors is induced magnetization $\mathbf{M}_i$, which is proportional to both the ambient field **F** at any time and a dimensionless material quantity called the volume magnetic susceptibility. $\mathbf{M}_i = \mathbf{F}\cdot\chi/\mu_o$ where the constant μ_o is $4\pi\times10^{-7}$ TmA^{-1} in SI units. In Ter-

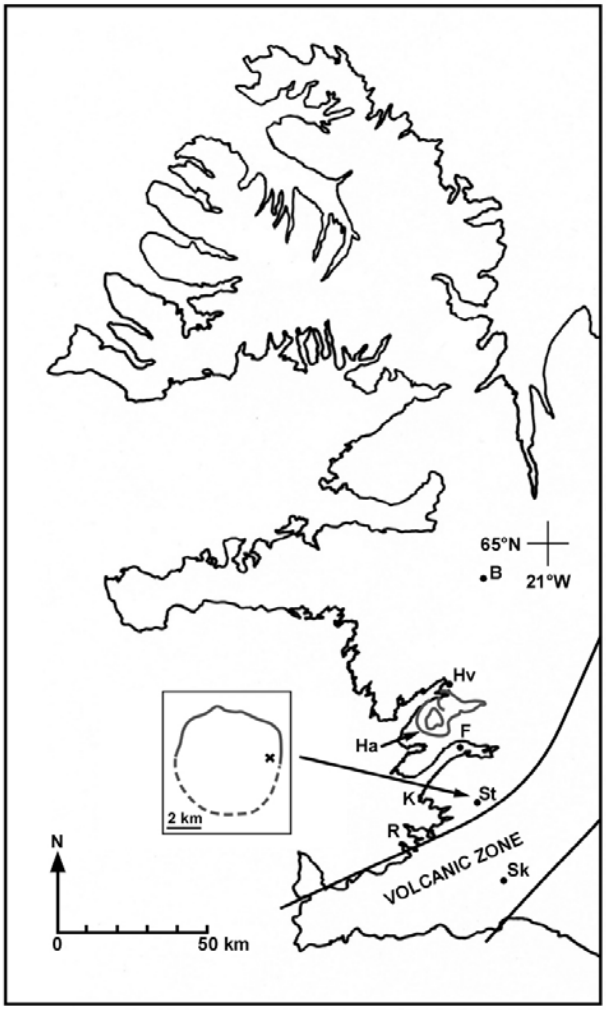

Figure 1. Outline map of western Iceland, showing approximate locations of several large magnetic anomalies found by Sigurgeirsson (1970a, 1979). Sk: Mt. Skálafell, St: Stardalur, F: Ferstikla, Hv: Hvanneyri, Ha: Mt. Hafnarfjall, B: Breiðakinnarsandur. Prominent negative anomalies also occur between Reykjavík (R) and Kjalarnes (K), see Jónsson and Kristjánsson (2002). The position of the main anomaly peak within the Stardalur caldera is shown with a cross in the inset. The outlines of the Hafnarfjall central volcano and two calderas within it (from Jóhannesson and Sæmundsson, 2009) are also shown. – *Kort af Vesturlandi. Nokkrir staðir þar sem óvenju mikil segulsviðsfrávik komu fram í flugmælingum Þorbjörns Sigurgeirssonar eru merktir. Einnig er sýnd afstaða hámarks-segulfráviksins í Stardal til öskjubrúnar þar, og útlínur Hafnarfjalls-megineldstöðvarinnar með tveim öskjum.*

tiary lavas in Iceland where F (the magnitude of $\mathbf{F}$) is currently close to 50 μT and the average susceptibility is about 0.025 SI units, the average induced magnetization has an intensity M_i of around 1 Am^{-1}. The other vector quantity is remanent magnetization (remanence, $\mathbf{M}_r$) which has generally originated in part during cooling of the material from its Curie point (transition temperature to ferromagnetic behavior) to a much lower temperature. This is called thermal remanence, TRM. Another way of acquiring remanence is through the growth of new magnetic minerals in the material (chemical remanence, CRM). In a cooling lava, these two processes may well operate more or less simultaneously, giving rise to thermo-chemical remanence (TCRM). Additionally, remanent magnetization often builds up gradually in a material when it is in an external magnetic field of constant direction. The time constant for this buildup (which generates a viscous remanence, VRM) can be from seconds to millions of years. For a rock in situ, all these components constitute its natural remanence (NRM). In exposed relatively unaltered Tertiary lavas in Iceland, the arithmetic average NRM intensity M_r is about 4 Am^{-1} (Kristjánsson, 2002). It is most commonly dominated by TRM which can be either in a direction close to that of the present geomagnetic field, or opposite to it. The average VRM intensity in lavas may be of the order of 0.3 Am^{-1}, but in some rock samples it exceeds their TRM intensity. Remanence intensities of 40 Am^{-1} or more are only found in very rare and isolated cases (apart from lightning strikes). Fresh Quaternary basalts may have a stronger average remanence than the Tertiary lavas, possibly 6 Am^{-1} (Kristjánsson, 1970, and other data) and distinctly lower susceptibility. Regional hydrothermal alteration tends to cause a progressive decrease in the intensity of primary remanence of lavas (Fig. 13 of Watkins and Walker, 1977). This decrease, along with enhanced tendency for VRM buildup, may reach significant proportions already at the upper boundary of the analcime zeolite zone, but the matter requires further study.

Geological research

Detailed geological studies in the Stardalur anomaly area (Friðleifsson and Tómasson, 1972; Friðleifsson and Kristjánsson, 1972; Friðleifsson, 1973, 1985) revealed the presence of an extinct and eroded volcanic complex. This complex is manifested by a caldera of about 6.5 km in diameter as well as cone sheets, rhyolite and dolerite intrusions, and small plugs around the caldera rim. See Fig. 1 of Friðleifsson and Kristjánsson (1972), which is also reproduced as Fig. 1b of Vahle *et al.* (2007). The southern half of the rim is covered by the so-called „Reykjavik gray basalts“, a lava sequence of Late Quaternary interglacial age which is widespread in this region. The main peak of the ground magnetic anomaly lies about 0.5 km inside the easternmost part of the caldera fault (Figure 1, inset).

Pálmason (1971) found by refraction seismic measurements that „Layer 3“ (with a p-wave velocity of 6.5 kms^{-1}) of the crust reaches up to 0.5 km depth under the Stardalur area. According to his results, the upper surface of this layer (presumed to be an intrusive complex of gabbroic cumulates) usually lay at 2.5–4 km depth outside the volcanic zones of Iceland.

An extensive project of sampling lava flows for stratigraphic mapping and paleomagnetic studies in mountains northwest and north of the Stardalur caldera was initiated in 1973 (Kristjánsson *et al.*, 1980). Most of these lava flows had reverse magnetic polarity. A K-Ar age determination on a normally magnetized rhyolitic hyaloclastite belonging to the latest phase of the volcanism yielded an age of about 1.9 m.y. (when recomputed with current decay constants). It may therefore be expected that the thick mostly reversely magnetic lava sequence found in the above sampling project belongs to the lower part of the Matuyama geomagnetic chron. Also, rocks of Matuyama age probably cause the wide negative anomaly lineation through Stardalur. If the localized magnetic anomaly there is due to rocks of comparable age as the acidic hyaloclastite, these rocks might accordingly date from the Reunion or Olduvai subchrons at 2.1 and 1.9–1.8 m.y. respectively. They may also be of the same age as the thin N3 polarity zone of lava flows originally mapped by T. Einarsson and Þ. Sigurgeirsson in the 1950s (see Goguitchaichvili *et al.*, 1999).

DRILLING AT STARDALUR, AND STUDIES ON THE DRILL CORE IN 1969–1973

Drill holes and sampling of nearby outcrops

The enigmatic nature of the Stardalur magnetic anomaly contributed to a decision to drill three holes within the Stardalur caldera in 1969–1970, by the National Energy Authority of Iceland. Hole 1 was located at the main peak of the magnetic anomaly. Below fresh olivine tholeiite lavas (of the Reykjavik gray lava sequence) and tuff-breccia, the drill entered altered but strongly magnetic olivine tholeiite lava flows at 41 m depth (Friðleifsson and Tómasson, 1972). A continuous 6 cm diameter core was recovered down to 143 m, and cuttings to 200 m. According to drill logs and inspection of the core, there were some 20 lavas present in the 41–200 m interval, without significant interbeds. Drill hole 2 inside the caldera about 2 km to the west of the first hole encountered mostly tuffs and minor intrusives to 240 m depth. Hole 3 another 2 km to the west passed through 90 m of lavas and intrusives which to our knowledge did not have unusual magnetic properties.

Various surface outcrops (dikes, cone sheets, pillows, gabbros etc.) were sampled in the early 1970s around Stardalur and in other volcanic centers in search of strongly magnetized materials. Basaltic andesites and dikes yielded rather high magnetization values (Table 1 of Friðleifsson and Kristjánsson, 1972), but not sufficiently high to explain the local anomaly peak. Andesites later sampled elsewhere have also given some high values (Kristjánsson *et al.*, 1977) but dikes in general seem not to be very different from lava flows in this respect (Kristjánsson, 1970 and other data).

Initial studies on petrology and magnetization

Steinþórsson and Sigvaldason (1971) reported on the content of iron and some trace elements in 17 samples from the first Stardalur core. The iron averaged 11% by weight (15.6% Fe_2O_3) which is rather high for basalts but not exceptional; extrusives in central-volcano calderas tend to be more iron-rich than others (K. Grönvold, *pers. comm.*, 2013). An unusually high percentage of this iron appeared to reside in opaque grains which included crystals of exsolved titanomagnetite (50–100 μm), slender ilmenite crystals of up to 25 μm length, small clustered euhedral crystals of magnetite, 3–4 μm, and rare pyrite. Steinþórsson and Sigvaldason (1971, p. 9) concluded that iron in the magma crystallized in titanomagnetite (at the expense of FeMg-silicates) because of high oxygen fugacity. The lavas had suffered zeolitization and also contained mixed-layer clay minerals, but epidote was not found.

Búason (1971) obtained 102 core specimens of 3.0–3.1 cm diameter and 3.2–3.4 cm length from the 6-cm core for magnetic studies. Some additional magnetic measurements on selected pieces of the 6-cm core were made by Friðleifsson and Kristjánsson (1972), see below. The lavas appeared at first sight to be fairly solid, but their average density was only around 2500 kg m^{-3} due to small-scale porosity. Using an astatic magnetometer, Búason found an average NRM intensity M_r of 61 Am^{-1}; this property varied rather erratically with depth (upper dots of Figure 2) and did not show any correlation with the iron content of the lavas, or with their boundaries. We have checked Búason's intensity measurements with a MEDA fluxgate magnetometer, and they are very sat-

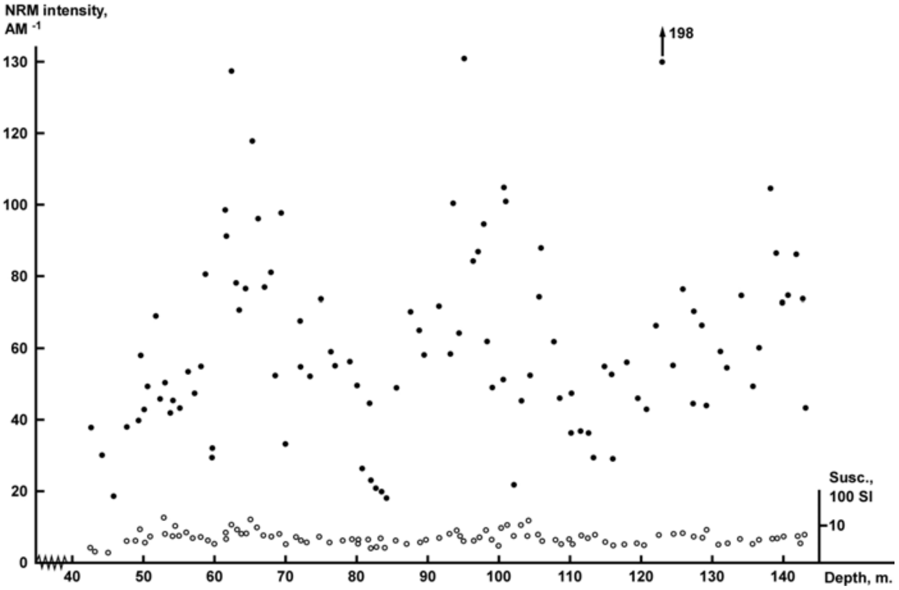

Figure 2. Natural remanence intensities (upper dots) and volume susceptibilities for samples from 41–143 m depth in Stardalur drill hole 1. – *Styrkur varanlegrar segulmögnunar (efri punktar) og segulhrifastuðull (segulviðtak) fyrir sýni af óvenju sterkt segulmögnuðu bergi úr kjarnaholu við Stardalsbæinn.*

isfactory within error margins of a few percent. Búason also noted that the mean inclination of the remanence was +81° with a standard deviation of only 4°. The mean inclination in 827 Quaternary lavas >1 m.y. old in Iceland (L. Kristjánsson, unpublished data) is 71° with a standard deviation of 10°; current secular-variation changes in the field direction are of the order of 4° per century. We have later ascertained that very little viscous or other secondary components are present in the remanence (see below). Neither is there any pronounced anisotropy of the magnetic susceptibility χ in the core material (within 1%, in 9 specimens measured) which might have explained the uniform remanence inclination. Assuming that the remanence is of primary origin, it is therefore possible that all the lavas in the 41–143 m depth interval were emplaced as part of caldera-filling material within a period which was short relative to geomagnetic secular variation time scales, say less than a millennium. It may be mentioned that very uniform remanence directions have been found in sequences of comparable volume, for instance in lava units at different levels within the large Quaternary tablemountain Hlöðufell in Southern Iceland (L. Kristjánsson, unpublished data).

Búason (1971) also measured the susceptibility of powdered samples from 41–200 m depth. He found that material in drill cuttings from below 143 m depth was similar to the core samples in this respect, and he obtained an overall solid-rock average χ of 0.07 SI volume units from his total of 34 samples.

Rock-magnetic studies on samples from the drilling

Friðleifsson and Kristjánsson (1972) obtained strong-field thermomagnetic curves in air on five samples from the Stardalur core and two from cuttings below 143 m. Curie points were in the range 560–620°C, with considerable drop in room-temperature saturation magnetization being caused by the heating. This points to the presence of fairly pure but cation-deficient magnetite (Fe_3O_4), becoming oxidized towards maghemite (γ-Fe_2O_3) and then converting to hematite (α-Fe_2O_3) which is much less magnetic than magnetite or maghemite. Similar behavior on heating is fairly often observed in samples from Icelandic lavas, especially if they have suffered some in-situ oxidation or zeolite facies alteration (e.g. Kristjánsson, 1972 and unpublished data; Goguitchaichvili *et al.*, 1999).

It is known that the effective size of magnetite grains greatly influences their magnetic behavior (see Dunlop, 2002; Tauxe, 2010). Thus, in very small grains (<1 μm) all the molecular dipole moments tend to be aligned even in the absence of any external magnetic field. If these small grains (called single-domain grains) are non-spherical in shape, it can be quite difficult to change their remanent magnetization by external magnetic fields, i.e., they have high magnetic coercivity. Larger grains are composed of regions having different magnetization directions. Such multi-domain grains have low coercivity because the domain boundaries will migrate under the influence of moderate magnetic fields. One possible explanation for the high intensity of natural remanence in the core was considered to be the presence of single-domain magnetite. This was tested by alternating field (AF) demagnetization of the natural remanence in five samples from the Stardalur core (Fig. 4 of Friðleifsson and Kristjánsson, 1972). Four demagnetization curves had shapes which are fairly typical for Icelandic Tertiary basalt lavas, with median destructive fields (MDFs, where half of the original remanence has been removed) around 20 mT. Single-domain magnetite (especially in elongated grains) may be expected to have higher values of this parameter which is closely related to their coercivity. One of the five core pieces which was unusually fine-grained and highly oxidized, indeed had an MDF exceeding 60 mT. All five samples exhibited very stable directions of remanence, varying by only 1–2° on AF demagnetization to 25 mT peak field. This indicated that almost no viscous remanence is present, a result confirmed by a six-month storage experiment. Other soft (i.e. of very low coercivity) secondary components such as might be caused by drilling equipment, were also not in evidence.

The presence in a rock of a major magnetization component due to single-domain grains can also be to some extent inferred from the ratio M_r/M_i between the magnitudes of its remanent and induced magnetization vectors. This so-called Königsberger ratio in the Stardalur core, computed for the average properties given above in μT field, is about 23 as compared to 4 in typical Tertiary lavas in Iceland. This may indicate a significant contribution to the remanence from single-domain material. However, when pieces of the four low-MDF samples were heated to 610°C in air and cooled in a field of 50 μT, the Königsberger ratios of their new artificial remanence averaged 14, which is in the lower part of a range obtained for other similarly reheated rock material from Iceland (Table 3 of Friðleifsson and Kristjánsson, 1972; Fig. 4 of Kristjánsson, 1972).

Past intensity of the geomagnetic field

The advanced alteration state of the Stardalur lavas as well as the chemical changes taking place in their magnetic minerals upon laboratory heating have so far precluded any detailed experiments to find the paleo-intensity of the local geomagnetic field during emplacement of the lava pile drilled through. Judging from worldwide research results (Tauxe, 2010, Fig. 14.15; Goguitchaichvili *et al.*, 1999), it is possible that this intensity could occasionally have been at least 50% higher than the intensity of the present field in Iceland. The present field in turn appears to be roughly similar to that of the long-term average field during times when the geomagnetic dynamo is in a stable state. It should also be kept in mind that during buildup of that pile, the ambient field seen by each new lava was considerably strengthened by fields caused by the underlying lavas. Such locally strong fields could be a partial explanation of the high Königsberger ratios of the NRM.

DEVELOPMENTS TO 1990

Little research directly relevant to the Stardalur magnetic anomaly was carried out between 1973 and 1990. In that period however, magnetic surveys of all of Iceland and parts of the surrounding shelf were completed by Þ. Sigurgeirsson and others (see Kristjánsson *et al.*, 1989; Jónsson *et al.*, 1991). Several localized anomalies were found, some of which lie within the Quaternary areas (perhaps mostly connected with occurrences of pillow lavas and other such rapidly cooled material). Anomalies also commonly occur at active or extinct volcanic complexes on shore, as well as off central western and eastern Iceland. These two categories of magnetic anomalies contain a few examples which are comparable to the Stardalur anomaly in both size and amplitude. In Figure 1, the locations of three prominent magnetic anomalies of the latter type onshore in western Iceland (Sigurgeirsson, 1979) are shown. A broad negative anomaly occurs over the central volcano mt. Hafnarfjall (Ha). A positive anomaly occurs at Hvanneyri (Hv, see below) south of the Hvítá river, accompanied by a small negative anomaly to the north across that river. A positive and a negative anomaly are also found over a caldera in high terrain at Breiðakinnarsandur (B) within the Reykjadalur central volcano (Jóhannesson, 1975; Jóhannesson and Sæmundsson, 2009).

No gravity data have been published from southwestern Iceland in recent decades, only a Bouguer gravity map of Iceland in scale 1:1,000,000 (Þorbergsson *et al.*, 1990). This map is based on low-pass filtered data, so that it does not show details of 5 km size or less. A gravity data base of Iceland at the National Energy Authority only has two points in the general vicinity of Stardalur (Þ. Högnadóttir, *pers. comm.*, 2012). To our knowledge, no attempt has been made at a joint interpretation of the available geological and geophysical results in the Stardalur area in terms of a crustal structure.

The general conclusions from the Stardalur investigations and other knowledge up to 1990, indicated that the causes of the very large amplitude of the main magnetic anomaly peak did not involve any single unique phenomenon. Rather, the anomaly might be due to a chance combination of somewhat unusual circumstances:

a) Rapid buildup of a pile (200×600 m in extent, at least 160 m high) of lavas of a uniform kind, having relatively high iron content

b) This iron residing in magnetite to a greater extent than is common in basalt lavas

c) The magnetite being pure (i.e. titanium-free) or nearly so, both in small grains and where slightly

cation-deficient magnetite had exsolved from larger grains of titanomagnetite during cooling
d) The ambient geomagnetic field being strong during this eruption episode.

RESEARCH IN 1990–2008

Helgason *et al.* (1990) and Steinþórsson *et al.* (1992) presented results of Mössbauer spectroscopy on respectively 8 and 20 samples from 15–175 m depth in the Stardalur drill hole as well as on 10 samples of typical Icelandic basalts, mostly from outside the Late Quaternary areas. Their observations confirmed that the strongly magnetized lava sequence in Stardalur contains exsolved magnetite in a very pure state. Helgason *et al.* (1990) state that practically no maghemite is present in their Stardalur core samples, while Steinþórsson *et al.* (1992) found that most of those lava samples from elsewhere in Iceland which they studied, contain a good deal of maghemite. The latter concluded that the maghemite is formed from magnetite by secondary hydrothermal alteration. In both papers the exsolution of pure magnetite in Stardalur is also ascribed to such alteration, but no explanation is offered for the absence of maghemite there. Helgason *et al.* (1990) further suggest that the strong remanence has resulted from the alteration. However, we find it difficult to visualize how secondary processes could produce the uniform steep remanence inclinations observed by Búason (1971).

Later in the 1990s, magnetic field measurements by satellites orbiting Mars revealed the presence of strongly magnetic near-surface materials (Acuña *et al.*, 1999); a minimum value of M_t~50 Am^{-1} was inferred. This, as well as reports from Mars landers on magnetic properties of exposed formations in 2004, created new interest in the magnetism and petrology of the Stardalur core. Gunnlaugsson *et al.* (2004, 2006) concluded that a part of the magnetite in the core (presumably the small cubic grains of Steinþórsson and Sigvaldason (1971)) is very pure and did exsolve from olivine at high temperature during cooling. A similar conclusion was reached on the origin of unusually high NRM intensity (~40 Am^{-1}) in an olivine tholeiite lava flow MM 2 from Eastern Iceland (Kristjánsson and Guðmundsson, 2005). Observations by Gunnlaugsson *et al.* (2006, 2008) on magnetic separates indicated that the natural remanent magnetization in small magnetite grains from olivine might be several times higher per weight unit than in an equal amount of magnetite in typical Icelandic lavas.

Vahle *et al.* (2007) measured various magnetic properties of nine samples from the strongly magnetized part of the original Stardalur core, and made a detailed study of the mineralogy of two of these (at 101.0 and 135.15 m depth) by electron microscopy (their Figs. 4 and 5) and other techniques. Vahle *et al.* concurred with the suggestion of Gunnlaugsson *et al.* (2004) that the small magnetite grains may have been generated from olivine by exsolution. They also demonstrated that a minor proportion of the magnetite in the larger grains had been oxidized towards maghemite composition in situ, as evidenced by shrinkage cracks in some of these. In thermomagnetic curves obtained in air, the magnetization of samples decayed progressively with time spent at high temperature, while curves obtained in an argon atmosphere were approximately reversible. These authors concluded from their various observations that the maghemite and some of the magnetite may have formed during secondary hydrothermal alteration at 250–350°C. However, evidence from a 1920 m long core recovered from the lava pile of Eastern Iceland (Bleil *et al.*, 1982) indicates that secondary formation of magnetite accompanies the appearance of epidote at 250°C or more (see Pálmason, 2005, p. 72). In the Stardalur core, mixed-layer clays and chlorite which presumably form at 200–250°C are seen (Steinþórsson and Sigvaldason, 1971; Vahle *et al.*, 2007, p. 123) but no epidote. Hall (1985) states that the formation of secondary magnetite occurs in the vicinity of dikes at burial depths exceeding 2100 m and becomes relatively important below 2900 m. The lava pile above Stardalur is not expected to have reached such thickness (Friðleifsson, 1985).

A comprehensive total-field magnetic survey of the Reykjavík area and offshore at 500 m altitude a.s.l. (Jónsson and Kristjánsson, 2002) confirmed that a localized negative central-volcano anomaly east of the city noted by Sigurgeirsson (1970a) extends up to the tip of the Kjalarnes promontory (Figure 1). Gunnlaugsson *et al.* (2008) obtained Mössbauer spectra on strongly magnetized intrusive rocks from the Kjalarnes coast, suggesting that their remanence resides in titanomaghemite.

Pálmason's (1971) results on the upwarping of his crustal Layer 3 at Stardalur were confirmed by Bjarnason *et al.* (1993). They found that the depth to the lower crust (defined by a sharp change in the p-wave velocity gradient at about 6.5 km/s) was 2.5 km at Stardalur. A similar upwarping of the lower crustal layers from its mean depth of 4.5 km has been noted beneath both active and extinct volcanic complexes in Iceland (Flóvenz and Gunnarsson, 1991; Brandsdóttir and Menke, 2008).

RESEARCH ON THE STARDALUR CORE IN 2008–2010

We have carried out measurements of magnetic susceptibility in those 95 of Þ. Búason's (1971) 102 3-cm core specimens which are still preserved at the University of Iceland, using a Bartington MS2 audio-frequency susceptibility bridge (lower graph of Figure 2). The average value of susceptibility χ in these (including data for two of the lost specimens) is 0.067 SI units, similar to that found by Búason (1971). A lower average evident in Fig. 2 of Vahle *et al.* (2007) appears to be due to a calibration error. Within- and between-lava variations in susceptibility in the core are less pronounced than those in remanence intensity (Figure 2), as is generally the case with lava flows (e.g. Table 1a of Bleil *et al.*, 1982). There is a slight positive correlation ($R^2 = 0.31$) between the susceptibility and the NRM intensity, assuming direct proportionality. A positive correlation is in agreement with the observation of Steinþórsson and Sigvaldason (1971) who noted that the oxidation state of the titanomagnetite was always high: large variations in oxidation would tend to cause a negative correlation between these parameters (Wilson *et al.*, 1968). Vahle *et al.* (2007) who fitted the susceptibility and intensity data from 20 samples (including some at less than 41 m depth) with a power law, had found a higher correlation coefficient. Roughly, the susceptibility of a basalt sample is proportional to its magnetite content, with 1 vol. % magnetite causing a χ of 0.027 SI units. If allowance is made for the variable purity of magnetite in Icelandic Tertiary basalts, it may be estimated that they contain on average about 1% of magnetite by volume, and the Stardalur lavas 2.5%.

The question of the presence of single-domain magnetite in the Stardalur core has already been considered above. A common procedure for evaluating the overall domain state of a magnetic sample is to take it through a hysteresis loop to its saturation magnetization. The ratio of saturation remanence to saturation magnetization (M_{rs}/M_s) obtained from such a loop may be plotted against the ratio between two coercive forces (H_{cr}/H_c), i.e. the external fields required to null the remanence and the total magnetization respectively. A relatively high value (0.5–1) of the former ratio in a sample combined with a low value (which usually means less than 1.5 or 2) of the latter is considered to indicate the presence of single-domain magnetite. Several published studies on Icelandic basalt lavas, connected with attempts at deducing paleo-field intensities (e.g. Fig. 3a of Brown *et al.*, 2006), have shown that their M_{rs}/M_s vs. H_{cr}/H_c values mostly fall in an intermediate category on these so-called Day plots. The intermediate behavior may be due to all the magnetic grains being composed of a small number of magnetic domains each (termed pseudo-single-domain grains), and/or to the sample consisting of a mixture of single-domain and multi-domain grains. Such plots therefore provide only a rather qualitative criterion for the effective grain size, and opinions on their detailed interpretation have varied considerably (Dunlop, 2002).

Day-plot data reported by Kristjánsson *et al.* (2010; S. A. McEnroe, *pers. comm.*, 2010) on 12 samples from the original Stardalur core showed that they had M_{rs}/M_s values well below 0.5, like Icelandic lavas in general. Further work on these aspects is in progress. Alternating field demagnetization of NRM was carried out on small arbitrarily oriented pieces from seven strongly magnetized samples (depths: 47.6, 59.8, 84.3, 87.7, 96.6, 101.0 and 139.7 m), using a Molspin two-axis tumbler demagnetizer. As had been found for four samples in 1970 and the majority of Vahle *et al.*'s (2007) nine samples, the median destructive fields (MDFs) of their remanence were in the range 17–23 mT.

Gradual systematic changes in remanence directions during the AF demagnetization were noted in some cases. The cumulative amount of these changes was of the order of 3° of arc or less after 60 mT treatment (when 1–9% of the NRM intensity was left). Such changes might be due to a small amount of their magnetization being a secondary high-coercivity CRM in the magnetite that is derived from olivine. Alternatively, this could reflect a gradually changing direction of the ambient field during original cooling of the lavas through the temperature interval in which their main remanence component became fixed.

On storage of the seven samples in the Earth's field for over two years, the intensity of the VRM acquired amounted to only about 0.1% or less of their original NRM intensity. Subsequently, these seven samples were demagnetized at 90 mT and then given an anhysteretic remanence (ARM) by subjecting them simultaneously to a steady 50 μT magnetic field and a parallel sinusoidally alternating field of amplitude 90 mT for five seconds. The steady field was supplied by an attachment furnished with the Molspin demagnetizer. The characteristics of ARM have generally (Soffel, 1991) been found to be analogous to those of TRM. In each of the seven samples the MDF of the ARM was a little lower than the MDF of its NRM: averages were 18 and 20 mT. With stronger alternating fields (not attainable in our equipment) these averages would have been even more similar, which supports the idea that the NRM in the Stardalur core is TRM. The intensity of the ARM in the seven samples was only a fraction (7–22%) of their NRM intensity, but comparison studies on other Icelandic basalts would be required for an interpretation of that observation.

NEW GROUND SURVEY AT STARDALUR IN 2011

A ground magnetic survey of the main peak of the Stardalur anomaly was carried out on five magnetically quiet days in 2011. The number of points measured was 432, using Barringer GM-122 and Geometrics G-856 proton free-precession magnetometers. The probe height was 2 m above ground. Positions were obtained from a hand-held Garmin Etrex GPS instrument to about 4 m relative accuracy. The survey was intended to delineate approximately the shape of the main peak of the anomaly within the 58 μT contour, and to improve estimates of the highest fields attained. Results are shown in Figure 3, after some smoothing (F. Pálsson, *pers. comm.*, 2011) to attenuate small-scale features clearly caused by the landscape and rocks in the top few meters of the ground. Maximum field values observed were in the range 81.2–81.4 μT. We have not managed to locate the drill hole 1 from 1969–1970.

The anomaly peak strikes 20–25° east of north. This is not very different from the strike of the fissure swarm transecting the Stardalur volcanic center which is 30–35° east. The similarity in trends indicates that the source rocks of the Stardalur anomaly peak were generated in eruptions on a short fissure. The broad aeromagnetic lineations in southwestern Iceland which are probably due to Brunhes, Matuyama and Gauss age formations (Jónsson *et al.*, 1991) reach greater deviations from north. This could be due to lateral offsets between neighboring fissure swarms, as is evident in the Reykjanes peninsula (Sigurgeirsson, 1970a; Kristjánsson *et al.*, 1989).

The anomaly peak was simulated with a simple model of its source (Figure 4). With the following constraints (which are not very realistic), a tolerable fit to the smoothed contour map of Figure 3 was obtained:

– The source is assumed to be composed of three flat-topped vertical columns in partial contact. Each has a square cross section, and a total magnetization intensity M_t of 64 Am^{-1} in a vertical direction. The columns reach great depth.
– That part of the observed field in Figure 3 which is due to sources other than the above columns, is assumed to have a constant strength F of 57.6 μT, an inclination of +75° and a declination of 0°.
– Increasing altitude of the ground towards the east by up to 30 m east of the road to the farm was allowed for. Otherwise the altitude of the probe above sea level was assumed constant at 190 m, and minor

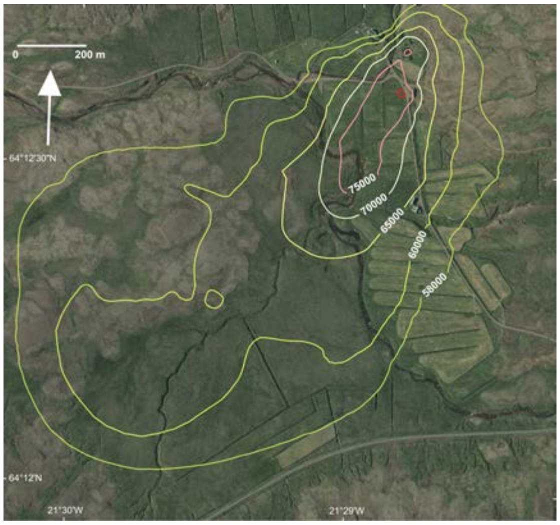

Figure 3. Aerial photo of fields of the Stardalur farm. The main farm buildings are in the north-east part of the photo. Access to the farm is from the Reykjavík – Þingvellir highway #36, seen near the south edge of the figure. Smoothed total-field contours in nT (1000 nT = 1 μT) are included, based on ground measurements at the points shown in Figure 4. – *Loftmynd af Stardal, bæjarhús eru norðaustantil. Afleggjari kemur að bænum frá veginum yfir Mosfellsheiði, sem sést neðst. Jafnstyrkslínur fyrir nokkur gildi heildarsviðsins í 2 m hæð frá jörð hafa verið teiknaðar inn á myndina, eftir minniháttar útjöfnun mæligilda.*

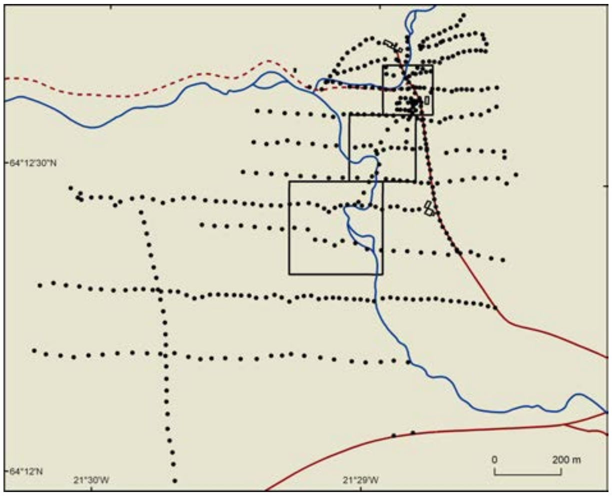

Figure 4. Sketch of some of the roads and tracks (red), streams (blue) and farm buildings in Figure 3, along with points where total-field measurements were made. The three squares show the dimensions of vertical uniformily magnetized columns used for simulating the anomaly peak; see text. However, it is more likely that the actual body causing the anomaly has a smoothly sloping surface. – *Skissa af vegum, slóðum, ám og byggingum á 3. mynd, ásamt mælipunktum fyrir sviðsstyrk í megin-toppi segulfráviksins. Þverskurðarfletir lóðréttra bergsúlna sem notaðar voru sem einfalt líkan til að reikna nálgun fyrir frávikið, eru sýndir. Sjá nánar í megintexta.*

topographic features in the fields of the farm were not taken into account.
– The northernmost square column has its upper surface at a depth of 35 m from the probe, the central one at 90 m and the southern one at 150 m.

Gravity was measured at seven points along the road towards the main Stardalur farm buildings (Figure 3), and at two points on the track towards west from these buildings. A smooth regional trend is seen, except for a point situated on the 65 μT contour 500 m south of the main buildings where a positive anomaly reaching 1–2 mgal above the trend occurred. It has no clear relation to the magnetic anomaly. It could be due to a small intrusive body of appreciably higher density than the 2500 kg m^{-3} found for the magnetic lava series.

GROUND SURVEY AT HVANNEYRI IN 2012

Þ. Sigurgeirsson made separate surveys at low altitude, probably 300 m, over the magnetic anomaly sites at Ferstikla in southwestern Iceland and at Hvanneyri in western Iceland (Figure 1). Records from the former survey seem to have been lost, but a contour map based on Sigurgeirsson's three flight lines at Hvanneyri was published by Kristjánsson *et al.* (1989). The contours of this map (Figure 5a) trend 30–40° east. The peak within the 56 μT contour in the aeromagnetic results occurs over flat meadowland which lies a few m above sea level. To the east and southeast of these meadows, the ground slopes up to about 20 m a.s.l. We have made total-field mea-

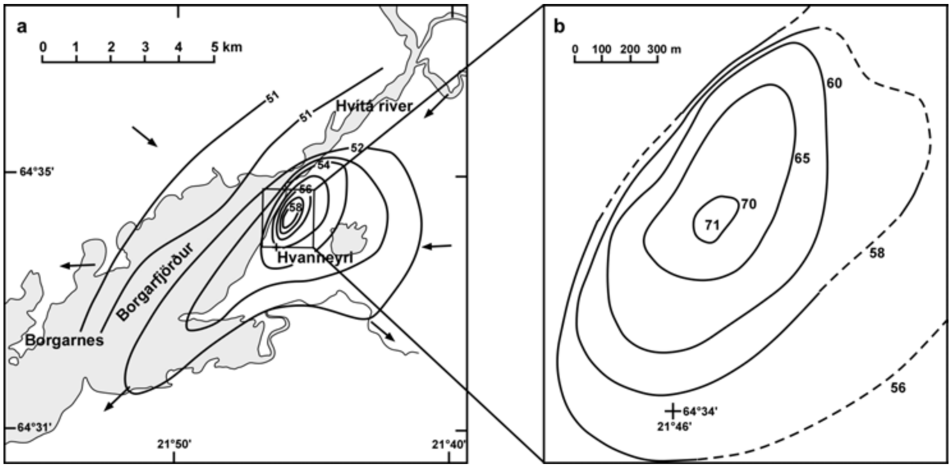

Figure 5. a) Contours (in μT) of a positive total-field aeromagnetic anomaly near the Agricultural University at Hvanneyri on the southeastern shore of the Borgarfjörður fjord. It was surveyed in 1970 by Þ. Sigurgeirsson (Kristjánsson *et al.*, 1989) on three flight lines indicated by arrows. The small box encloses the area of Figure 5b. b) Total-field intensity contours drawn from a ground magnetic survey on meadows northwest of the University buildings in 2012. – *a) Jafnstyrkslínur fyrir jákvætt segulfrávik innst á suðurströnd Borgarfjarðar. Mælingar voru gerðar úr flugvél af Þorbirni Sigurgeirssyni 1970, á þrem línum sem sýndar eru með örvum. Litli kassinn sýnir staðsetningu Myndar 5b. b) Jafnstyrkslínur fyrir segulsviðsmælingar í 2 m hæð yfir jörð, gerðar 2012 á engjum við fjörðinn. Háskólabyggðin á Hvanneyri stendur um 20 m ofar, nálægt suðausturhorni kortsins.*

surements in 552 points on the flat lower ground in this area, using the same instruments as in the recent Stardalur ground survey. A contour map of the major peak at ground level (Figure 5b) shows considerable similarity with the Stardalur ground anomaly. The field intensity F reaches up to 18.6 μT above the current IGRF value (52.45 μT), as compared to the 29 μT maximum deviation at Stardalur. This anomaly is very steep on its northwest side, suggesting that here the source rocks reach within tens of m of the surface. The results fully confirm the inference from the airborne survey regarding the trend of the anomaly contours, which is 30–40° east in Fig. 5b as in Figure 5a. A broad anomaly peak to the northeast (with fields up to about 63 μT) has not been surveyed in detail and is not shown. It makes the axis of the 56 μT contour about 3 km long. Many hillocks with lava outcrops lie north and northeast of the map of Figure 5b; four normally magnetized samples taken from two of these about 100 m north of the map however had a mean remanence intensity of 4 Am^{-1}, which is equal to the mean for Tertiary Icelandic lavas.

The tectonic map of Iceland by Jóhannesson and Sæmundsson (2009) shows two calderas at the Hafnarfjall central volcano (Figure 1), one of which is only partly exposed. Sigurgeirsson's magnetic anomaly at Hvanneyri appears to lie outside the Hafnarfjall volcano.

DISCUSSION AND CONCLUSIONS

The discovery of the Stardalur magnetic anomaly in 1968 occurred at the beginning of considerable growth of research activity in the geosciences in Iceland. Among tasks undertaken through the 1970s was the stratigraphic, structural and geochemical mapping of several volcanic centers (e.g. Friðleifsson, 1973; Jóhannesson, 1975). Observations at extinct centers demonstrated various common traits in these, including in particular the presence of magnetic anomalies

(Sigurgeirsson, 1970b,c, 1979) which in turn aided in identifying hidden remains of other such centers (Kristjánsson *et al.*, 1977; Kristjánsson, 1987). In the case of the Stardalur anomaly, much progress was made in 1968–1973 by locating its main peak, drilling to obtain samples from what appears to be the main source body of this peak, and studying their properties. However, the momentum in mapping of both the volcanic centers in Iceland and the lava pile outside the currently active volcanic zones has diminished somewhat since 1980. Therefore, our understanding of the geophysical anomalies accompanying the centers is still very uncertain. Thus, the Reykjavík (Jónsson and Kristjánsson, 2002) and Stardalur anomalies are almost the only ones where detailed magnetic surveys have been carried out in the last three decades. Indeed the general problem of the origin of anomaly lineations in Iceland has not been solved: for instance, it is not known whether the positive anomalies which coincide with fissure swarms on the Reykjanes peninsula (Kristjánsson, 1970, 1972) are due to primary or secondary remanence or even to induced magnetization, in buried extrusives and/or intrusives.

As stated above, our general conclusion is that the Stardalur magnetic anomaly peak is due a sequence of lava flows which were erupted in rapid succession within a caldera. These along with much of the other caldera-filling material were emplaced in a short period (subchron) of normal geomagnetic polarity within a long reverse-polarity chron, presumably the Matuyama. The lavas had high concentrations of unusually pure magnetite which appears in part to be produced from titanomagnetite by solvus exsolution, in part to consist of a fine-grained type derived from olivine by high-temperature oxy-exsolution. The magnetic phases do not give rise to single-domain magnetic properties in the bulk rock, as would be observed in for instance the shape of strong-field hysteresis curves (Day plots) or high median destructive fields of the natural remanence. However, the properties of the core samples are also not entirely characteristic for multi-domain magnetite, cf. the total absence of viscous magnetization.

It is clear that unusual coinciding factors caused the lavas at Stardalur to have a mean remanent magnetization intensity of around 15 times that for Tertiary lavas in Iceland. Some authors (e.g. Helgason *et al.*, 1990; Vahle *et al.*, 2007) consider this strong remanence to have been caused by secondary hydrothermal alteration, but the question of what processes could have brought such alteration about in Stardalur and not in general elsewhere, remains open. Judging from the stability and uniformity of the remanence directions in the drill core, it seems more plausible that the remanence is largely primary, dating from a period of rapid filling of the caldera by extrusives. However, in that case it needs to be explained how the lavas retained their strong remanence intensity through the hydrothermal alteration which they have clearly suffered.

The presence of a relatively intense ambient geomagnetic field would have aided in the acquisition of the strong remanent magnetization, regardless of whether this remanence was of primary or secondary origin. Unfortunately, currently available methods are unlikely to be successful in determining the paleofield intensity. So far, not much has been found out about the origin and the shaping of the source structure, or why its lavas originally acquired their peculiar chemical and petrographic properties.

It is clear that much additional geophysical and geological work needs to be done at the central-volcano complexes of Iceland. This need is exemplified by the magnetic anomaly at Hvanneyri (Sigurgeirsson, 1979; Figure 5a,b) whose main peak has interesting similarities with the Stardalur anomaly. The source of the Hvanneyri anomaly may lie in formations related to the Hafnarfjall volcano and its associated gravity anomaly; alternatively, it seems possible that these belong to a separate volcanic center extending across the innermost part of Borgarfjörður. The relation of these formations to the major unconformity in the Borgarfjörður area (see Jóhannesson and Sæmundsson, 2009) is also uncertain.

Acknowledgements

Þorbjörg Ágústsdóttir carried out the gravity measurements at Stardalur. Finnur Pálsson processed the magnetic field data and drafted Figure 3, Rósa Ólafsdóttir drafted the other figures. The author acknowledges constructive reviews of the original manuscript by Kristján Sæmundsson and Sigurður Steinþórsson as well as useful discussions through the years with them, the late Þorbjörn Sigurgeirsson, Haraldur Páll Gunnlaugsson, Suzanne McEnroe and others.

ÁGRIP

Snemma í sögu ýmiskonar svæðisbundinna jarðeðlisfræðirannsókna á Íslandi komu víða fram áhugaverð fráviksgildi í mæliniðurstöðum, sem tengja mátti við óreglur í byggingu jarðskorpunnar. Þannig fannst í námunda við bæinn Stardal í Mosfellsbæ óvenju sterkt þyngdarsvið í mælingum Trausta Einarssonar sem birtust 1954, óvenju sterkt jarðsegulsvið í mælingum sem Þorbjörn Sigurgeirsson framkvæmdi úr flugvél 1968 og birtust á korti 1970, og óvenjuleg lagskipting jarðskorpunnar í hljóðsveiflumælingum Guðmundar Pálmasonar sem birtust 1971. Af þessum rannsóknum vöktu segulsviðsmælingarnar einna mesta athygli, því að fráviksgildi í þeim við Stardal var að hámarki um 4,5 μT meðan slík frávik voru oftast milli 0,5 og 2 μT annarsstaðar. Þessi uppgötvun leiddi brátt til frekari segulmælinga, bæði í lítilli hæð úr flugvél og á jörðu niðri. Segulfrávikið náði yfir svæði um 7 km í þvermál, og á því voru nokkrir misháir toppar. Orkustofnun stóð fyrir borunum þarna, og var ein staðsett við langhæsta topp segulfráviksins. Þar var tekinn 6-cm kjarni niður á 143 m dýpi og síðan svarf að 200 m. Frá 41 m dýpi fór borunin í gegnum stafla af talsvert ummynduðum ólívín-þóleiít hraunlögum. Margháttaðar athuganir voru gerðar á sýnum úr borkjarnanum á næstu árum. Meðal-styrkur varanlegrar segulmögnunar í því bergi var um 15-falt meðaltalsgildi úr íslenskum hraunlögum frá síðtertier tíma. Útreikningar til samanburðar við ofannefndan segulsviðstopp bentu til þess að hraunlögin mynduðu hæð (grafna í yngri myndanir, efst þeirra er Reykjavíkurgrágrýti) að stærð um 200×600 m sem stefndi NA-NNA. Jafnframt voru gerðar ýmsar jarðfræðirannsóknir sem m.a. leiddu í ljós að berggrunnur svæðisins milli Hvalfjarðar og Stardals hafði myndast fyrir um 2 milljónum ára á Matuyama-segulskeiði, þegar jarðsegulsviðið sneri oftast nær öfugt við stefnu þess í dag. Uppspretta hins breiða segulfráviks við Stardal er greinilega tengd öskjusigi um 6,5 km í þvermál. Þar hefur þá orðið eldvirkni og ummyndun á stuttu tímabili þegar sviðið sneri eins og nú. Hugsanlega er tímabilið það sama og Trausti Einarsson og Þorbjörn Sigurgeirsson kenndu á sjötta áratug síðustu aldar við hraunasyrpuna N3 í fjöllum sunnan Hvalfjarðar. Aðal-segulsteindin í borkjarnanum er seguljárn (magnetít), óvenju títan-snautt en að einhverju leyti oxað í átt að maghemíti. Hluti þess er myndaður eins og algengt er, við útfellingu (solvus exsolution) innan korna úr títanómagnetíti. Annar hluti er í litlum kornum sem virðast hafa orðið til við útfellingu (oxy-exsolution) úr ólivínkristöllum. Ekki er full-ljóst að hve miklu leyti þetta hefur gerst við upphaflega kólnun bergsins og að hve miklu leyti við þá síðari ummyndun sem það hefur greinilega orðið fyrir. Líklegra virðist að segulmögnunin sé upprunaleg fremur en að hún orsakist af ummynduninni. Riðstraumsafsegulmögnun og mælingar á segulheldni (hysteresis) bergsýnanna benda til þess að magnetítkorn bergsins séu yfirleitt ekki nógu lítil til að hafa svokallaða einsvæða (single domain) eiginleika, sem hefðu einir og sér getað skýrt hina sterku segulmögnun bergsins. Skýringa á henni verður því að leita að hluta í samspili hins háa innihalds þess af magnetíti (sem er um 2,5-falt meðalgildi í tertíer-hraunum hér), hreinleika þess, og hugsanlega óvenju mikils styrks jarðsegulsviðsins þegar hraunin runnu. Enn er þá eftir að finna út, hversvegna svona miklu af magnetítríku ólivín-þóleiíti gaus þarna á þessum tíma. Kynntar eru niðurstöður nýrra mælinga á styrk segulsviðsins í hæsta frávikstoppnum í Stardal með nákvæmari staðsetningum en áður, og sýnt einfalt líkan af uppsprettu þessa topps. Einnig eru birt kort af segulfráviki við Hvanneyri í Borgarfirði, sem svipar talsvert til Stardals-fráviksins þótt sviðstyrkur þess niðri við jörð nái ekki eins háum gildum.

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