Reviewed research article

Extension of the Middle Miocene Kleifakot geomagnetic instability event in Ísafjörður, Northwest Iceland

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

Abstract — *Detailed records of past geomagnetic polarity transitions and excursions are seldom found in extrusive volcanics. One type of such events seems to involve very irregular variations of the magnetic field direction. Several examples of that type have been discovered in paleomagnetic surveys on the Neogene lava pile of Iceland. Lava sequences spanning the most notable event are accessible in the two tributary fjords Mjóifjörður and Ísafjörður south of Ísafjarðardjúp, Northwest Iceland. Paleofield direction results from about 80 sampling sites in these sequences have been described in previous publications. The present paper adds 20 sampled sites in Ísafjörður, extending the area where parts of this „Kleifakot instability event" of the geomagnetic field are recorded, to 5–6 kilometers along the fjord. Intermediate paleofield directions in the collection often agree closely with each other in correlated strata, even more than 4 kilometers apart. Events like this can provide valuable correlation tools for future stratigraphic mapping and various studies on volcanological features in the relatively uncharted region around Ísafjarðardjúp and beyond. Globally, recognition of the existence of such events will aid in the interpretation of results in other kinds of paleomagnetic studies. The role of geomagnetic paleo-intensity determinations is discussed briefly in this context.*

INTRODUCTION

Paleomagnetic research and some of its methods

The existence of the Earth's magnetic field has fascinated both scientists and the general public for centuries, but many aspects of its sources, its long-term history and its characteristics are still not well known. The configuration of this vector field at the Earth's surface resembles a field that would be created by a magnetic „dipole" (i.e. a short bar magnet or a current coil close to its center). Gradual changes observed worldwide in directions and intensities of the field on time scales of years to millennia, are termed its „secular variation".

Paleomagnetism is the branch of geoscience which involves research on the remanent magnetization (remanence) vectors in geological formations. It is primarily based on the fact that in many rocks the remanence carries information about the direction of the geomagnetic field prevailing at certain times in their history. A convenient way of presenting and comparing such directional results from different sites makes use of the so-called virtual geomagnetic pole (VGP) corresponding to the known paleomagnetic field direction at a site. A VGP position is calculated from a primary paleomagnetic direction (corrected for tectonic tilt of the strata) and the site coordinates, assuming the geomagnetic field to be caused by only a central dipole magnet pointing away from the position of that VGP. In addition to the secular variation, the field alternates at irregular intervals between opposite polarities, termed „normal" (N, with VGPs mostly in high northern latitudes) and „reverse" (R).

The natural remanence (NRM) in a rock sample may consist of components of different ages, being due to different processes, and having different stability when subjected to heating or magnetic fields. Two types of remanence are most common in Icelandic lava flows and hence of interest to the present study. They are thermal remanence (primary TRM) acquired by the rock during its original cooling, and viscous remanence (secondary VRM) assumed to have been built up gradually in the current interval of normal polarity. In most of those lava flows in Iceland which have not suffered re-heating above 100°C in situ with hydrothermal alteration, the latter component can be eliminated by appropriate treatment with alternating magnetic fields (AF demagnetization). Usually, peak fields of 20 or even 10 milli-Tesla (mT) will suffice to isolate a TRM component which is consistent from one sample from another. Such internal consistency in a unit is indeed a crucial test of its reliability as a recorder of the geomagnetic field direction during its emplacement.

In igneous rocks that have been heated to more than 100°C on burial or been deformed, the primary remanence has decayed, with concurrently increasing preponderance of secondary components. Above 250°C, the original magnetic minerals may be replaced. A number of experimental and statistical techniques have been developed for research on poor-quality rocks, involving assumptions which are sometimes not substantiated. Coe *et al.* (2014) discuss an example where a far-reaching incorrect conclusion on the properties of the geomagnetic field persisted in the geoscience literature for a quarter-century.

Each polarity transition may take a few thousand years. Ideas of these transitions, their frequency and relations to the secular variation have changed much in recent decades and continue to be debated. This also applies to so-called excursions of the geomagnetic field, when VGPs appear to wander for a while far from their usual habitat in the vicinity of one geographic pole or the other without a polarity reversal taking place. The evidence for the transitions and excursions has been derived from many different kinds of geological materials. The coverage of each of these records is generally incomplete, and the primary remanence of formations which originally preserved them may be unstable or disturbed by subsequent processes.

Some relevant results from abroad on transitions and excursions

The extensive literature on geomagnetic transitions and excursions will not be reviewed here. Examples of two apparent types of behavior in lava sequences are given below. One type yields a cluster of mid- and low-latitude VGP positions (often termed intermediate or transitional, T). In the other type, VGP positions seem to have moved irregularly all over the globe.

A complex geomagnetic event close in age to the one described in the present paper is an R-T-N-T-N transition in the island of Gran Canaria (Leonhardt *et al.*, 2002). Some 32 lava units were erupted during the central T-N-T part of this transition, which occurred at about 14 Ma. It is largely composed of clusters of VGPs; one at around 40°S is recorded in 13 flows. Directions in units of that cluster correlated well between two sampling profiles overlapping in age, about half a kilometer apart. In another example of a VGP cluster (Glen *et al.*, 2003), nine successive flows with low-latitude poles occur in a partial record of a transition or excursion of about 10 Ma age, also in the Canary Islands.

Watkins (e.g. 1969) reported results from a 71-lava section in Steens Mountain in southeastern Oregon where the geomagnetic field direction appeared to be changing with unusual irregularity between thick zones of reverse polarity below and normal polarity above. The lava flows of Steens Mountain have subsequently been studied in detail (Coe *et al.*, 2014 and references therein), resulting in the definition of a complex R-T-N-T-N-T-R-T-N transition, including some clustered groups. The age of this episode has been determined to be about 16.7 Ma.

Relevant paleomagnetic research in Iceland

The lava pile above sea level in Iceland probably contains millions of flows, of ages from 0 to at least 16 Ma. Research on magnetically stable lava series in Iceland contributed early on to the development of some key concepts in this branch of geoscience. Among these concepts are the conventional statistical parameters used in the processing, interpretation and comparison of directional results. Thus, the consistency of N directions having a vector sum of length R is estimated through a precision parameter k = N-1/N-R, an angular standard deviation (asd) of the sample directions around the vector sum, and a 95% confidence angle (α_{95}) for the sum direction (Fisher, 1953).

Research on Icelandic lavas has continued to provide much robust information on the paleo-geomagnetic field. The large number of high-quality directional data which may be used directly without need for much prior processing, allows one to appreciate various possibilities and limitations of the paleomagnetic method. Paleomagnetic directions from several thousand Icelandic lava flows have been published (Kristjánsson and Jónsson, 2007). These are mostly obtained from lava flows of > 1 Ma age, as part of stratigraphic mapping projects outside the central active volcanic regions. With polarity zones being on average composed of 15–20 lava units, they have often been very useful as aids in correlating lava sequences up to tens of kilometers apart.

The overall proportion of VGPs situated below 40°N or S is around 10%, increasing with age (Kristjánsson, 2013, p. 558). These VGPs sometimes appear to have been recorded during polarity transitions, while in other cases they seem to be major excursions of the VGP to mid- or low latitudes.

Clustered and irregularly varying paleomagnetic directions in Iceland

The relatively few cases where more than four intermediate poles are observed in successive lavas in Iceland, mostly include one or two groups each, forming conspicuous clusters within areas of say 20–30° size on the globe. See Kristjánsson (2015, p. 310) for examples of these. They tend to be found in thin series of flows (flow units, or compound flows) which are likely to have been emplaced in rapid succession compared to thicker flows (McDougall *et al.*, 1984). This may be concluded both from geological evidence and from the rate of directional changes in the field. In the ordinary secular variation, such changes as well as the resulting VGP movements may be of the order of 5° per century, according to observatory records and archeomagnetic studies.

A steady progression of the VGP in latitude is only rarely observed in Iceland, the clearest case still being the early Quaternary „R3-N3“ transition discovered by Sigurgeirsson (1957) and later studied in more detail by others. This transition was used for stratigraphic correlation across a distance of some 25 kilometers. Other intermediate paleomagnetic directions have also occasionally aided in stratigraphic work. Kristjánsson (1995) cited observations on a single-lava excursion extending over more than 10 kilometers in East Iceland. Kristjánsson and Guðmundsson (2001) present an example where a series of lavas with irregularly varying remanence directions at a polarity-zone boundary correlate well individually across distances of 2–7 kilometers in West Iceland.

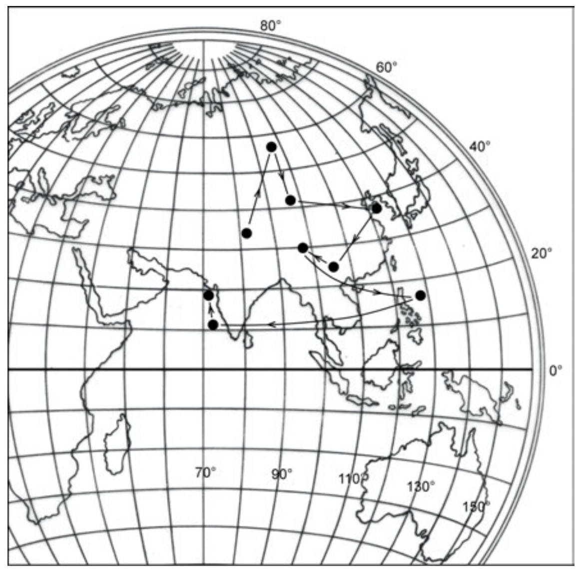

Figure 1. An unusually wide cluster of virtual geomagnetic pole positions in middle and low latitudes, from lava flows NT 33–46 at a polarity boundary of about 3 Ma age in West Iceland. – *Nokkuð dreifðar staðsetningar sýndar-segulskauta á skilum segulskeiða í hraunlagastafla vestanlands, um 3 milljón ára.*

A rather wide cluster of low- and mid-latitude VGPs in Iceland occurs within a series of thin lava flows at a reverse-to-normal polarity boundary of about 3 Ma age. The cluster is found in the thin lavas numbered NT 33–46 in the large 1973 paleomagnetic survey by Watkins *et al.* (1977) in West Iceland. In that survey, most of these units were omitted. During subsequent sampling by the author (L. Kristjánsson, unpubl. data, 1975), faults were found to cause some repetition in this lava group, reducing it to nine successive units. Their VGP positions (Figure 1) were in northern low and mid- latitudes, based on stepwise AF demagnetization of 5 or 6 samples from each flow, up to 30 mT peak field. The 95% confidence angles α_{95} for mean directions are less than 10°, except for those in the three youngest units which are 12–15° due to poor magnetic stability in some samples. A 9-m layer of glacially deposited clastic sediments occurs immediately above the sequence of Figure 1, but otherwise there is little or no sediment between the flows.

Several cases of the occurrence of widely scattered VGPs during apparent transitions or excursions have been noted in lava collections from Iceland. They generally include less than 10 successive flows. Some are listed in the paper by Kristjánsson (2015, p. 311–312), who agrees with the conclusion of Harrison (1980) that randomized behavior of the field direction occurs when the main dipole source is of diminished strength. At these times, the field configuration is mainly due to multipole sources. Due to their complex geometry, observed paleomagnetic directions will vary more rapidly and irregularly than they do when a near-axial dipole dominates. Fields during transitions and major excursions may also be expected to be relatively weak, as is well established in Iceland (Kristjánsson, 2013, p. 553-555).

THE KLEIFAKOT EXCURSION

Sampling in Ísafjarðardjúp and in profile JD, to 2012

Two unusually thick zones involving more than 10 flows with irregularly varying VGPs were described respectively by McDougall *et al.* (1984) and by Kristjánsson and Jóhannesson (1996). Both of these zones are in the Northwest peninsula, and are flanked by normal-polarity sequences above and below. The former zone occurs in flows number 16–26 spanning about 120 m thickness in profile JD, one of some forty profiles sampled in 1975–1978 (dots in Figure 2a) to make composite sections along A-B and D-E. The latter zone some 30 kilometers to the northeast occupies segments of three profiles in the two innermost tributary fjords of Ísafjarðardjúp. They are part of a composite section of twelve profiles sampled in 1982-1985 (circles in Figure 2a). These segments were flows DD 21-23 and DE 2-16 on the southeast side of a valley at the head of Mjóifjörður, and DF 1-12 similarly situated in Ísafjörður. Their approximate locations are shown by small capitals in Figure 2b.

According to Kristjánsson and Jóhannesson (1989, 1996), flows DD 21–23 are the same as the flows DE 2,4 and 5 respectively (c. 500 m away), based on very similar remanence directions and lithology. The flows DE 9 and 14 also have the same directions as DF 2 and 8 sampled more than 4 kilometers downdip, in agreement with prior conclusions from geological observations. Allowing for the overlap, the excursion event covers at least 15 successive sampled flows (i.e. DD 21–23, DE 7–13, DF 8–12), plus possibly some unexposed units. Their total thickness is 150 m including minor sediments.

It seems possible that the two excursion events recorded in the projects of McDougall *et al.* (1984) and Kristjánsson and Jóhannesson (1996) are of similar or even identical age, estimated by Kristjánsson (2015) to be about 13 Ma. The estimate was based on K-Ar determinations by McDougall *et al.* (1984) in JD and nearby profiles. Kristjánsson (2015) wished to investigate whether the excursion in Ísafjarðardjúp which he called the Kleifakot event, could be studied in additional localities. It should be noted that while the actual tectonic dip is locally about 4° in a direction 105° east, apparent dips to the northeast are only of the order of 1° as the fjords run close to the strike (Figures 2b, 3). It should also be noted that the landscape relief between Mjóifjörður and Ísafjörður and east of Ísafjörður drops to below 300 m and becomes more rounded than in most profiles previously sampled for paleomagnetic studies in the peninsula. Exposures in lava flows here are therefore somewhat intermittent, often laterally discontinuous and only 1-6 m in height at altitude intervals of 10-20 m on the soil-covered hillsides.

Kristjánsson (2015) selected four locations for new profiles, where 51 sites were sampled in 2012–2014. Profile DX is situated in the valley of Mjóifjörður near the lower part of DE (which was under snow cover at the time), and DV mostly follows the northeast edge of a gully at Hestakleif on the northwest side of innermost Ísafjörður between DE and DF. Two profiles DT and DU are close together about

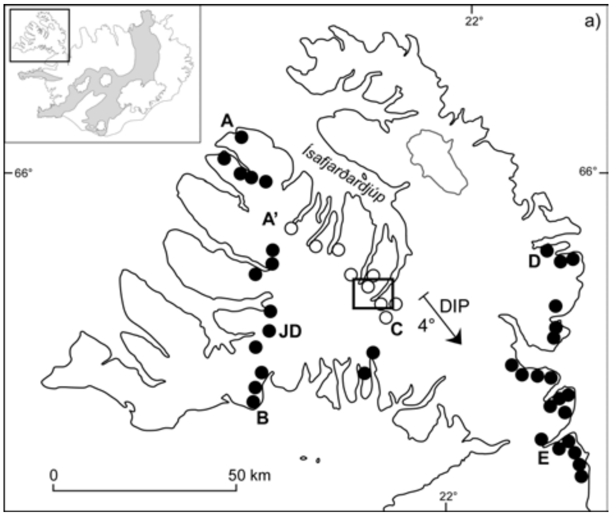

Figure 2. a) The Northwest peninsula of Iceland, showing the positions of most of the profiles sampled by McDougall *et al.* (1984) as dots and of those sampled by Kristjánsson and Jóhannesson (1996) as circles. The arrow indicates an estimate of average tectonic tilt in the peninsula, which however varies considerably from place to place. The inset shows the active volcanic zones (stippled) and ice caps of Iceland, and the box Figure 2b. Modified from Kristjánsson (2015). *– a) Vestfirðir, með fyrri sýnatökusniðum (McDougall o.fl., 1984; Kristjánsson og Jóhannesson, 1996). Ör sýnir áætlaðan meðal-jarðlagahalla, en hann er talsvert breytilegur milli staða.*

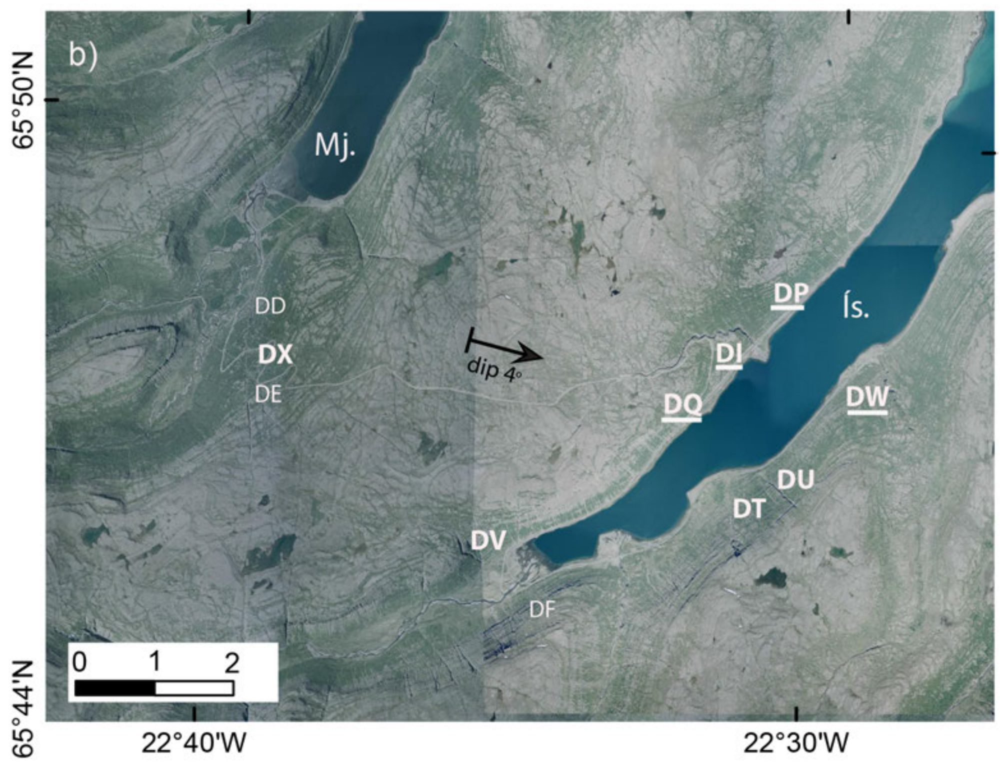

Figure 2. b) The locations of three profiles sampled by Kristjánsson and Jóhannesson (1989, 1996) in Mjóifjörður (Mj.) and Ísafjörður (Ís.) are shown in small capital letters. Profiles sampled later by the author (Kristjánsson, 2015, and present paper) represented by larger capitals, the latter ones being underlined. The arrow indicates the local dip and down-dip direction in this part of Ísafjörður. Aerial photograph from Loftmyndir Corp. *– b) Sýnatökusnið í Mjóafirði og Ísafirði; þau sem safnað var úr 2012–2016 eru með stóru letri. Ör sýnir jarðlagahalla. Loftmynd birt með leyfi Loftmynda ehf.*

Figure 3. View across Ísafjörður, showing the regular stratigraphy in the area. However, many outcrops are small and discontinuous, and some flows may be entirely hidden by soil. Profile DW wiggles from sea level up to about 100 m altitude on the southwest side of the stream Álftagrófará seen at the left-hand edge of the photo; profile DU is near its right-hand edge. A slight apparent downward tilt of the strata from right to left changes to an upward tilt farther northeast. – *Horft til sniðs DW í Álftagrófará á austurströnd Ísafjarðar, nálægt vinstri kanti myndarinnar. Hraunastaflinn hefur hér lítilsháttar sýndarhalla út eftir (frá sniði DU hægra megin), en utar í firðinum snýst hann við. Ljósm./Photo. L.Kr. 2014.*

3 kilometers north of DF, see Figure 2b. It was decided to collect at least 5 oriented 25-mm core samples from each lava in the new profiles instead of 4 in the 1980s survey, in anticipation of relatively low remanence intensities which turned out to be the case. The lavas were also somewhat altered by hydrothermal activity, and many dike intrusions were noted in Ísafjörður. This was unexpected, in view of the fact that the nearest volcanic center (Hjartarson and Sæmundsson, 2014) lies more than 15 kilometers away, to the south-southeast.

Laboratory methods, and 2012–2014 field work

Both in the study of Kristjánsson (2015) and in its continuation reported here, AF demagnetization was routinely carried out on all specimens at 10, 15, 20, 25 and 30 mT peak fields in a tumbler device. Additional treatment steps of 35 and 40 mT were often required, in order to confirm the elimination of a viscous component of unusually high coercivity. In some cases, duplicate treatment was applied at the 30 mT or higher steps, to compensate for minor amounts of rotational remanence acquired. A number of samples had to be rejected due to unstable or aberrant remanence directions. The units thus affected were generally resampled in a new location, removed meters or tens of meters from the initial one. The demagnetizing step yielding the smallest α_{95}-angle was selected as the best mean for each site.

The results presented in Table 1 of Kristjánsson (2015) showed that the within-flow agreement is generally excellent. The estimates k of the precision parameter usually are greater than 200 and the α_{95}-values are smaller than 6°. This accuracy permits the use of remanence directions for correlation of individual lava flows in different sampling profiles. Some of these correlations are shown in Figure 4 (modified from Kristjánsson, 2015). The method is in particular justified during periods of irregularly varying field. The field direction is then unlikely to precisely repeat itself at later times, so that the occurrence of closely similar remanence directions at two sites will indicate that they represent either the same flow or two flow units erupted a short time (centuries or less) apart. Aided also by the overall apparent dip and superficial lithological observations on outcrops and cores, Kristjánsson (2015) merged the results of the new profiles into a single visualization of VGP movement. For this pole path the 25 successive excursion flows DX 1–3 and 6, DV 1–7 and DT 2–14 were selected. These are shown as red dots in Figure 5, connected by arbitrary curves (segments of great circles, or modifications thereof to avoid overlaps). The three normal-polarity lavas sampled at the top of profile DU are also included. Some VGPs from the profiles of Kristjánsson and Jóhannesson (1996) were identical to poles in Figure 5, while in other cases (partly due to the presence of unexposed and inaccessible flows in the profiles) it was not certain where in the time sequence they belong. The excursion zone is underlain by the normal-polarity zone DD 3–20 of Kristjánsson and Jóhannesson (1996).

New sampling in Ísafjörður, 2014–2016

As a test of the persistence of Kleifakot-event sequences in the lava pile, additional sampling for paleomagnetic studies was carried out in 2014-2016 in profiles on the coasts of Ísafjörður (Figure 2b). The main one was DW near the Álftagrófará stream (Figure 3), with flow DW 0 at sea level. Also sampled were DQ along the old road across mt. Eyrarfjall, and DI at the Eyrargil gully, flows number 1 in all these profiles being just above the present road. Flow DI 2 could be followed northeast to the stream Laugará where it was sampled at road level as site DP 1.

In this continuation, 6 to 8 core samples were initially drilled at each site and oriented in azimuth using sun shots, sightings on distant geographic objects, and/or sightings on nearby objects with positions known from GPS measurements. Additional samples were subsequently collected when deemed necessary, cf. the preceding section. The measurements were made in an Institut Dr. Förster static fluxgate magnetometer setup, as in previous projects. AF demagnetization was carried out in a Molspin tumbler demagnetizer at the peak-field steps listed above.

Site-average results are shown in Table 1. Very similar remanence directions are sometimes found in some successive sites, such as DW 5 and 5A having visually different lithology. Sites DQ 0 and 1 which were sampled below and above the coastal road respectively, also have identical directions. Site DF 0 was cored at sea level 700 m northeast of DF 1, where sampled above the road in 1983. In the latter cases, these sites may each belong to one flow of over 20 m thickness. The directions obviously have excellent internal consistency, with all the α-angles except in DF 0 being smaller than 3.5°. Values of the precision constant k mostly lie in the range 350–1100. All the samples collected are used in computing average remanence intensities (after 10 mT AF treatment) which are generally low relative to the overall mean values of 3–4 Am^{-1} for lava collections in Iceland outside the volcanic zones (Kristjánsson, 2013, 2015).

Table 1. Paleomagnetic results from Ísafjörður lava sites, 2014–2016. – *Niðurstöður nýlegra bergsegulmælinga á kjarnasýnum úr Ísafirði.*

SITE	N	n	Dec	Inc	Lon	Lat	Alf	J10	POL
DW Álftagrófará – Ísafjörður East									
DW 0	15	11	156	+70	354	+31	2	0.97	NT
DW 1	14	10	110	+18	46	+1	3	1.00	E
DW 2	7	7	80	+14	74	+11	3	1.14	NT
DW 3				Inaccessible					
DW 4	10	10	64	+41	82	+32	3	0.91	NT
DW 5	13	6	204	-38	306	-43	3	0.62	R
DW 5A	7	7	206	-40	304	-44	3	1.53	R
DW 6	7	7	173	+31	344	-7	2	2.44	E
DW 7	7	7	176	+42	341	+0	3	0.63	E
DW 8	8	8	261	+62	276	+35	2	7.91	NT
DW 9	6	6	32	+59	107	+59	3	1.19	N
DQ Eyrarfjall road – Ísafjörður West									
DQ 0	7	7	69	-7	88	+5	3	1.33	E
DQ 1	8	6	71	-3	86	+6	3	0.63	E
DQ 2	7	5	233	-53	266	-45	3	1.07	R
DQ 3	8	8	354	+49	166	+54	3	0.31	N
DI Eyrargil – Ísafjörður West									
DI 1	7	7	73	-4	84	+5	2	1.07	E
DI 2	6	6	239	-55	259	-44	3	0.52	R
DI 3	7	7	4	+28	152	+39	2	0.75	NT
DI 4	7	7	354	+63	169	+68	3	0.32	N
DP Laugará – Ísafjörður West									
DP 1	8	7	226	-50	276	-45	2	1.05	R
DF Kleifakotsmúli – Ísafjörður East									
DF 0	7	7	295	+44	236	+34	7	0.58	NT

N = number of core samples collected. n = number of samples used in averaging of remanence directions. Dec = declination, inc = inclination, lon = VGP longitude, lat = VGP latitude, alf = 95% confidence angle (α_{95}) for the average direction, all in degrees. J10 = mean remanence intensity (all samples) after demagnetization at 10 mT peak field, Am^{-1}. Pol = polarity (N = normal, R = reverse, T = VGP latitude below 40°, E = VGP latitude below 10°). – *n er fjöldi nothæfra sýna af þeim N sem safnað var. Dec, inc lýsa segulstefnunni, lon, lat og pol lýsa staðsetningu sýndar-segulskauts, alf er 95% óvissuhorn segulstefnunnar, J10 er meðalstyrkur segulmögnunar sýnanna.*

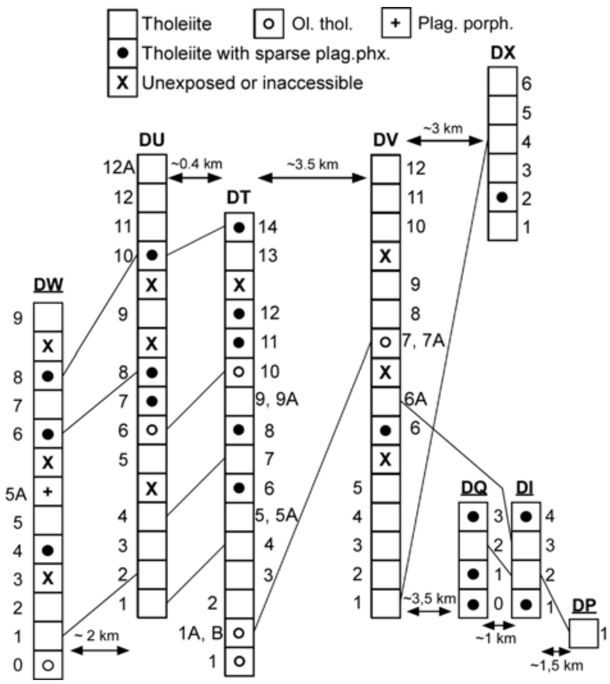

Figure 4. A very simplified scheme of outcrops sampled by Kristjánsson (2015) and of those added in the present paper (profile names underlined). Lines indicate some of the definite correlations between individual sites which are based on lithology and the apparent dip but primarily on a coincidence of remanence directions (Table 2). Approximate distances between the profiles are indicated. – *Mjög einfölduð mynd af opnum sem safnað var kjarnasýnum úr 2012–2014 og 2014–2016, sumum tengingum milli þeirra, og fjarlægðum.*

The large black dots in Figure 5 denote VGP positions from flows DV 9, DW 4, 9, DQ 1, 3 and DI 4 which clearly lie more than 10° away from any of the poles making up the red composite pole path from Kristjánsson's (2015) profiles. The smaller black dots similarly represent poles from flows DE 5, 8, 10, 16 and DF 9, 11, 12 in the profiles of Kristjánsson and Jóhannesson (1996). They are selected for insertion here to emphasize that the movement of the virtual pole during this excursion must be truly complex. Its wanderings do not seem to be confined to any preferred intervals in longitude or latitude.

These results show that exposures belonging to the Kleifakot geomagnetic event reach for at least 5–6 kilometers along strike on both sides of Ísafjörður, measured from profile DF on the southeast side and DV on the northwest side.

The new profiles and some of the correlations between them are shown schematically in Figure 4. Table 2 is a list of pairs of remanence directions employed for correlation purposes by Kristjánsson and Jóhannesson (1996), Kristjánsson (2015) and the present study.

ON THE INTENSITY OF THE PALEOMAGNETIC FIELD

Estimates of the absolute intensity of the geomagnetic field during emplacement of igneous bodies are of scientific value regarding its long-term characteristics, especially during transitions and excursions when it is relatively weak (Kristjánsson 2013, Fig. 7). One might expect that such measurements in situations like the Kleifakot geomagnetic event could yield interesting results about the field when in an unstable state.

From our demagnetization results and other evidence on the lavas from the Kleifakot event in Ísafjarðardjúp (Kristjánsson, 2015, p. 315), they are however unlikely to pass suitability tests for paleointensity studies. In several of the excursion outcrops at higher altitude in profile JD (Figure 2a), the VRM component in some samples is however small and can be removed by AF treatment at 10 mT or less with minimal effect on the TRM. They might possibly provide some satisfactory paleointensity results, if supported by consistency between samples collected from widely spaced sites in a unit as well as between

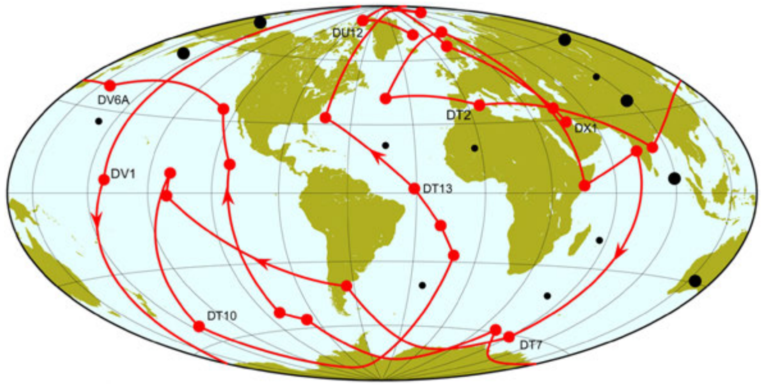

Figure 5. The irregular pole path displayed in Fig. 7 of Kristjánsson (2015), composed from 28 flows in profiles DX, DV, DT and DU of Figure 4, see text. Several VGPs from other profiles which lie far away from the poles on this imaginary path, cannot be fitted into its time sequence with certainty. They are shown as isolated black dots. Those from flows in profiles DE and DF (Kristjánsson and Jóhannesson,1996) are small, while the larger dots are from units listed in Kristjánsson (2015) and the present study. – *Ímyndaður ferill sýndar-segulskauts í um 25 hraunlögum í þekktri tímaröð, þegar jarðsegulsviðið var óvenju lengi í óstöðugu ástandi. Á kortið (Kristjánsson, 2015) hefur nú verið bætt staðsetningum segulskauta úr mörgum öðrum lögum í sniðunum á Mynd 2b sem ekki er fullljóst hvar eigi að vera í tímaröðinni. Stærri punktarnir byggja á mæligögnum úr söfnun 2012-2016, hinir á eldri mælingum.*

Table 2. Angular differences (rounded off to the nearest degree) of remanence directions in 39 matched pairs of excursion lava sites from Tables 1 in Kristjánsson and Jóhannesson (1996), Kristjánsson (2015) and the present paper. Distances between the sites in each pair are from 0.2 kilometers to more than 4 kilometers, see Figs. 2b and 4. These pairs whose visually estimated lithology is generally similar, can be used with some confidence for correlations, cf. text. – *Horn milli mældra segulstefna úr hraunum í þeim hlutum allra sýnatökusniða í Mjóafirði og Ísafirði, þar sem sviðið er að breytast óreglubundið. Fjarlægð milli staðanna í hverju pari er frá 0,2 km upp í meira en 4 km.*

DD 21 – DE 2	6°	DD 22 – DE 4	5°	DD 23 – DE 5	$13^{\circ a)}$	DE 9 – DF 2	1°
DE 14 – DF 8	7°	DX 1 – DE 2	6°	DX 3 – DE 3	6°	DX 4- DE 4	3°
DX 5 – DE 6,7	3°	DT 4 – DU 1	1°	DT 5 – DU 2	4°	DT 6 – DU 3	6°
DT 7 – DU 4	5°	DT 9 – DU 5	6°	DT 10 – DU 6	4°	DT 12 – DU 8	2°
DT13 – DU 9	2°	DT 14 – DU 10	2°	DV 7 – DT 1	6°	DX 4 – DV 1	3°
DX 5 – DV 3	4°	DE 11 – DV 7A	5°	DF 1 – DV 6	3°	DV 8 – DT 3	1°
DF 0 – DF 1	2°	DW 1 – DU 2	3°	DW 2 – DU 3	3°	DW 5A – DT 8	5°
DW 6 – DU 8	12°	DW 7 – DU 9	9°	DW 8 – DU 10	6°	DQ 1 – DI 1	2°
DQ 2 – DI 2	4°	DI 2 – DV 4	9°	DI 3 – DV 6A	4°	DQ 2 – DP 1	6°
DW 0 – DT 2	7°	DF 2 – DW 0	1°	DF 3- DT 3	3°		

a) Both sites have low remanence intensity and rather high α_{95}.

samples measured with different procedures. It must be kept in mind that such consistency is often absent, even when advanced experimental methods are applied (Biggin and Paterson, 2014).

CONCLUSIONS AND DISCUSSION

The paper briefly reviews various results from previous paleomagnetic research on polarity transitions and excursions in Iceland and abroad, with emphasis on cases with clustering of low- to mid-latitude VGPs in successive flows (e.g. Figure 1) and on cases where the VGP moves about the globe in an irregular fashion. An unusual example of the latter kind was originally described by Kristjánsson and Jóhannesson (1989, 1996) from lava profiles sampled in Ísafjarðardjúp, Northwest Iceland. Kristjánsson (2015) confirmed the persistence of this geomagnetic excursion in the lava pile by detailed sampling at 51 sites in four new profiles, and thorough demagnetization of secondary remanence components. He estimated that this Kleifakot instability event is around 13 Ma age, if contemporaneous with the K-Ar dated excursion in profile JD of Figure 2a. Covering the emplacement of some 25 successive lava flows of 220 m total thickness, the event may have lasted for perhaps 100 thousand years judging from overall rates of buildup of the lava pile in the peninsula (McDougall *et al.*, 1984; Kristjánsson, 2015, p. 322–323). This paper adds 20 lava sites from five locations to the excursion sites already described, extending significantly the area in Ísafjörður where the event is recorded. In the present study some samples had to be rejected due to discordant directional results, but excellent within-site agreement was eventually obtained.

Some previous instances of the use of intermediate remanence directions to support stratigraphic correlations in Icelandic lavas were quoted above. The results in Table 2 used in Figure 4 further demonstrate the value of this method and confirm the good quality of direction results from our lavas. The angular differences between the 39 correlated site pairs rarely exceed 8°, averaging less than 5°. Comparable agreement occurred in the paired sites discussed by Kristjánsson and Guðmundsson (2001, p. 40) as well as in profile JD (Table 2 of Kristjánsson, 2015), where fewer samples were generally collected. The angular differences include effects of all random and systematic errors in orientation and measurement of the samples. The measured remanence directions can also have been influenced by unavoidable noise sources such as local magnetic anomalies at the time of initial cooling, slight movement of outcrops by recent erosional processes, and undetected lateral variations in the tectonic tilt vector. In some cases, one may be comparing two units emplaced at slightly different times.

Figure 6. A typical appearance of the contact between a lava flow and an undisturbed clastic sediment, in the fjords of Ísafjarðardjúp. Total height about 1.2 m. – *Dæmi um hvernig hraunlag leggst á set í staflanum sunnan Djúps. Ekkert gjall er þar á milli. Ljósm./Photo. L.Kr. 2015.*

The rate of buildup of the lava pile seems to vary somewhat within the area of the sampled profiles. For this reason it is not often possible to follow individual lava flows for more than a couple of kilometers laterally, in particular where exposures are incomplete. Thus, units DF 2 and 3 are the only ones of the excursion flows DF 1–12 whose remanence directions find definite counterparts in profiles DT, DU and DW along the fjord (Table 2). Even so, the Kleifakot event as a whole promises to be a useful stratigraphic marker in the coastal areas of inner Ísafjarðardjúp where little geological work has yet been carried out, and also farther away. A transitional series of a few flows was correlated similarly by Kristjánsson *et al.* (2004, p. 590) across some 5 kilometers between their profiles GL and AF in central North Iceland, with only a partial match in individual directions.

The presence of paleomagnetic directions which can be correlated with ease and some certainty over distances of kilometers, offers further opportunities for research. For instance, spatial variations in the chemical composition of extensive lava flows can be studied, and also their provenance. The mode of emplacement of the flows in Northwest Iceland, which has hardly been studied at all, may be quite different from that in for instance many of the historical lava flows in Iceland. Preliminary inspection of the lower boundaries of lavas in the fjords of Ísafjarðardjúp often reveals an abrupt contact with undisturbed underlying sediment, and the presence of vertical vesicles (Figure 6). This indicates that the flows were of a highly fluid kind, rather than having a slow-moving front covered in scoria which would leave a basal deposit (cf. Óskarsson and Riishuus, 2014, Fig. 8f).

On the basis of long experience, the present writer believes that the way to optimize the scientific value of paleomagnetic research in Iceland is to concentrate on projects involving remanence directions in extensive lava sequences combined with thorough stratigraphic mapping, selected petrological/geochemical analyses, and radiometric dating. As an example, comprehensive stratigraphic/tectonic mapping and sampling for various laboratory measurements in the whole of Mjóifjörður, Ísafjörður and their valleys to the southwest may be envisaged. Such a project would however require resources not available at present. Paleointensity determinations might be attempted at a later stage, focusing on unaltered rocks at high altitude.

Confirming the occurrence of geomagnetic excursions and other instances of temporary instability and/or weakening of the geomagnetic field is relevant to various research areas within paleomagnetism. Thus, theories of the geodynamo must allow for the possibility of such episodes. Those studying results of remanence measurements on ocean sediments also need to recognize them, in order to distinguish them from apparent large directional fluctuations caused by artifacts. See for instance Fig. 3 of Krijgsman and Kent (2004) where rapid polarity changes are seen to occur in a 10-meter segment of a DSDP core, possibly of 13–14 Ma age. Lastly, periods of geomagnetic instability and low field intensity can result in misinterpretation of ocean-ridge magnetic anomaly lineations, if not taken into account as such.

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ÁGRIP

Upplýsingar um stefnu fornsegulsviðs jarðar má fá úr mælingum á varanlegri segulmögnun berglaga. Þrátt fyrir marghattaðar rannsóknir áratugum saman er enn margt óljóst um hegðun sviðsins, ekki síst á þeim tímabilum þegar jarðsegulskautin hafa flakkað langt frá heimskautunum. Það er vegna þess hve þær upplýsingar sem berglögin varðveita eru ófullkomnar og oft bjagaðar á ýmsan hátt. Ljóst er þó að slíkt flakk endar ýmist með því að sviðið snúist alveg við, eða að segulskautin færist til baka í fyrra horf. Í síðtertier hraunastafla Íslands og einnig erlendis má finna syrpur laga, sem geta bent til þess að segulskauta-flakkið hafi stundum hægt mjög á sér í miðjum klíðum. Eru gefin dæmi um það í þessari grein; hugsanlega stafar slíkt þó oft af hraðri upphleðslu laganna. Í einhver önnur skipti virðist sviðið hafa breyst mjög óreglulega um mun lengra tímabil en þau fáeinu árþúsund sem hver umsnúningur er almennt talinn hafa tekið. Tvö áberandi tilfelli af þeirri tegund fundust fyrir mörgum árum í rannsóknum á jarðlagastafla Vestfjarða, annað á Dynjandisheiði og hitt innst í Mjóafirði og Ísafirði í Ísafjarðardjúpi. Þau gætu raunar verið frá alveg sama tíma, fyrir um 13 milljónum ára. Í greininni er sagt frá framhaldi athugana á þeim hraunasyrpum í Ísafirði sem varðveita hinar óreglulegu segulstefnur. Höfundur hefur kennt þetta tímabil við eyðibýlin Kleifakot. Stefnurnar má mæla með nákvæmni upp á nokkrar gráður, og oft nota þær ásamt öðrum gögnum til að tengja saman af miklu öryggi fjarlægar opnur í sama hraunlag eða í samtíma lögum, milli þeirra sniða sem sýnum hefur verið safnað úr. Rekja mátti í upphafi þessara rannsókna útbreiðslu Kleifakots-syrpanna um meira en 4 kílómetra vegalengd milli fjarðarbotnanna. Opnur í jarðlögin eru ófullkomnar þegar norðar dregur þaðan. Nokkra þolinmæði hefur þurft við segulmælingarnar vegna þess að hin upprunalega segulmögnun hraunanna er frekar dauf og hefur orðið fyrir áhrifum af síðari ummyndun á svæðinu. Nú hefur fundist, að syrpurnar teygi sig a.m.k. 5–6 kílómetra út eftir Ísafirði báðum megin. Þær gætu því líklega nýst vel í átaki við stratigrafiska kortlagningu, berg-

segulmælingar, valdar bergfræðirannsóknir, og aldursgreiningar á staflanum í Inn-Djúpinu. Í slíku átaki sem er löngu orðið tímabært, mætti jafnframt m.a. varpa ljósi á þætti í eðli eldvirkninnar sem myndaði hina eldri hluta landsins. Að auki getur þekking á tilvist óstöðugleika-tímabila í sögu jarðsegulsviðsins nýst við túlkun mælinga á segulmögnun sjávarsetlaga og á segulsviðs-frávikum yfir úthafshryggjum. Oft eru gerðar tilraunir til að meta styrk fornsegulsviðsins og auka þannig skilning á hegðun þess, til dæmis meðan á umsnúningum og öðru meiriháttar flakki segulskautanna stendur. Eiginleikar bergsins í viðkomandi hraunlögum í Ísafjarðardjúpi virðast þó gera það miður heppilegt til þesskonar tilrauna.

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