Reviewed research article

Paleomagnetic observations at three locations in the Pleistocene lava sequences of southwest and south Iceland

Leó Kristjánsson
Institute of Earth Sciences, Science Institute, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland
leo@raunvis.hi.is

Abstract — *Magnetic polarity measurements on lava samples were introduced in the 1950s as an aid in stratigraphic research in Iceland, and applied by T. Einarsson especially on Pleistocene sequences in southwest and south Iceland. However, the stratigraphy of these sequences is often complex, and Einarsson's mapping has only been followed up to a limited extent. The present detailed laboratory study on magnetic remanence directions in lava flows is focused on three locations within the above region. In two of these locations (in southwest Iceland), profiles spanning the boundary between the polarity zones named R2 and N2 by Einarsson were sampled. The potential of using this boundary for correlation over short distances was confirmed. In a third location (in south Iceland), three normal-polarity zones are present in a 500 m thick lava and sediment sequence of dominantly reverse polarity. The stability and within-lava agreement of primary remanence vectors is generally excellent. Remanence directions in successive lava units are in many cases very similar, indicating that the volcanism was episodic. In comparison to geomagnetic poles obtained in previous paleomagnetic collections of older lava series in Iceland, the poles derived from these and other Pleistocene lavas are rarely situated in low latitudes.*

INTRODUCTION – PREVIOUS WORK

In Iceland, research on the age and stratigraphy of lava sequences is fundamental to many other earth science studies of local and regional interest. Often it is also relevant to global processes such as climate changes. One of the methods employed in stratigraphic research in Iceland since the early 1950s (Hospers, 1953) is the measurement of the direction vectors of remanent magnetization (remanence) in lava flows. The remanence acquired by the rock on cooling, which has a direction more or less identical to that of the ambient geomagnetic field, may remain stable for tens of millions of years (m.y.). An important aspect of this research concerns complete reversals of the geomagnetic field which have taken place at irregular intervals. In the first half of the 20th century, these intervals were thought to be millions of years in duration. Hospers (1953) introduced a useful concept called a "virtual geomagnetic pole" (VGP). This is the magnetic (south) pole corresponding to a field direction observed somewhere on the Earth, on the assumption that the geomagnetic field is due to a dipole (resembling a short bar magnet) at its center. The slow "secular variation" of the geomagnetic field was thought of as a semi-regular wobbling of the VGP around the geographic pole between abrupt reversals of polarity.

Following the work of Hospers, application of the paleomagnetic method in Iceland was taken up by Einarsson and Sigurgeirsson (1955). Einarsson carried out measurements of the polarity of basalt lava flows and other bodies with a field compass, mostly in hillside profiles in many parts of the country. Descriptions of the strata, their magnetic polarity, and geological interpretation appeared in several of his publications, e.g., Einarsson (1957, 1962). Einarsson found that each series (zone) of lavas having "normal" or "reverse" polarity often consisted of tens of lava flows. He attempted to set up a scheme for the consecutive numbering of such polarity zones, especially in the strata emplaced during the cold climates of the last 3 m.y. Thus, zone N1 corresponded to the present magnetic epoch, R1 contained lavas from the last reverse epoch, and so on. Each of these zones varied in thickness between locations, but N2 and R2 were of the order of 150 m and 300 m thick respectively, N3 was only some 50 m, and R3 was 500 m.

Detailed work on worldwide volcanic sites dated by the potassium-argon (K-Ar) method in the 1960s, augmented by interpretation of magnetic anomaly lineations parallel to ocean ridges, revealed that on average at least 3–4 reversals had occurred every million years in the Cenozoic era. Several versions of a "geomagnetic polarity time scale" for these reversals have been published, with each revision incorporating additional reversal events named subchrons and cryptochrons (Ogg and Smith, 2004). It has been concluded from research on sedimentary and volcanic sequences that at least ten such short events may have occurred in the current normal-polarity epoch (now known as the Brunhes chron) which began at 0.78 Ma, and the situation may be analogous for previous chrons. The secular variation has also been found to include many "excursions" of the VGP's position to low latitudes.

Due to this increasing complexity in our knowledge of the geomagnetic field behaviour, as well as to the scarcity of radiometric age determinations so far obtained from Icelandic lavas, any correspondence between Einarsson's polarity zones and the geomagnetic polarity time scale is still uncertain. Einarsson (1962, p. 70) was also aware that one or more polarity zones might be missing in some of his profiles due to eruption rate variations, hiatuses or erosion. In some locations, the N2 might be tentatively identified with the Jaramillo normal-polarity subchron at 0.99–1.07 Ma, i.e., late in the Matuyama reverse magnetic chron which is supposed to span the interval 0.78–2.58 Ma ago (Ogg and Smith, 2004). However, in other places N2 could contain volcanics from an older long subchron in the Matuyama, namely the Olduvai at 1.78–1.95 Ma. In southwest Iceland, this correlation finds some support in the K-Ar dating of a presumed N2 unit (Kristjánsson *et al.*, 1980) which yielded an age of about 1.9 Ma (when recalculated with the decay constants used by Ogg and Smith). N3 may accordingly be the Reunion subchron which lasted between 2.13–2.15 Ma ago.

In addition to collaborating with Einarsson on polarity measurements in lava profiles, Sigurgeirsson (1957) designed a laboratory instrument for the accurate measurement of the primary remanence directions in hand samples. Sigurgeirsson carried out a number of such determinations, mostly on lavas near the boundaries between polarity zones in Einarsson's profiles in southwest Iceland. The best known of Sigurgeirsson's directional measurements are those at the R3-N3 boundary in various locations south of Hvalfjörður (H of Figure 1), resampled by Kristjánsson *et al.* (1980). Kristjánsson and Sigurgeirsson (1993), and others. This established that virtual poles formed an irregular path passing through low latitudes during the reversals, rather than the dipole simply decreasing to zero and then growing in the opposite sense while staying in near-axial orientation. It has also become clear from Icelandic data that the field intensity is reduced during the reversal process, with the dipole field becoming weaker than non-dipole field components when the VGP latitude is less than 25° or so (Figure 9 of Kristjánsson, 2008).

In 1964 a new stage began in paleomagnetic research on Icelandic lava sequences. That summer, a large collection of oriented drill cores was acquired by Doell (1972), mostly in Tjörnes (T of Figure 1) and the Snæfellsnes peninsula (S of Figure 1). Another collection effort was carried out in 1964–1965 in southwest and east Iceland by a U.K. – Icelandic expedition. In southwest Iceland the expedition sampled ten profiles of Pliocene and Pleistocene age, mapped by T. Einarsson around the Hvalfjörður fjord. The published account of this study (Wilson *et al.*, 1972) was somewhat incomplete. Firstly, the altitudes of lava boundaries mapped by Einarsson were shown in diagrams, but very little information on the lithology

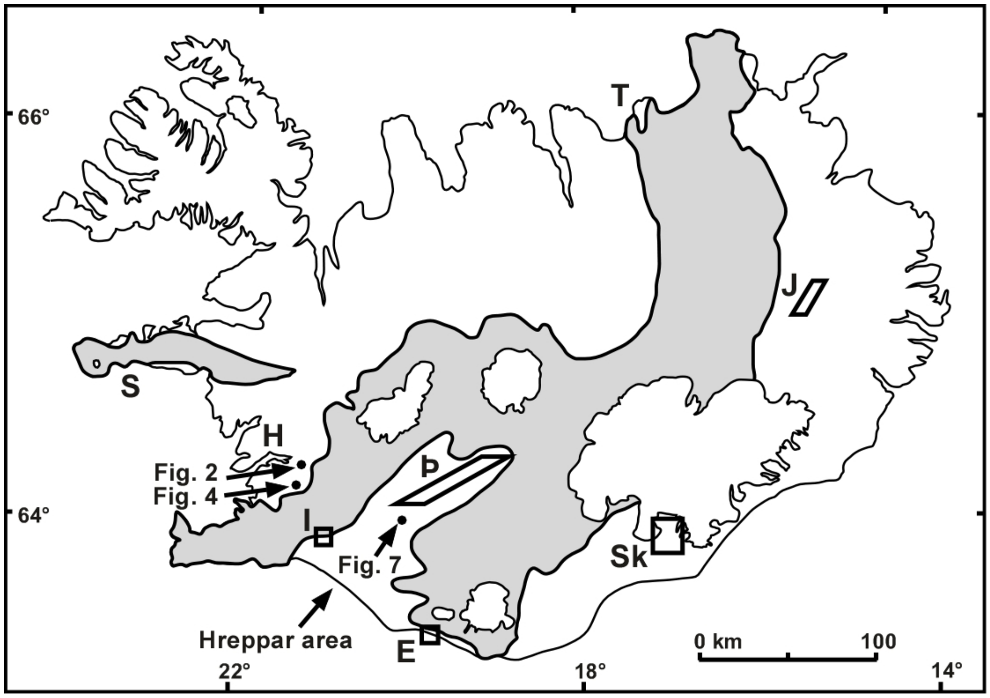

Figure 1. Index map of Iceland: the active volcanic zones (with basement outcrops of mostly less than 0.78 Ma age) are shaded. Locations of the surveys reported here are indicated, as well as some small areas where previous paleomagnetic sampling on lava flows of less than 3 Ma age has been carried out. S = Snæfellsnes peninsula, H = Hvalfjörður, T = Tjörnes promontory, Sk = Skaftafell area, E = Eyjafjöll, I = Ingólfsfjall, J = area in Jökuldalur containing profiles of Watkins *et al.* (1975) and Udagawa *et al.* (1999), Þ = area in Þjórsárdalur containing profiles of Kristjánsson *et al.* (1998). – *Kort af Íslandi, virku gosbeltin eru skyggð. Svæði sem fjallað er um hér og í nokkrum fyrri greinum um svipað efni eru afmörkuð lauslega.*

of the lavas or of the sediments between them was presented. Secondly, the paleomagnetic results were not presented in detail, but merely polarity information. Some maps of VGP positions were published later by the group, and the present author was given a printout of the remanence directions from all profiles. As only two samples were collected in each lava flow, it is necessary to re-sample the profiles of Wilson *et al.* (1972) if one wishes to obtain lava-mean direction values that can be used for studies of the geomagnetic secular variation.

Several laboratory paleomagnetic studies have been carried out in Iceland since the early 1970's, in some cases accompanied by radiometric dating. Projects involving long composite sections of profiles in stratigraphic succession were reviewed by Kristjánsson and Jónsson (2007) and Kristjánsson (2009). One of these sections (Kristjánsson *et al.*, 1980) overlaps with the areas in southwest Iceland covered by Einarsson (1957,1962). A number of other paleomagnetic studies have been on a smaller scale. Among them are studies on lavas mostly less than 2 Ma old, published by Watkins *et al.* (1975) and Udagawa *et al.* (1999) in Jökuldalur (J), Kristjánsson *et al.* (1988) in Eyjafjöll (E), Tjörnes (T) and Ingólfsfjall (I), Eiríksson *et al.* (1990) in Tjörnes, Kristjánsson *et al.* (1998) in Þjórsárdalur (Þ), and Helgason and Duncan (2001) in the Skaftafell area (Sk), see Figure 1.

Their results along with magnetic polarity measurements made in the field have aided in the compilation of regional geological maps of surface outcrops, such as the recent map by Sæmundsson *et al.* (2010).

THE PRESENT PROJECT

Although some of the publications listed in the last paragraph (as well as various student theses and institute reports of limited circulation) have followed up on details of T. Einarsson's paleomagnetic-stratigraphic mapping efforts, much remains to be done in that field. The work described in this paper continues some of Einarsson's (1962) studies and will hopefully stimulate others to extend them further. Three isolated areas were chosen, all presumably belonging to the Matuyama geomagnetic chron. These were in the Brynjudalur valley south of Hvalfjörður (Figures 1 and 2), on both sides of the Kjósarskarð pass (Figures 1 and 4), and near the Fossnes farm in the Þjórsárdalur valley (Figures 1 and 7). As in previous studies by the author and his collaborators in other profiles of Brunhes-Matuyama age (e.g. Kristjánsson *et al.*, 1988; Kristjánsson and Sigurgeirsson, 1993), the chief aim of the project was to locate geomagnetic excursions and boundaries of polarity zones. These might be promising for radiometric dating and for use as stratigraphic markers across larger areas.

Another motive for sampling these profiles was to obtain new data on the long-term secular variation of the geomagnetic field in the Pleistocene. The angular standard deviation (a.s.d.) of VGPs from Icelandic lavas seems to have had a significantly smaller amplitude in the last few million years than for instance during the period 10–15 Ma ago (Kristjánsson, 2008). Few if any other parts of the world seem capable of providing coverage of comparable intervals with magnetic direction data of comparable quality and quantity. Therefore, it is still not known whether this reduction in the a.s.d. is related to changes in other properties of the geomagnetic field such as its reversal frequency or its long-term mean intensity.

METHODS

Sampling of 25-mm diameter cores was carried out with a two-stroke gasoline-powered drill. The cores were oriented in situ with a Brunton compass, using sightings on the Sun or distant geographic objects for azimuth reference. At least four core samples were collected at each site. All remanence measurements on 21 mm long specimens from these cores were made with an Institut Dr. Förster four-probe fluxgate magnetometer. Many samples contained significant viscous magnetization (VRM) whose intensity could even exceed that of the primary remanence. However, this VRM was easily removed by stepwise treatment in a Molspin alternating-field demagnetizer. The peak fields applied were 10, 15, 20 and 25 milli-Tesla. A 30 mT step was also added in the Þórisgil and Kjósarskarð profiles, but it turned out to be unnecessary. An average direction was computed for each lava after each step, and the average with the smallest 95% confidence angle (α_{95}) was selected for inclusion in Appendix 1. The lava flows in all the sampled profiles generally carry a very stable primary remanence of moderate intensity, giving excellent directional agreement between the core samples. Only a few samples were rejected in each of the three areas, due to instability, suspected orientation errors or outcrop movement.

In the diagrams of the profiles, the sampled lavas have been classified roughly into lithological categories based on field criteria and inspection of the cores: tholeiites, olivine tholeiites, feldspar-porphyritic flows, and andesites. The clastic units in the profiles are also described in broad terms only.

PROFILE WB IN ÞÓRISGIL, BRYNJUDALUR, SW-ICELAND

A stratigraphic profile of the Þórisgil gully (Figure 2) in the Brynjudalur valley south of Hvalfjörður was published in Figure 31 of Einarsson (1962). It indicates that the lower part of the profile is occupied by the R2 series. This is followed by a 10 m layer of secondary breccia and fine conglomerate at an unspecified altitude and then 15 lava flows belonging to the N2 zone on the slopes of the Botnssúlur mountain.

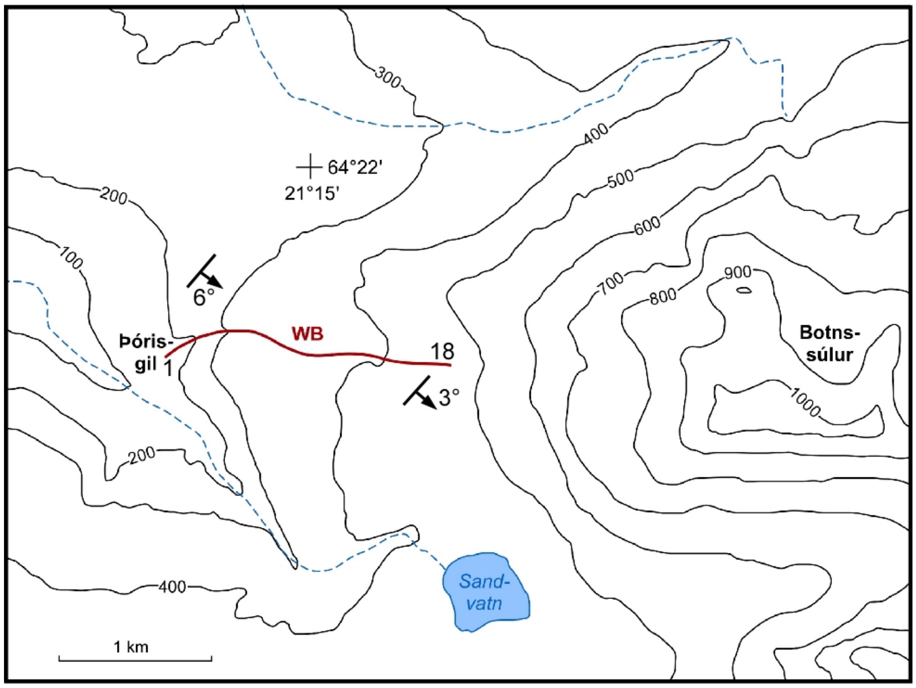

Figure 2. Location of the surroundings of profile WB, with flows 1–8 in the Þórisgil gully and 9–18 along the same stream to the slopes of Botnssúlur. – *Lega jarðlagasniðs WB í Þórisgili og ánni upp af því.*

The profile was subsequently sampled by Wilson *et al.* (1972) who named it WB. Wilson *et al.* (1972, p. 460) sketch the altitudes of flow boundaries, both as obtained by Einarsson and as derived from observations during the sampling. Their results which do not agree very well, are not reproduced here. The R2-N2 boundary in these sketches occurs at respectively 380 and 440 m.

The present author has resampled the R2-series as well as the four lowest lavas of the N2. The stratigraphic column in Figure 3 is based on his notes. Altitudes were measured with a handheld GPS receiver, to an accuracy of some 5 m. The mean primary remanence directions and intensities obtained are listed in Appendix 1. The directions have been corrected for tectonic tilt which is estimated to decrease from 6° at the base to 3° at the top, with a downdip direction of 130° east.

Successive directions are found to be grouped to a considerable extent. Thus they are very similar in flows WB 1 and 2, also almost constant in flows 6–11, and again very similar in flows 12–13. This probably is due to episodes of rapid buildup. Flow WB 6 is of unusual appearance and has unusual magnetic properties with very low remanence intensity and susceptibility, pointing to the presence of a highly oxidized magnetic mineral component. This flow (along with flows WB 1 and 8) also had a high coercivity of remanence, the median destructive field of the remanence in its samples being 50 mT or more while in the other lavas in this study it mostly ranged from less than 10 to 35 mT.

There do not seem to be any lava flows of intermediate directions present at the reverse-to-normal boundary which coincides with a thick intermittently exposed layer of tuff and hyaloclastite. Einarsson (1962, Fig. 32) describes a series of some 11 N2 "flow units" above a tillite which presumably overlies the lava numbered WB 18 here; this series was not sampled by Wilson *et al.* (1972) or in the present survey.

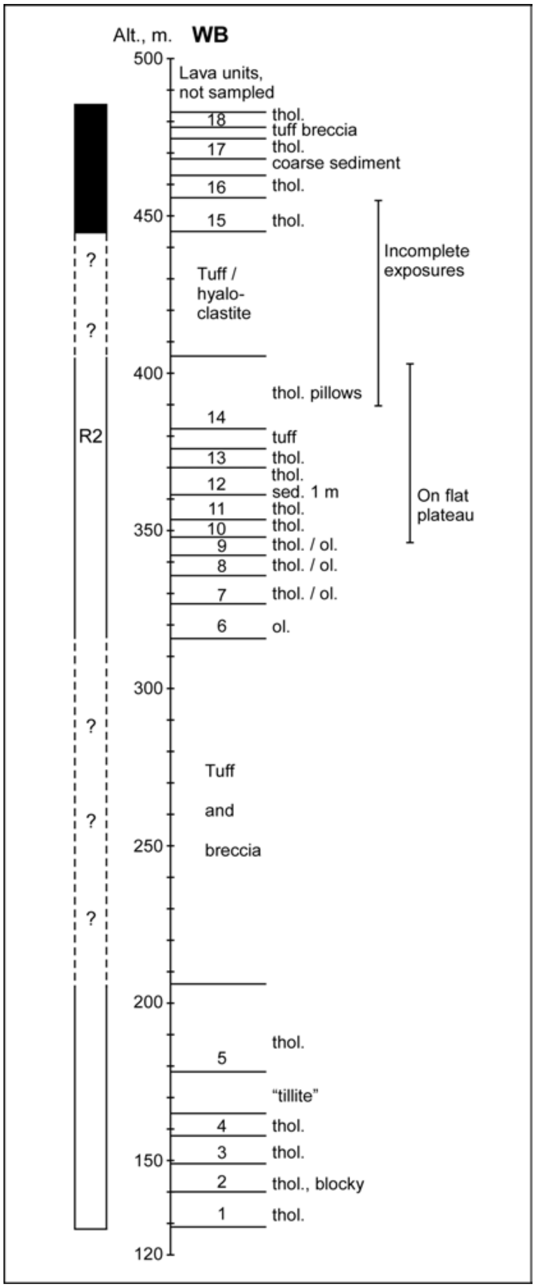

Figure 3. Stratigraphic sketch of profile WB in Þórisgil and Botnssúlur. Thol. = tholeiite, ol. = olivine tholeiite. Altitudes (in meters above sea level) and magnetic polarities (black = normal, white = reverse) are on the left. – *Skissa af jarðlögum í sniði WB og segulstefnu þeirra.*

PROFILES KJ, KI, KK, KP, KN, KO IN AND AROUND STÓRA-SAUÐAFELL, KJÓSARSKARÐ, SW-ICELAND

The so-called Kjósarskarð road (Highway 48) runs south from the Hvalfjörður fjord, along the Laxá river. Stóra-Sauðafell (Figures 1, 4 and 5) is a hill lying about 1 km west of this highway and 5–6 km south of one of Sigurgeirsson's (1957) R3–N3 transition sites, Kýrgil. The hill is just south of the map in Figure 30 of Einarsson (1962). The author is not aware of any previous published stratigraphic mapping in Stóra-Sauðafell or its vicinity. The main profile KJ sampled in this project (Figure 6) begins above a coarse-grained sediment. Exposures are not complete and are separated by detritus-covered hillside intervals of comparable vertical dimensions. The detritus probably hides clastic sediments but these or the flow boundaries are rarely seen; this accounts for the difference in presentation of Figures 3 and 6. The exposures KJ 16 consist of lava pods which appear to be embedded in a thick clastic unit.

The mean directions of the KJ flows are listed in Appendix 1, after correction for tectonic tilt which is estimated to be 9° in a direction 130° east for all the profiles of Figure 4. As in profile WB above, clustering of successive directions is seen in KJ 2–3, KJ 6–9, and KJ 10A–15. KJ 10 with a mid-latitude VGP may have been erupted at the beginning of the geomagnetic polarity transition between emplacement of the reverse zone KJ 1–10 and of the normal zone 10A–16.

The short profile KI 1–6 (to the right of the shallow gully in Figure 5) has more or less the same remanence directions as the flows KJ 1–6 although it should be stratigraphically lower. This is probably due to a fault located between them. A short profile KK northwest of KJ was also sampled in an attempt to reach lower levels in the lava pile. The two KK flows indicate that the thickness of the reverse series could be somewhat greater than the 80 m or so observed in KJ. One assumes that this series is the R2 of Einarsson (1962). The KK flows are unconformably overlain by several flows of the interglacial "Reykjavík gray basalt" lavas which also outcrop in the area between the road and Laxá (Sæmundsson *et al.*, 2010).

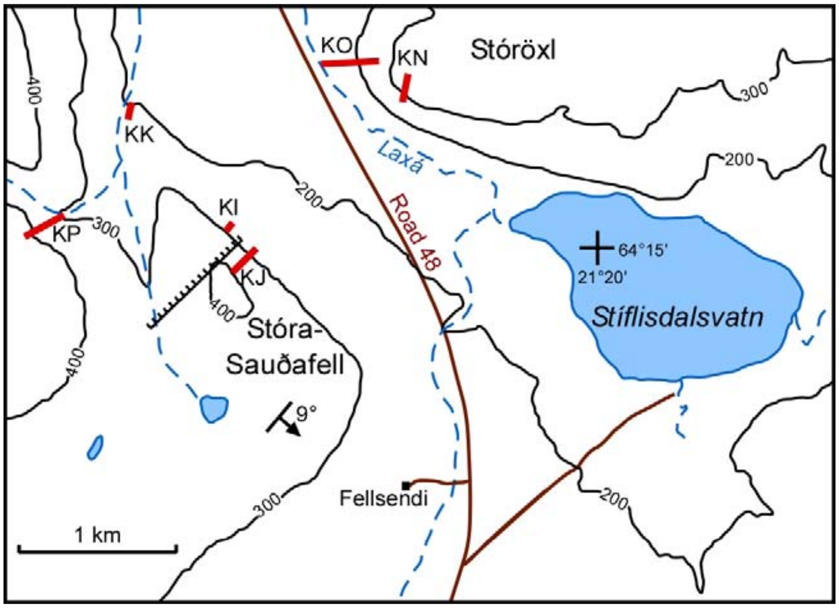

Figure 4. Location of profiles in Stóra-Sauðafell and its vicinity. A fault between profiles KJ and KI (Sæmundsson *et al.*, 2010) is shown. – *Staðsetning sniða í Stóra-Sauðafelli og umhverfis það í Kjósarskarði.*

Figure 5. Stóra-Sauðafell seen from road 48. Profile KJ lies near the middle of the photo and KI is to the right of the shallow gully, both beginning at the lowest lava exposures. – *Ljósmynd af Stóra-Sauðafelli, snið KJ er þar nálægt miðju og KI til hægri.*

The profile KP (Figures 4 and 6) begins at a sharp bend in a stream west of the northern end of Stóra-Sauðafell. The bottom flow KP 1 is well exposed but highly cracked so that it was impossible to collect core samples from it. However, fluxgate measurements in the field gave a reversed polarity. The lithology of this flow is characteristic of andesite although no such rocks are shown at that locality in the geological map by Sæmundsson *et al.* (2010). Some of the other flows in profile KP have textures reminiscent of quartz-rich tholeiite or even andesite. The top lava which is the only normally magnetized unit in the profile, presumably correlates with the normal-polarity series KJ 10A to 16. Successive directions are in some cases seen to be very similar, especially in KP 4–5 and 10–13.

Another two profiles KO and KN were sampled in the hill Stóröxl across the Laxá river (Figures 4 and 6). The lower slopes of this hill are largely covered by gravel with occasional exposures including acid tuff and the acid or intermediate lavas KO 2A (where only one reversely magnetized core sample was collected) and KO 2B. It is likely to belong to the same volcanic phase as KP 1. A layer of coarse tuff is encountered at 265 m altitude underneath profile KN. On top of the tuff there are several lava flows, the lowest one petering out towards the north. Six were sampled in

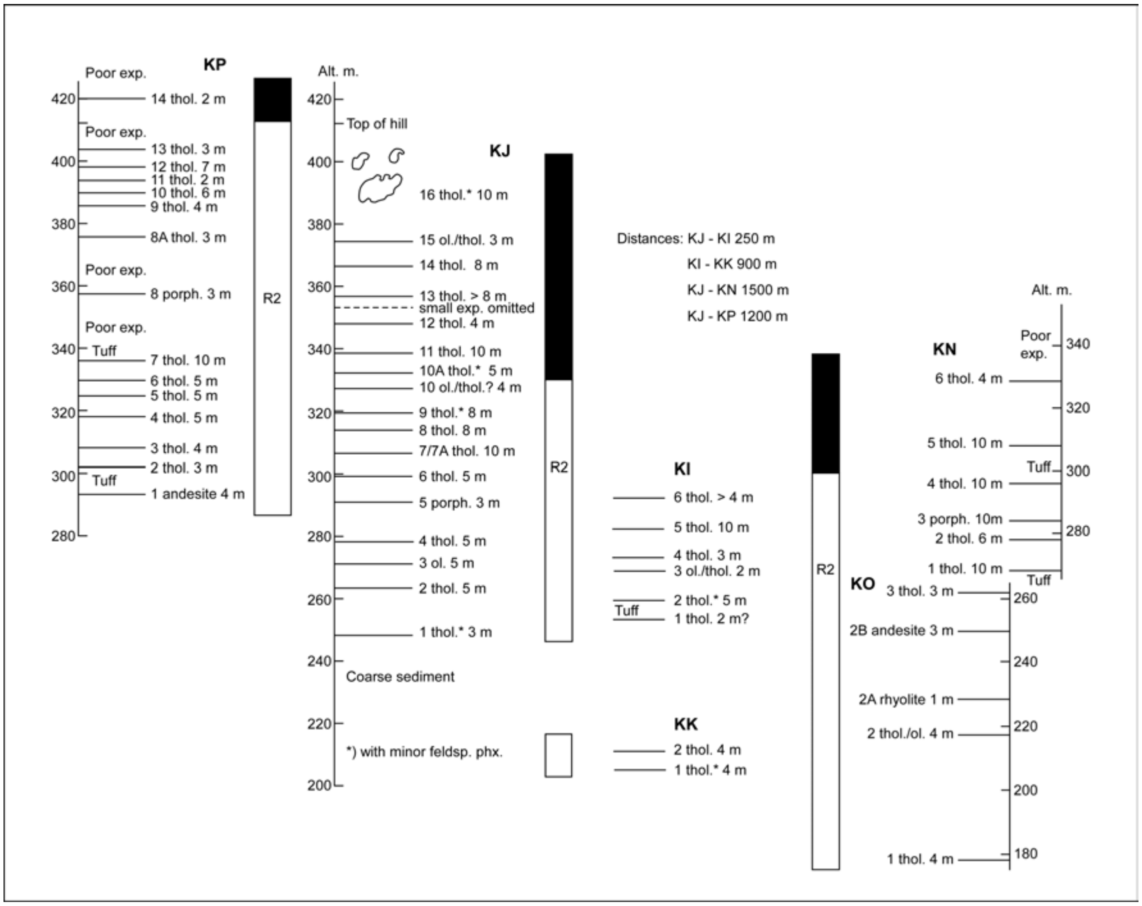

Figure 6. Stratigraphic sketch of the profiles in and around Stóra-Sauðafell. Altitudes of the sampling spots are indicated, along with lithological information and the thicknesses of lava exposures at these spots. – *Jarðlög í sniðunum á 4. mynd.*

this profile; exposures become unsatisfactory higher up. The bottom four lavas KN 1–4 are reversely magnetized, and the top two are normal (Appendix 1). Within each zone the remanence directions are very similar. It is most likely that this polarity reversal is the same as is found in KJ in Stóra-Sauðafell and in KP. The presence of the porphyritic flows KN 3 and KJ 5 which have similar directions of magnetization, could support this correlation. In Stóröxl and within 4 km to the north, the R2 polarity zone may have merged with R3 (Einarsson, 1962, Figure 30) due to disappearance of the thin N3 zone.

PROFILES HR AND FO AT FOSSNES, ÞJÓRSÁRDALUR, S-ICELAND

The "Hreppar Formation" lies between the two active volcanic zones in south Iceland (Figure 1). Geological research in that area began around 1900 (e.g., Pjetursson, 1905) but it has been quite sporadic and in part recorded only in institute reports and undergraduate theses. The formation consists of subaerially emplaced basalt lavas intercalated with pillow lavas and hyaloclastites, indicative of subglacial or subaqueous eruptions. Other clastic deposits indicating cold climate are also abundant, and so is evidence of landscapes formed by erosion. This along with complex tectonics (Khodayar and Franzson, 2004, 2007) and a scarcity of radiometric age determinations has made it difficult to reconstruct the geological history of the Hreppar region. Kristjánsson *et al.* (1998) review previous research within the region by Einarsson (1962, p. 132–142), Friðleifsson *et al.* (1980) and others. They also describe their study of stratigraphy and paleomagnetic polarities in several short sampling profiles along the Þjórsá river (roughly in the area Þ of Figure 1). From the polarities and K-Ar age determinations on four lava flows, Kristjánsson *et al.* (1998) concluded that a composite section of some 500–600 m thickness made up from these profiles covers the age interval from 2.2 Ma to less than 0.8 Ma. The youngest outcrops sampled may be 0.2 Ma old.

A paleomagnetic survey to supplement the results of Kristjánsson *et al.* (1998) was carried out in two adjacent and overlapping profiles HR and FO (Figure 7) near the Fossnes farm in Þjórsárdalur, totalling some 500 m in thickness. The work took place in conjunction with geological mapping of the surrounding area by Á. Geirsdóttir and Th. Thordarson (ms. in preparation) which focused both on the volcanic stratigraphy of this area, and on clastic sedimentary deposits (Geirsdóttir *et al.*, 1993, 1994). Sampling was also undertaken in nearby hills (Núpsfjall, Þjórsárholts-

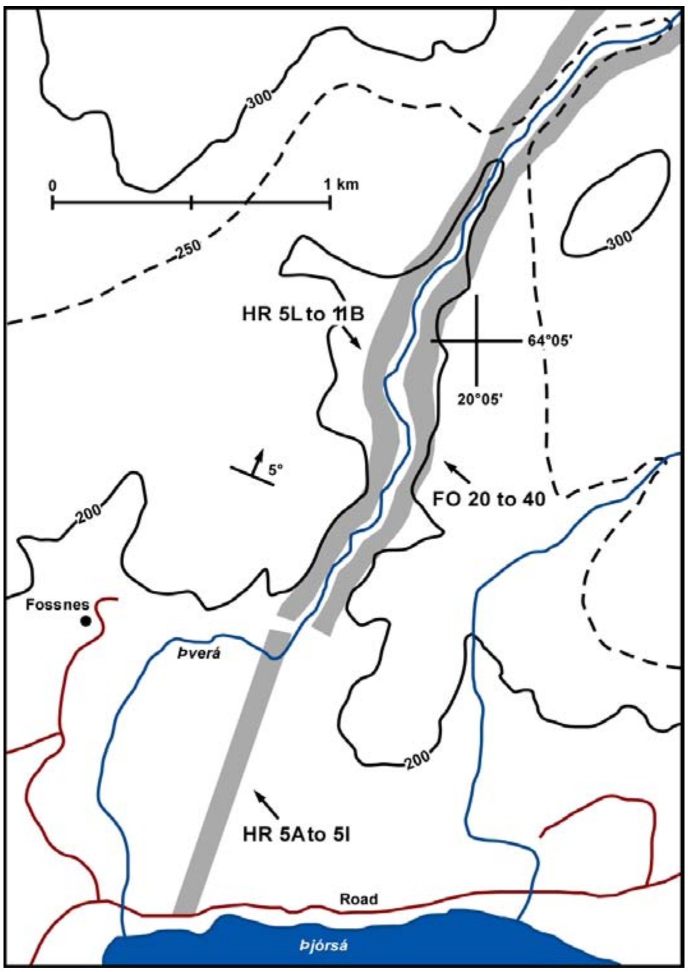

Figure 7. Approximate location of profiles HR and FO. The lava units HR 5A to 5I were sampled from the road at Þjórsá to just beyond the tributary Þverá as shown. The series HR 5L to 5V, 7, 9 and 11 were sampled successively along the west bank of Þverá up to near the top of the map. Lavas FO 20 to 40 were sampled along the east bank of Þverá, from near HR 5V to the top of the map. – *Lauslegt kort af staðsetningu sniðanna HR og FO við Fossnes í Þjórsárdal.*

holt, Gaukshöfði and Skriðufell, some 30 lava units in total). However, magnetic results obtained from these are not reported here, as they have not yet been fitted into a common stratigraphic scheme. The remanence directions given in Appendix 1 have been corrected for tectonic tilt which is estimated to average 5° with a down-dip direction of 30° east (Friðleifsson *et al.*, 1980; Á. Guðmundsson, pers. comm. 1992; Khodayar and Franzson, 2004).

A short description of some features of the two sampled profiles, based on unpublished information kindly supplied by Á. Guðmundsson, Á. Geirsdóttir and Th. Thordarson (pers. comm. 1992–2001), is as follows (Figure 8). According to the numbering of Friðleifsson *et al.* (1980), the Stratigraphic Units HR 5, 7, 9 and 11 consist mostly of lavas of tholeiitic lithology, while their Units 6, 8, 10 and 12 are rather heterogeneous tuffaceous sediments not differentiated in Figure 8. The bottom one-third of the composite column is composed of the series HR 5A through 5V, i.e., Unit 5 of Friðleifsson *et al.* (1980) which can be traced across several kilometers in the area. 11 out of over 20 mostly thin flows were sampled, 5A to 5H south of the Þverá stream and 5I to 5V along it. All were reversely magnetized except the top one 5V which is a lava lake. Nearby flows FO 20 and FO 21 on the east side of Þverá are also of normal polarity. Then we find sandstone and diamictite, a couple of reversely magnetized flows FO 22, 23, and FO 24 with a transitional direction on the boundary with another normal-polarity series of medium-grained basalts FO 25–32. It is not certain where some of the HR flows (sampled west of the stream above HR 5V) fit into the FO profile east of the stream, but HR 7A probably belongs to the same reverse zone as FO 22 whereas the normal-polarity units HR 9A,B,C,E correspond to the top part of FO 25–32. Although no faults are shown crossing the stream in maps accompanying the reports of Friðleifsson *et al.* (1980) and Khodayar and Franzson (2004), a fault zone may lie between flows FO 32 and 36B. Repetition in the lava sequence at this level is inferred from the similarity of the remanence directions in the reverse flows FO 33 and 34 with those in FO 35 (and HR 9D) and 36A respectively. At least two normal-polarity flows FO 36B, 37 are also found here. Finally, sediments containing the reversely magnetized FD 38 (a picrite) and HR 11A,B is in turn overlain by the normal-polarity lavas FD 39,40.

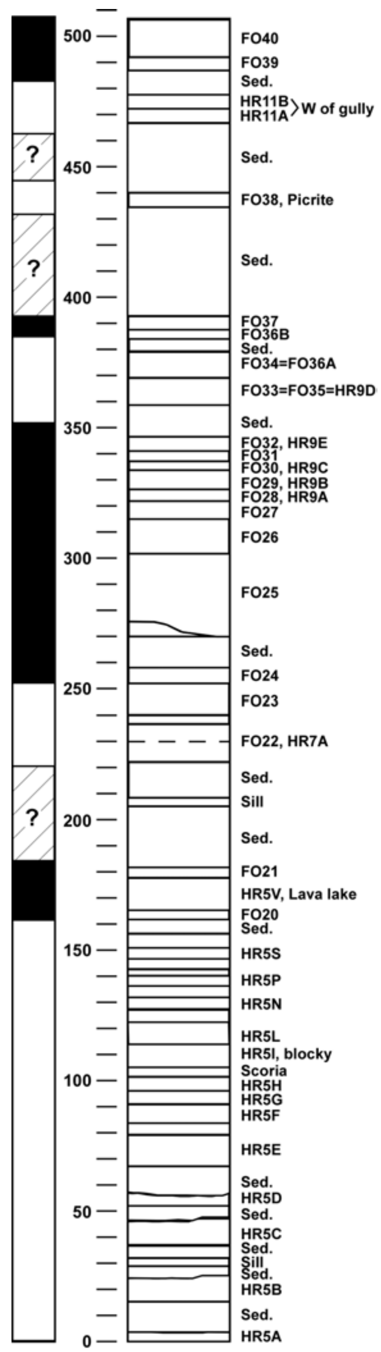

Figure 8. Stratigraphy of profiles HR and FO, simplified from an annotated drawing by Á. Geirsdóttir (pers. comm., 1996), with additional input from Th. Thordarson (pers. comm. 1996, 2001), Á. Guðmundsson (pers. comm., 1992) and the author. The magnetic polarities of the lavas are mostly based on laboratory measurements but partly on fluxgate measurements in the field. Thin sedimentary layers are assumed to have the same polarity as adjacent lavas. The numbers on the left-hand side refer to cumulative thicknesses (in meters), not altitudes. – *Jarðlög í sniðunum HR og FO, ásamt segulstefnu í þeim. Súlan er einfölduð úr teikningu frá Áslaugu Geirsdóttur og Þorvaldi Þórðarsyni. Tölur eiga við samanlagðar þykktir, ekki hæð.*

The scheme presented in Figure 8 is a tentative one, as exposures in the Fossnes profiles are somewhat incomplete. Much additional work is therefore needed before the history of interacting volcanism and glaciations in this area can be fully understood. Assuming with reference to the stratigraphic and dating results of Kristjánsson *et al.* (1998) that this sequence was emplaced in the Matuyama reverse chron, Figure 8 appears to record at least three normal-polarity events in a 500 m thick profile. The presence of three magnetic events is in contrast to for instance Figure 3 where only one reversal is found in a 350 m thickness of lava and clastic rocks. This indicates a higher rate of eruptive activity in FO/HR than in the WB profile, provided that the normal-polarity zones in FO/HR are not due to stratigraphic complexities.

SECULAR VARIATION RESULTS

It is notable that few mid–or low-latitude virtual geomagnetic poles are found in the presumed Pleistocene lavas in the three areas studied here. The VGP in only one out of some 90 lavas of Appendix 1 (excluding probable duplications in KI and in FO/HR) is positioned in a latitude lower than 40° N or S, and two VGPs lie between 40° and 50° in latitude, while in lava sequences of more than 5 Ma age in Iceland around 20% of poles are found below 50° (cf. Kristjánsson, 2008). This is one aspect of a long-term change occurring in the character of the paleomagnetic field as recorded in Icelandic lavas. This change has also caused the scatter (a.s.d.) of VGP positions in published lava collections (Kristjánsson, 2008, 2009 and additional data) about their respective means to decrease significantly during the last 15 Ma (Figure 9). Results of this kind can provide valuable constraints on models of the behavior of the geomagnetic field through time.

SUMMARY AND DISCUSSION

The present paleomagnetic study of three small areas within lava series of less than 3 Ma age in southwest and south Iceland has similar aims as some previous laboratory paleomagnetic studies of Icelandic lavas in this age range, published for instance by Doell (1972), Wilson *et al.* (1972), Watkins *et al.* (1975), Kristjánsson *et al.* (1980, 1988, 1998), Eiríksson *et al.* (1990), Udagawa *et al.* (1999), and Helgason and Duncan (2001). Primarily, they have attempted to locate geomagnetic excursions and polarity-zone boundaries, which might be radiometrically dated and used in stratigraphic correlations between igneous units. Such correlations are especially difficult in areas affected by glaciations during eruptions, due to the heterogeneity of products, lack of overlap between units from different vents, and landscapes formed by contemporaneous erosion. The few radiometric age determinations so far available from the Pleistocene in Iceland do not have sufficient resolution to allow definite correlations between them, especially as the number of suggested short intervals of normal polarity during the Matuyama chron in the literature has been increasing in recent years. Therefore, the present study and those listed above represent only very small steps towards stratigraphic mapping of the Pleistocene volcanism in Iceland. Further efforts of a similar nature should be undertaken in close collaboration with specialists in petrology, sedimentology and glacial geology. Eventually, correlations with an improved international geomagnetic polarity time scale might also be attained.

Among the results presented in this paper is the confirmation of a boundary between thick reverse and normal polarity zones in the Botnssúlur mountain (Figure 3). The paper also contains the first description of a similar boundary which can probably

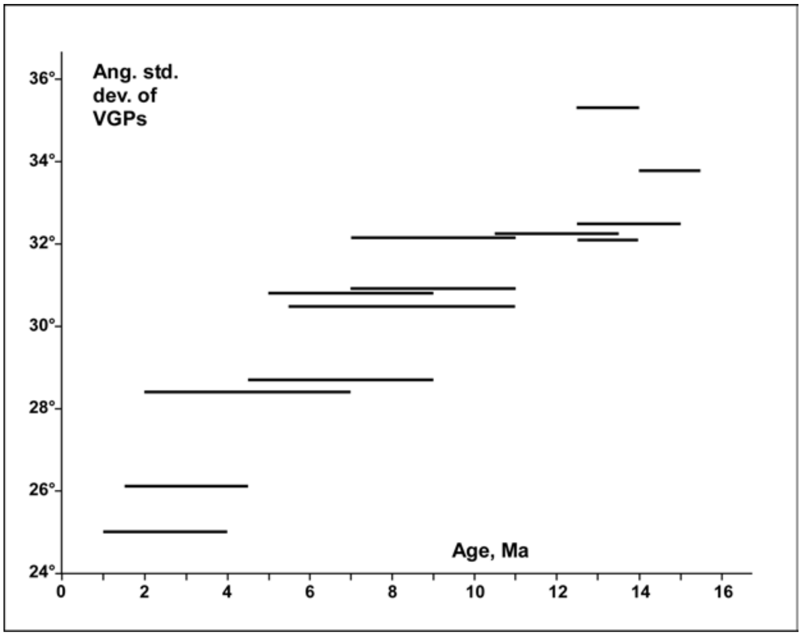

Figure 9. Angular standard deviation (a.s.d.) values for collections of virtual magnetic poles from Icelandic lavas, approximated by the parameter δ of Wilson (1959, Appendix). Each horizontal line indicates a single survey (or a few smaller lava collections of similar ages combined, including the present one) on 300–500 lavas of the basalt lava pile, carried out since 1972 (5139 in total). In more than half of the lavas, at least four samples were collected from each. The 95% confidence limits for the a.s.d. values do not exceed $\pm 2°$. Each age range is uncertain by at least 0.5 m.y. at either end. – *Á lóðrétta ás teikningarinnar er mælikvarði á flökt segulskautsins frá meðalstaðsetningu þess. Þetta er reiknað fyrir syrpur hraunlaga af svipuðum aldri í mismunandi landshlutum, 300–500 í hóp. Aldursóvissa á endum hverrar línu er a.m.k. 0,5 milljón ár.*

be traced for over 2 km from the Stóra-Sauðafell area (Figures 4 and 6) across the Laxá river to Stóröxl. Here, the reverse zone contains rhyolitic/andesitic material seen in profiles KP and KO. It is probably older than the normal-polarity Móskarðshnjúkar rhyolite 7 km west of Stóra-Sauðafell which has been K-Ar dated at about 1.9 Ma (Kristjánsson *et al.*, 1980).

The results presented above demonstrate the occurrence of three normal-polarity zones FO 20–21, 25–32, 36B–37 and the base of a fourth zone FO 39–40 in an otherwise reversely magnetized sequence expected to date from the Matuyama chron. Further radiometric (^{40}Ar–^{39}Ar) age determinations of these geomagnetic events and some of the main sediment sequences of Figure 8 would greatly aid in understanding the buildup of the Hreppar formation. While it is shown here that the paleomagnetic method is useful in detecting repetition of strata due to faults crossing the sampled profiles, additional mapping in the area is needed in order to exclude the possibility of stratigraphic confusion caused by landscape effects during the period of active volcanism and by subsequent tectonic movements.

The present results confirm previous observations by the author regarding a long-term decrease in the scatter of virtual geomagnetic poles. One possible cause of this decrease is that reversal transitions may each have taken less time (compared to chron lengths) in the Pleistocene than in the period 3–15 Ma ago. Detailed transitional pole paths as found at the R3–N3 boundary (Sigurgeirsson, 1957; Kristjánsson and Sigurgeirsson, 1993) are therefore a rare occurrence in the lava pile of Iceland, and attempts to locate them should concentrate on rapidly emplaced pahoehoe series of "flow units".

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Bergsegulmælingar á hraunum frá Pleistósentímabili á þrem svæðum suðvestan- og sunnanlands

Eftir að rannsóknir J. Hospers á segulstefnum í bergi hér höfðu vakið athygli, hóf Trausti Einarsson um 1953 að kanna legu jarðmyndana víða um land með hjálp áttavitamælinga á sýnum úr hraunlögum. Helsta rit hans um þau mál (Einarsson, 1962) fjallar að mestu leyti um myndanir frá Pleistósen-tímabili. Frekari rannsóknir á segulstefnu í Pleistósen hraunlögum hafa verið gerðar síðar á nokkrum afmörkuðum svæðum, en víða á landinu hefur athugunum Trausta ekki verið haldið áfram. Í þessari grein er sagt frá sýnasöfnun í jarðlagasniðum á þrem stöðum og bergsegulmælingum á þeim sýnum í rannsóknastofu. Sniðin eru í Þórisgili í Brynjudal og Botnssúlum þar upp af, við Kjósarskarð beggja vegna Laxár, og við bæinn Fossnes í Gnúpverjahreppi. Safnað var úr um 100 hraunlögum alls, og reyndust þau vera góður efniviður til mælinganna. Í fyrstnefnda sniðinu var staðfest niðurstaða Trausta Einarssonar (1962) og Wilson o.fl. (1972) um að í Botnssúlum leggist syrpa með „rétta“ segulstefnu ofan á aðra þykka með „öfuga“ segulstefnu sem Trausti nefndi R2. Í sniðunum í Kjósarskarði kemur fyrir samskonar umsnúningur jarðsegulsviðsins sem er mögulegt að fylgja a.m.k. tveggja kílómetra leið. Gæti það ásamt tilvist ísúrs og súrs bergs í sniðunum verið mjög gagnlegt fyrir frekari kortlagningu á því svæði. Við Fossnes koma þrjár þunnar syrpur rétt segulmagnaðra hraunlaga fyrir inni í um 500 m þykku sniði af seti og hraunum sem að mestu eru öfugt segulmögnuð. Upphleðsla staflans á öllum stöðunum virðist hafa verið nokkuð rykkjótt. Niðurstöður varðandi flökt jarðsegulsviðsins (út frá meðalstefnu þess) á þessum tíma eru í samræmi við fyrri ályktanir höfundar um að þetta flökt hafi farið minnkandi sl. 15 milljón ár.

REFERENCES

Doell, R. R. 1972. Palaeomagnetic studies of Icelandic lava flows. *Geophys. J. Royal Astron. Soc.* 26, 459–479.

Einarsson, T. 1957. Magneto-geological mapping in Iceland with the use of a compass. *Adv. Phys.* 6, 232–239.

Einarsson, T. 1962. Upper Tertiary and Pleistocene Rocks in Iceland. *Soc. Sci. Isl.* Rit 36, 197 pp. + maps.

Einarsson, T. and Þ. Sigurgeirsson 1955. Rock magnetism in Iceland. *Nature* 175, 892.

Eiríksson, J., A. I. Gudmundsson, L. Kristjánsson and K. Gunnarsson 1990. Palaeomagnetism of Pliocene-Pleistocene sediments and lava flows on Tjörnes and Flatey, North Iceland. *Boreas* 19, 39–55.

Friðleifsson, I. B., G. I. Haraldsson, L. S. Georgsson, E. Gunnlaugsson and B. J. Björnsson 1980. *Jarðhiti í Gnúpverjahreppi (Geothermal occurrences in the Gnúpverjahreppur district).* National Energy Authority Report OS80010/JHD06, 47 pp.

Geirsdóttir, Á., Þ. Þórðarson and L. Kristjánsson 1993. The interactive impact of climate deterioration and volcanic activity on facies assemblages in late Pliocene to early Pleistocene strata of the Hreppar Formation, South Central Iceland (abstract). *Eos Trans. AGU* 74 (43, Suppl.), 131.

Geirsdóttir, Á., Þ. Þórðarson and L. Kristjánsson 1994. Áhrif eldvirkni og loftslagsbreytinga á upphleðslu jarðlaga í Gnúpverjahreppi (Effect of volcanism and climate changes on the emplacement of strata in the Gnúpverjahreppur district). *Geosci. Soc. Iceland, Spring meeting abstracts* p. 6.

Helgason, J. and R. A. Duncan 2001. Glacial-interglacial history of the Skaftafell region, southeast Iceland. *Geology* 29, 179–182.

Hospers, J. 1953. Reversals of the main geomagnetic field, I-II. *Proc. Kon. Nederl. Akad. Wet.* B56, 467–491.

Khodayar, M. and H. Franzson 2004. *Stratigraphy and tectonics of eastern Núpur/western Hagafjall in Gnúpverjahreppur, South Iceland.* Iceland Geosurvey Report ISOR-2004/017, 42 p.

Khodayar, M. and H. Franzson 2007. Fracture pattern of Thjórsárdalur central volcano with respect to rift-jump and a migrating transform zone in South Iceland. *J. Struct. Geol.* 29, 898–912.

Kristjánsson, L. 2008. Paleomagnetic research on Icelandic lava flows. *Jökull* 58, 101–116.

Kristjánsson, L. 2009. A new study of paleomagnetic directions in the Miocene lava pile between Arnarfjörður and Breiðafjörður in the Vestfirðir peninsula, northwest Iceland. *Jökull* 59, 33–50.

Kristjánsson, L. and G. Jónsson 2007. Paleomagnetism and magnetic anomalies in Iceland. *J. Geodyn.* 43, 30–54.

Kristjánsson, L. and M. Sigurgeirsson 1993. The R3–N3 and R5–N5 paleomagnetic transition zones in SW-Iceland revisited. *J. Geomag. Geol.* 45, 275–288.

Kristjánsson, L., I. B. Fridleifsson and N. D. Watkins 1980. Stratigraphy and paleomagnetism of the Esja, Eyrarfjall and Akrafjall mountains, SW-Iceland. *J. Geophys.* 47, 31–42.

Kristjánsson, L., H. Jóhannesson, J. Eiríksson and A. I. Gudmundsson 1988. Brunhes-Matuyama paleomagnetism in three lava sections in Iceland. *Can. J. Earth Sci.* 25, 215–225.

Kristjánsson, L., R. A. Duncan and Á. Gudmundsson 1998. Stratigraphy, paleomagnetism and age of volcanics in the upper regions of the Thjorsardalur valley, central southern Iceland. *Boreas* 27, 1–13.

Ogg, J. G. and A. G. Smith 2004. The geomagnetic polarity time scale. *In:* F. M. Gradstein, J. G. Ogg and A. G. Smith, eds. *A Geologic Time Scale 2004*. Cambridge Univ. Press, Cambridge, 63–86.

Pjetursson, H. 1905. Om Islands Geologi. *Medd. Dansk Geol. Forening* 11, 106 pp.

Sigurgeirsson, Þ. 1957. Direction of magnetization in Icelandic basalts. *Adv. Phys.* 6, 240–246.

Sæmundsson, K., H. Jóhannesson, Á. Hjartarson, S. G. Kristinsson and M. Á. Sigurgeirsson 2010. *Geological Map of Southwest Iceland*, 1:100.000. Iceland Geo-Survey, Reykjavík.

Udagawa, S., H. Kitagawa, A. Gudmundsson, O. Hiroi, T. Koyaguchi, H. Tanaka, L. Kristjánsson and M. Kono 1999. Age and magnetism of lavas in the Jökuldalur area, Eastern Iceland: Gilsá event revisited. *Phys. Earth Planet. Inter.* 115, 147–171.

Watkins, N. D., L. Kristjánsson and I. McDougall 1975. A detailed survey of the type location for the Gilsá geomagnetic polarity event. *Earth Planet. Sci. Lett.* 27, 436–444.

Wilson, R. L. 1959. Remanent magnetism of Late Secondary and Early Tertiary British rocks. *Phil. Mag.* 4, 750–755.

Wilson, R. L., N. D. Watkins, T. Einarsson, T. Sigurgeirsson, S. E. Haggerty, P. J. Smith, P. Dagley and A. McCormack 1972. Palaeomagnetism of ten lava sequences from south-western Iceland. *Geophys. J. Royal Astron. Soc.* 29, 459–471.

Appendix 1. Paleomagnetic directions from profiles in three areas. – *Segulstefnur í hraunum á þrem svæðum.*

WB Þórisgil, Brynjudalur, Hvalfjörður (64°21.300'N, 21°16.338'W)

Flow	N	Dec.	Inc.	Lon.	Lat.	Alf.	J100	Pol.
WB 1	6	205	-70	277	-74	4	0.94	R
WB 2	5	210	-67	277	-68	2	1.00	R
WB 3	5	252	-87	172	-66	6	3.50	R
WB 4	5	122	-54	57	-45	5	1.64	R
WB 5	5	244	-80	205	-66	3	12.24	R
WB 6	4	165	-79	110	-83	2	0.16	R
WB 7	4	182	-76	259	-89	4	0.49	R
WB 8	4	177	-79	146	-85	4	1.71	R
WB 9	5	169	-79	118	-84	2	3.40	R
WB 10	4	182	-79	169	-85	4	9.39	R
WB 11	5	180	-82	159	-81	2	2.83	R
WB 12	5	198	-59	308	-63	4	0.32	R
WB 13	5	196	-64	306	-69	3	1.36	R
WB 14	8	213	-82	192	-75	5	17.12	R
WB 15	4	335	+77	263	+79	3	2.22	N
WB 16	4	351	+61	176	+68	5	13.38	N
WB 17	4	302	+65	247	+54	4	4.13	N
WB 18	5	11	+56	139	+61	2	4.91	N

Appendix 1. cont.

KJ Stóra-Sauðafell, Kjósarskarð (64°15.002'N, 21°22.684'W)								
KJ 1	4	149	-53	25	-54	5	1.13	R
KJ 2	4	176	-72	357	-83	3	0.70	R
KJ 3	4	185	-71	320	-81	4	3.67	R
KJ 4	4	198	-60	305	-65	2	1.79	R
KJ 5	4	213	-74	247	-74	2	2.61	R
KJ 6	4	179	-72	343	-87	2	17.44	R
KJ 7	5	185	-71	320	-80	2	5.97	R
KJ 8	5	188	-73	303	-82	1	8.79	R
KJ 9	5	196	-73	275	-81	5	5.63	R
KJ 10	7	191	-49	322	-55	5	0.96	R
KJ 10A	5	39	+68	83	+66	3	3.37	N
KJ 11	4	43	+69	75	+65	4	2.34	N
KJ 12	4	29	+70	92	+72	3	2.49	N
KJ 13	4	40	+70	77	+67	3	1.51	N
KJ 14	5	22	+55	113	+70	3	2.30	N
KJ 15	5	35	+68	89	+67	2	9.46	N
KJ 16	6	353	+66	175	+74	4	2.81	N
KI Stóra-Sauðafell, Kjósarskarð (supplementary profile)								
KI 1	5	195	-51	315	-56	4	1.96	R
KI 2	4	143	-46	30	-46	2	4.14	R
KI 3	4	186	-72	312	-82	3	0.77	R
KI 4	4	189	-60	322	-66	7	0.33	R
KI 5	5	199	-58	306	-62	2	1.48	R
KI 6	4	175	-68	353	-76	3	6.32	R
KK North end of Stóra-Sauðafell, Kjósarskarð								
KK 1	6	191	-61	316	-67	3	2.06	R
KK 2	4	200	-58	305	-61	3	2.14	R
KP Hrútagil, west of Kjósarskarð (64°15.083'N, 21°24.108'W)								
KP 2	3	173	-72	7	-81	3	2.54	R
KP 3	6	169	-60	359	-66	2	3.03	R
KP 4	6	186	-62	327	-69	2	4.25	R
KP 5	4	190	-59	321	-65	4	1.92	R
KP 6	5	222	-70	255	-67	2	0.99	R
KP 7	4	245	-77	215	-64	6	3.87	R
KP 8	5	152	-53	21	-55	2	1.39	R
KP 8A	4	224	-78	220	-72	1	5.13	R
KP 9	5	243	-75	226	-62	2	2.45	R
KP 10	5	208	-73	256	-76	2	4.26	R
KP 11	4	209	-73	259	-75	3	3.16	R
KP 12	4	202	-64	283	-74	4	1.67	R
KP 13	4	208	-71	268	-73	3	2.54	R
KP 14	6	52	+69	67	+61	4	1.02	N
KN Stóröxl, Kjósarskarð (64°15.47'N 21°21.55'W)								
KN 1	4	210	-78	222	-78	2	2.90	R
KN 2	4	199	-76	244	-81	2	5.81	R
KN 3	5	200	-74	260	-80	2	4.18	R
KN 4	4	196	-73	275	-81	5	4.76	R
KN 5	5	49	+67	75	+60	4	5.60	N
KN 6	5	47	+62	85	+56	7	4.86	N

Appendix 1. cont.

KO Stóröxl, Kjósarskarð (64°15.60'N, 21°22.09'W)								
KO 1	4	235	-72	237	-64	2	1.72	R
KO 2	6	144	-79	100	-75	4	5.93	R
KO 2B	4	184	-61	331	-67	6	2.77	R
KO 3	4	196	-69	296	-75	4	0.53	R
HR/FO Þverá-Fossnes, Þjórsárdalur (64°03.821'N, 20°06.334'W) Lavas in approx. stratigraphic order. See text for probable duplications								
HR 5A	4	281	-87	174	-62	5	4.6	R
HR 5B	4	227	-71	250	-65	3	13.7	R
HR 5D	4	195	-80	200	-82	4	2.2	R
HR 5F	4	206	-75	247	-78	4	3.2	R
HR 5H	4	225	-87	172	-68	2	0.3	R
HR 5I	4	139	-62	48	-59	3	7.6	R
HR 5L	4	260	-78	208	-59	3	3.3	R
HR 5N	4	83	-88	151	-63	2	2.3	R
HR 5P	4	29	-86	154	-58	4	5.8	R
HR 5S	4	114	-86	141	-66	6	1.7	R
FO 20	5	339	+68	210	+72	4	11.5	N
HR 5V	4	348	+59	182	+64	4	9.0	N
FO 21	7	342	+60	192	+65	3	8.0	N
HR 7A	5	189	-84	168	-76	2	2.8	R
FO 22	4	186	-55	330	-61	9	2.3	R
FO 23	4	173	-61	354	-67	7	0.8	R
FO 24	4	353	-16	167	+18	7	0.7	NT
FO 25	4	79	+82	15	+63	12	2.3	N
FO 26	4	29	+80	26	+77	3	1.6	N
FO 27	4	16	+77	56	+83	4	1.6	N
FO 28	4	40	+79	39	+73	4	3.2	N
HR 9A	4	40	+85	2	+71	5	2.3	N
FO 29	4	24	+73	86	+77	2	1.8	N
HR 9B	5	30	+78	41	+77	6	2.6	N
FO 30	4	65	+76	41	+63	4	3.7	N
HR 9C	4	37	+76	56	+74	4	9.5	N
FO 31	4	57	+75	50	+64	3	3.2	N
FO 32	5	45	+74	61	+69	7	4.2	N
HR 9E	4	60	+79	32	+66	5	4.9	N
FO 33	4	105	-72	94	-54	12	1.3	R
FO 35	4	99	-73	100	-54	6	1.9	R
HR 9D	4	124	-70	77	-61	3	2.1	R
FO 34	4	50	+74	55	+67	2	1.3	N
FO 36A	4	10	-86	158	-57	5	1.4	R
FO 36B	3	17	+53	133	+58	2	0.7	N
FO 37	4	13	+60	136	+65	4	3.6	N
FO 38	4	193	-73	281	-82	4	2.2	R
HR 11A,B	4	81	-82	131	-58	5	0.6	R
FO 39	4	48	+74	58	+68	3	3.3	N
FO 40	4	29	+61	109	+63	9	1.9	N

N = number of samples averaged. Dec, inc = declination and inclination of each remanence direction. Lon, lat = coordinates of the corresponding virtual geomagnetic pole (VGP). Alf = 95% confidence angle for the mean direction, in degrees. J100 = mean remanence intensity after 10 mT (100 Oe) alternating field treatment, in A/m. Pol = polarity, with N = normal, R = reverse, T = low-latitude VGP. The coordinates given are those at the lowest lava flow. The tectonic tilt corrections applied may be uncertain by up to 2°. – *N = fjöldi sýna. Dec, inc = misvísun og halli segulstefnu. Lon, lat = lengd og breidd sýndar-segulskauts. Alf = óvissa í segulstefnunni. J100 = styrkur segulmögnunar. Pol segir til um hvort segulstefnan er „rétt“ (N) eða „öfug“ (R). Staðsetning neðsta hraunlags er gefin.*