New evidence on an episode of geomagnetic instability, recorded in Middle Miocene lava flows in Northwest Iceland

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ABSTRACT

Information on the character of paleomagnetic polarity transitions and major excursions is important to understanding of the generation of the geomagnetic field. The main aim of this study was to extend previous observations on a complex excursion event at around 13 Ma, recorded in lava flows south of the Ísafjarðardjúp fjord in the Northwest peninsula of Iceland. Core samples were collected in four short hillside profiles, for measurement of their remanence vectors after conventional alternating-field treatment. Despite minor hydrothermal alteration in the area, reliable estimates of primary geomagnetic directions were obtained in 49 of the 51 sites sampled. It is shown that large directional variations were taking place between at least 25 successive flows. Judging from the overall rate of buildup of the local lava pile, the duration of this event may reach 100 kyr. The results support findings in the literature on the occurrence of other episodes of geomagnetic instability in the Neogene. The excursion sequence in Ísafjarðardjúp will also be of value for stratigraphic correlation in the Northwest peninsula (and even farther afield), as it is probably contemporaneous with an excursion found 30 km away.

Keywords: paleomagnetism, Neogene, excursions, stratigraphy, basalt

1. INTRODUCTION

1.1. Intermediate paleomagnetic poles in Icelandic lavas

Improving our observational evidence of the character of paleomagnetic reversals is obviously of importance for models of the geomagnetic field and of its generation. The virtual geomagnetic pole (VGP) might for instance travel at a steady pace from one geographic pole region to the other, it might do so in several steps, or it might move irregularly over the globe before settling down in high latitudes. In the study of paleomagnetic directions in sediments, the original signal from time-variable directions tends to be smoothed by a slow rate of accumulation and other diagenetic factors. In contrast, only spot readings of the field are obtained from sequences of lava flows, and the interval between individual lavas is often long compared to secular variation time scales.

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Lava sequences are therefore generally not very helpful in the detailed charting of VGP movements, such as may occur at polarity transitions and major excursions.

The lava pile exposed in Iceland (Fig. 1) contains strata of ages from 0 to about 16 Ma. Paleomagnetic directions from several thousands of lava flows have been published, mostly on rocks of >1 Ma age outside the central active volcanic zones. The overall proportion of the corresponding VGPs below 40°N or S is around 10%, higher in the older sequences (*Kristjánsson, 2013, p. 558*). These VGPs occur both between zones of lavas with higher-latitude poles of opposing polarities, and as apparent major excursions of the pole. The lava sequences of Iceland have so far only furnished few examples suggestive of smooth transitional VGP paths. The best-known path segment which extends through a latitude interval of some 50°, was described by *Sigurgeirsson (1957)* and studied in more detail by *Kristjánsson and Sigurgeirsson (1993)* and *Goguitchaichvili et al. (1999)*.

Those cases where more than four intermediate magnetic poles are observed in successive flows, mostly include one or two clustered groups. They tend to be found in thin series of flows (flow units, or compound flows). These are likely to have been emplaced in rapid succession, relative to the lava pile in general where the time interval between lavas may average 5−10 kyr. Published examples of such pole clusters include those found by *Sigurgeirsson (1957)* in lava flows of the Hvalfjörður fjord and the Borgarfjörður valleys in West Iceland, resampled by *Kristjánsson and Sigurgeirsson (1993)*. Among other instances are flow units V11A-G in the Norðurdalur valley, East Iceland (*Watkins and Walker, 1977*), flows GS 2-6 in the Tjörnes peninsula of Northeast Iceland (*Kristjánsson et al., 1988*; *Camps et al., 2011*), two clusters in profile NT of *Watkins et al. (1977)*; *L. Kristjánsson (unpublished data, 1975)* in the Borgarfjörður valleys, and the late-Quaternary Skálamælifell excursion on the Reykjanes peninsula, Southwest Iceland (*Jicha et al., 2011*). See Fig. 1.

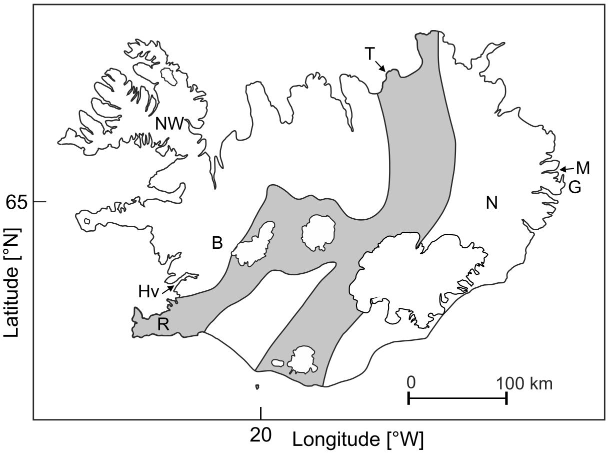

Fig. 1. Map of Iceland, showing the main active volcanic zones (gray), ice caps and some locations referred to in the text. NW - Northwest peninsula, B - Borgarfjörður valleys, Hv - Hvalfjörður fjord, T - Tjörnes peninsula, N - Norðurdalur valley, R - Reykjanes peninsula, M - Mjóifjörður, G - Gerpir.

1.2. Complex geomagnetic transitions and excursions in Icelandic lava formations

Several occurrences from Iceland of widely variable VGP positions in paleomagnetic transitions or excursions have been reported in the literature. However, each of these generally involves ten or fewer lava flows; see for instance a list in *Kristjánsson and Jóhannesson (1989, p. 130)* and global maps of pole positions from later collections by *Kristjánsson and Sigurgeirsson (1993, Fig. 7), Kristjánsson et al. (2004, Fig. 5)* and *Kristjánsson (2009, Fig. 4)*.

An episode of geomagnetic instability covering at least 12 successive lava flows was noted in results from a large 1975−78 field project of mapping and sampling for paleomagnetic and stratigraphic research in the Northwest peninsula. Some 40 profiles with partial stratigraphic overlap were mapped, forming two composite sections along A-B and D-E in Fig. 2a. 1261 flows were sampled for magnetic measurements, and over 70 K-Ar age determinations were made (*McDougall et al., 1984*). They yielded ages from 12 to 15 Ma in the western section and 8 to 12 Ma in the eastern one. By interpolation of the K-Ar dates, the age of the excursion which occurs in flows 16–26 of profile JD (Fig. 2a) was estimated by *Kristjánsson and Jóhannesson (1996)* to be somewhere in the range 12.5−12.9 Ma. It may be described as an N-T-R-T-N event, T signifying VGPs below 40°N or S. See Section 4.2 below for results of new paleomagnetic sampling in this profile.

At least three geomagnetic instability events were found in a subsequent project where 307 lava flows were sampled in 1982−85 for paleomagnetic measurements (*Kristjánsson and Jóhannesson, 1996*). The sampling involved 12 profiles (not all shown separately in

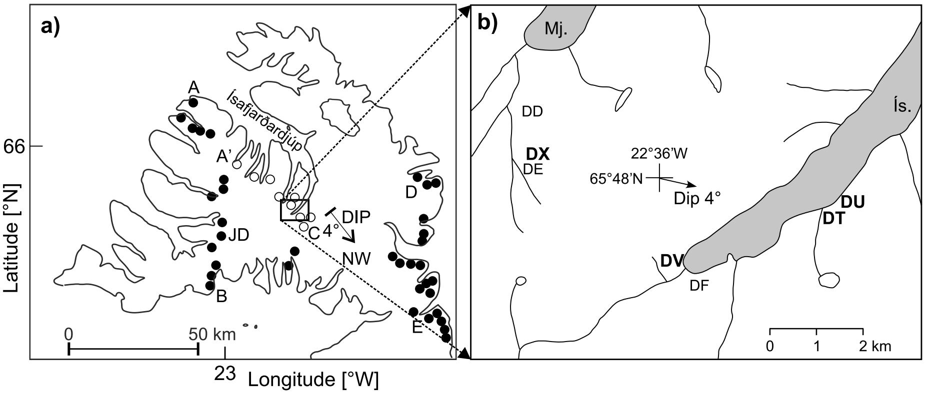

Fig. 2. a) Map of the Northwest peninsula of Iceland, adapted from *Kristjánsson and Jóhannesson (1989)*. Dots: profiles sampled by *McDougall et al. (1984)*. Circles: profiles sampled by *Kristjánsson and Jóhannesson (1996)*. The estimated average southeasterly tectonic dip in the peninsula is shown. However, it varies in magnitude from 0° to 10°, and in direction between East and South; in the area of Fig. 2b (small box) the lavas dip about 105°E. **b)** Enlargement from the map in a), showing some streams and small lakes. Approximate locations of the base of four new sampling profiles DT, DU, DV and DX (in bold) as well as of three profiles DD, DE, DF of *Kristjánsson and Jóhannesson (1996)* are indicated. Mj. - Mjóifjörður fjord, Ís. - Ísafjörður fjord.

Fig. 2a), making up a composite section along A'-C south of the main fjord Ísafjarðardjúp of the Northwest peninsula. In particular, large changes in field directions were recorded in at least 15 successive flows of 140 m total thickness, within three profiles partly overlapping in age. These profiles were DD and DE on the eastern side of the Mjóifjörður tributary fjord, and DF at the eastern side of Ísafjörður (Fig. 2b). A table of the VGP positions in question was originally presented by *Kristjánsson and Jóhannesson (1989)*, and a global map of these appeared as Fig. 8 of *Kristjánsson and Sigurgeirsson (1993)*. The episode appeared to be an N-T-N-T-R-T-R-T-N excursion. No new radiometric ages were obtained in this project, but *Kristjánsson and Jóhannesson (1989, 1996)* suggested tentative correlations between polarity zones and other stratigraphic markers in the Ísafjarðardjúp composite section A'-C (Fig. 2a) and in the western section A-B of *McDougall et al. (1984)*. They concluded that the lava sequence with highly variable remanence directions in their profiles DD, DE and DF might date from the same episode as the lavas in profile JD.

2. NEW SAMPLING IN THE ÍSAFJÖRÐUR AND MJÓIFJÖRÐUR FJORDS

During the paleomagnetic sampling in Ísafjarðardjúp in 1982–85 (*Kristjánsson and Jóhannesson, 1996*), occurrences of dikes were noted in the vicinity of the profiles DD, DE and DF. The lavas had also suffered more hydrothermal alteration than many of those sampled so far in the western part of the Northwest peninsula. It is provisionally estimated that the profiles reach at least well down into the chabazite-thomsonite zeolite zone.

It was desired to confirm that the erratically varying remanence directions in the above profiles reflect variations in the ambient field during emplacement, rather than being artifacts caused by intrusions or local alteration. For this purpose, four new profiles were sampled in their vicinity in 2012–14 (Fig. 2b). Two of these were DT 1-14 about 3 km from DF, and DU 1-12A beginning a further 0.4 km from the base of DT (Fig. 3). The bearing between DF and DT is close to the local strike direction of the lava pile, so that one could expect an apparent dip of not more than 1° down from DF to DT along the fjord. A third profile DV 1-12 lies across the valley from DF. The fourth profile is DX 1-6 in Mjóifjörður, about 0.2 km north of the lowest part of the former profile DE.

Fig. 3. View across the Ísafjörður fjord, illustrating the simple lava stratigraphy and the moderately good exposures in the area. The sampling profiles DT and DU start below the letters and reach up to 110 and 140 m altitude respectively, while the local slopes reach to 300–350 m.

Exposures in the new profiles are not as complete as in those sampled in the previous field project, although some flows can be followed for hundreds of meters. Commonly, discontinuous outcrops of 1–6 m height lying tens of meters apart laterally, are separated by soil- or scree-covered gaps. Scoriaceous flow tops are seen in some cases, and occasionally also thin (<0.2 m) reddish or brown volcanoclastic sediments between the flows. A simplified stratigraphic scheme, similar to those of *Kristjánsson et al. (2003)* is shown in Fig. 4. GPS coordinates of all sampling sites may be obtained from the author on request.

At least five 25-mm core samples were obtained from each lava flow in the profiles, spread over a few meters to tens of meters laterally. Their azimuth directions were measured by sighting on the Sun or distant geographic objects with a Brunton compass. The accuracy of orientation is of the order of 2°. Flows DT 9, 9A and 11 to 14 as well as DV 1 and 6 were each sampled in two places over 100 m apart, and the remanence results were combined. Only one sample was recovered from flow DV 12, because of difficult access.

Judging from lithology, the lava flows in the new profiles are mostly tholeiites (Fig. 4). For many of these the description "sparsely plagioclase-porphyritic" (*Kristjánsson, 2009*) may be applied, but the amount of phenocrysts often varies between samples. A few olivine tholeiite compound flows are also found.

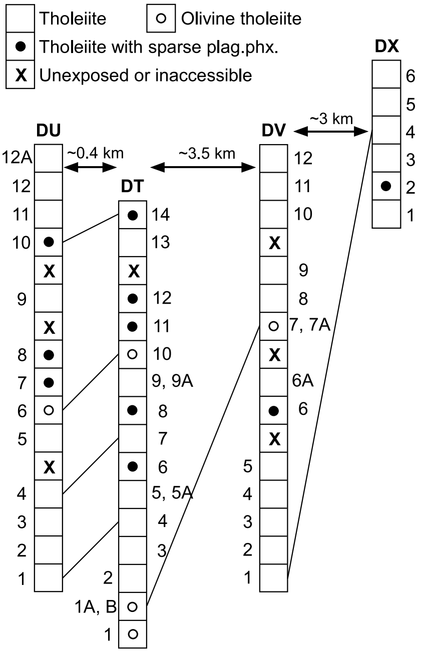

Fig. 4. Schematic stratigraphy of the new profiles sampled in Ísafjörður and Mjóifjörður, indicating lithologic types and intervals where flows are most likely to have been missed. Definite correlations between the profiles (not all are shown) are based on the dip and strike, similar lithology, and identical remanence directions in pairs of flows, see Section 4.1.

3. MAGNETIC MEASUREMENTS ON CORE SAMPLES

3.1. Remanence directions

The remanence of one 20–22 mm long specimen from each sample was measured in a four-sensor Institut Dr. Förster fluxgate magnetometer. Alternating field (AF) demagnetization was carried out in a Molspin device with a 2-axis tumbler, all samples being initially treated at 10, 15, 20, 25 and 30 mT peak fields. Their behavior was broadly similar to that reported in earlier studies from the Northwest peninsula. In a small proportion of the current collection, this remanence was very soft and unstable in direction as shown by two examples DV 3-1 and DU 6-3 in Fig. 5. A significant secondary (viscous) component of the remanence was often present. The inset in Fig. 5 displays a Zijderveld plot for one of the samples, whose viscous remanence was fully removed by the 15 mT treatment. In a few cases AF treatment of up to 25 mT peak field was needed for the complete elimination of the viscous component, in contrast to relatively unaltered lavas in the peninsula where 10 mT treatment usually suffices. The AF treatment in

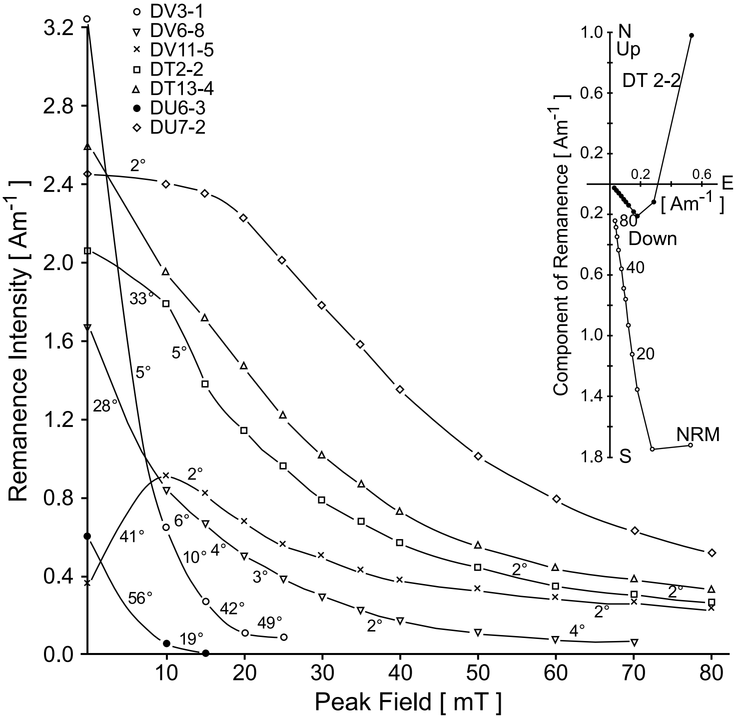

Fig. 5. Stepwise alternating field (AF) demagnetization curves of seven samples from profiles DT, DU and DV. Numbers at the curves indicate the directional change between successive steps, if it exceeds 1.5°. The inset is a Zijderveld diagram for one of the stable samples, at the same AF demagnetization steps. Projections on the horizontal plane are shown as dots, those on the vertical plane as circles.

stepwise increasing fields was terminated when at least four successive steps had given directions agreeing within 2°. At fields of 30 mT and higher, unexpected changes in directions sometimes occurred due to rotational remanence or instability. In such cases the AF treatment was repeated with the specimen in an inverted position, the results being averaged. With these precautions, only very minor (and apparently random) directional changes occurred up to 80 mT. One sampling site (DT 1B) seems to have been baked by the overlying flow, and a few samples were suspected of remagnetization by dikes. One sample was affected by a lightning strike. Additional samples were later collected from some flows that had given problems in initial measurements.

Results for mean remanence directions (corrected for the estimated local tectonic tilt of 4° towards 105°E) and the corresponding VGP positions are listed in Table 1. Values of precision parameters (k) and 95% confidence radii (α_{95}) for the directions, derived by conventional methods (*Fisher, 1953*), are also listed for each lava flow. Remanence intensities from weakly magnetized and unstable samples are included in the arithmetic flow-average intensities (after 10 mT treatment) given in Table 1; samples suspected of reheating by intrusions or overlying flows are excluded.

3.2. Other magnetic properties

The remanence intensities in Table 1 after 10 mT AF treatment are generally low. The excursion flows (excluding the normal-polarity flows at the top of profile DU) average about 1.3 Am^{-1}, whereas the corresponding average values from other surveys outside the volcanic zones are mostly 3–4 Am^{-1} (*Kristjánsson, 2009*). Initial volume susceptibilities in the transitional flows of the present survey average 0.02–0.025 SI units, as is the case in general for lavas in the older regions of Iceland.

Low-field thermomagnetic curves were obtained on seven crushed samples in air, using a Bartington MS2 W/F audio-frequency susceptibility bridge and furnace. In all the samples, slight to moderate increase in susceptibility was observed to set in at between 250°C and 400°C, before a final Curie point of an original phase (titano-magnetite or -maghemite) was reached. These Curie points were in the range 510–550°C, in some cases with minor tails towards 600°C in the thermomagnetic curves. The room-temperature susceptibility decreased by 10–50%. A correlation was not observed between the shape of the curves and the stability of the presumed primary remanence to AF demagnetization. However, in these as well as in collections of less altered lava flows in Iceland, unstable samples appear to exhibit more complex thermomagnetic curves and a steeper initial rise (Hopkinson effect) in susceptibility than those with relatively high median destructive fields. Thermomagnetic curves on samples from the less altered lavas often yield Curie points below 500°C, and a considerable increase in their room-temperature susceptibility or saturation magnetization may occur (*L. Kristjánsson, unpublished data, 1968–2002*). This evidence indicates that Icelandic Neogene lavas generally are not ideal material for absolute paleointensity determinations by currently available methods.

Table 1. Mean dip-corrected paleomagnetic remanence directions and virtual geomagnetic poles (VGPs) from flows in profiles DT, DU, DV and DX. *N/n* - number of core samples collected/used. *Dec* - declination, *Inc* - inclination, *k* - Fisher's precision parameter, and α_{95} - 95% confidence angle for the mean direction. *Lon*, *Lat* - east longitude and north latitude of the corresponding VGP. J_{10} - arithmetic mean remanence intensity after 10 mT AF treatment, see text. *Pol* - polarity (N - normal, R - reverse, T - VGP latitude between 40°and 10°, E - VGP latitude below 10°). The coordinates given for the lowest flow in each profile were obtained with a manual Garmin eTrex GPS receiver.

Lava	*N/n*	*Dec* [°]	*Inc* [°]	*Lon* [°]	*Lat* [°]	*k*	α_{95} [°]	J_{10} [Am^{-1}]	*Pol*
DT Ísafjörður, east side. DT 1 is at 65°47.681′N, 22°31.638′W									
DT 1	5/5	70	+13	83	+14	503	3.4	2.02	NT
DT 1A	5/5	70	+17	83	+16	568	3.2	1.40	NT
DT 1B	9/0	Unstable samples; baked by DT 2							N?
DT 2	6/6	135	+72	6	+38	630	2.7	1.46	NT
DT 3	5/5	215	+76	317	+42	1637	1.9	1.65	N
DT 4	5/5	46	+80	29	+73	228	5.1	0.32	N
DT 5	5/5	109	+14	47	−1	201	5.4	0.85	E
DT 5A	5/5	109	+23	45	+3	226	5.1	0.84	E
DT 6	5/5	78	+23	74	+16	211	5.3	1.84	NT
DT 7	12/5	131	−68	60	−61	699	2.9	0.50	R
DT 8	6/5	212	−38	296	−41	205	5.4	1.03	R
DT 9	6/6	296	−24	219	−1	781	2.4	0.86	E
DT 9A	8/4	298	−7	220	+8	1038	2.9	0.57	E
DT 10	10/5	299	−80	185	−53	1042	2.4	0.33	R
DT 11	14/9	169	−7	349	−27	341	2.8	0.59	RT
DT 12	10/8	176	+21	341	−13	925	1.8	0.94	RT
DT 13	12/12	189	+44	329	+2	340	3.4	3.06	E
DT 14	11/11	247	+64	287	+33	696	1.7	2.23	NT
DU Ísafjörður, east side. DU 1 is at 65°47.731′N, 22°31.110′W									
DU 1	5/5	42	+80	31	+74	868	2.6	2.35	N
DU 2	5/5	106	+18	49	+2	352	4.1	1.51	E
DU 3	6/6	77	+17	76	+13	752	2.4	1.92	NT
DU 4	8/6	118	−68	73	−56	370	3.5	0.40	R
DU 5	6/5	301	−22	215	+1	178	5.7	0.34	E
DU 6	11/8	307	−77	187	−46	457	2.6	0.49	R
DU 7	8/6	175	+17	343	−15	484	3.0	1.51	RT
DU 8	5/5	178	+20	339	−14	472	3.5	2.07	RT
DU 9	5/5	188	+43	330	+1	2066	1.7	4.38	E
DU 10	5/5	249	+62	285	+32	776	2.7	1.98	NT
DU 11	7/6	16	+76	76	+83	1341	1.8	2.08	N
DU 12	5/5	334	+77	257	+80	215	5.2	1.50	N
DU 12A	7/7	27	+86	352	+73	1018	1.9	7.03	N

Table 1. Continuation.

Lava	*N/n*	*Dec* [°]	*Inc* [°]	*Lon* [°]	*Lat* [°]	*k*	α_{95} [°]	J_{10} [Am^{-1}]	*Pol*
DV Ísafjörður, west side. DV 1 is at 65°47.014′N, 22°35.468′W									
DV 1	12/9	328	–30	188	+5	312	2.9	1.27	E
DV 2	10/7	139	–62	42	–59	138	5.2	0.41	R
DV 3	7/6	229	–63	263	–56	331	3.7	2.11	R
DV 4	7/6	241	–64	249	–52	597	2.7	1.36	R
DV 5	5/5	234	–68	250	–59	1548	1.9	1.66	R
DV 6	12/9	297	+44	234	+34	336	2.8	0.61	NT
DV 6A	10/8	1	+26	156	+38	306	3.2	0.39	NT
DV 7	5/5	69	+19	83	+17	232	5.0	2.10	NT
DV 7A	6/6	70	+22	81	+18	400	3.4	1.64	NT
DV 8	5/5	213	+76	318	+41	569	3.2	2.30	N
DV 9	7/6	52	–65	120	–30	116	6.2	0.16	RT
DV 10	6/6	110	–11	51	–13	771	2.4	0.71	RT
DV 11	5/3	191	–64	315	–69	2470	2.5	0.66	R
DV 12	1/1	206	–34	305	–40	-	-	1.35	R
DX Mjóifjörður, east side. DX 1 is at 65°48.205′N, 22°39.135′W									
DX 1	6/6	96	+54	46	+29	409	3.3	1.29	NT
DX 2	6/6	95	+61	44	+35	242	4.3	1.32	NT
DX 3	5/5	72	+83	14	+66	388	3.9	1.81	N
DX 4	6/4	330	–32	185	+4	307	5.3	1.41	E
DX 5	5/5	238	–63	253	–53	371	4.1	1.84	R
DX 6	6/5	275	+21	247	+12	167	5.9	0.58	NT

4. INTERPRETATION OF THE NEW REMANENCE DIRECTION RESULTS, AND CORRELATIONS

4.1. Local correlations

It is seen from Table 1 that the agreement of the accepted sample directions within each flow is excellent, with k values generally exceeding 200 and α_{95}-radii being 6° or less. Remanence directions differing by less than 10° are occasionally found at two successive sampling sites. This can be due to flows that were erupted in a short time interval compared to secular variation time scales (sites DT 1/1A, DU 7/8, DV 3/4, 7/7A, DX 1/2). In a few cases the base and top of the same flow may have been sampled, with the middle part being obscured by soil cover (DT 5/5A, DV 4/5). In other cases, angular differences exceeding 10° were found between remanence directions in sites which had been expected from field evidence to have been emplaced a short time apart (DT 9/9A, DU 12/12A, DV 6/6A).

The directions mostly vary between lavas in each profile in an erratic fashion as in the excursion of profiles DD, DE and DF of *Kristjánsson and Jóhannesson (1996).*

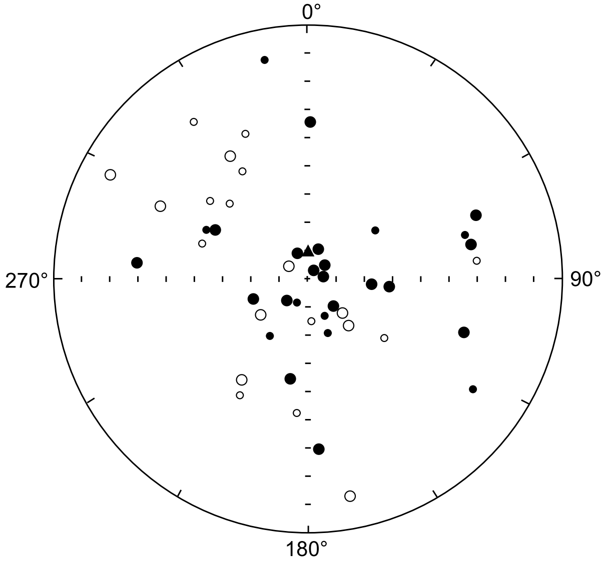

Fig. 6. Stereographic projection of remanence directions in non-overlapping segments of the four new sampling profiles (large symbols; full circles indicate positive inclinations, open circles negative inclinations). Directions from the flows DE 8–16 and DF 1–12 of *Kristjánsson and Jóhannesson (1996)* which cover most of the excursion interval are also shown (small symbols). Triangle: central axial dipole field.

A stereographic plot of remanence directions in non-overlapping segments of the four new profiles is shown as large symbols in Fig. 6. Not included are data points from some flow units in directional clusters, as well as data from the underlying normal-polarity sequence DD 3 to 20.

There is an apparent dip of 1–2° between the profiles DT and DU (Fig. 3). Some thin lava units in both may be covered by soil, and some small, crumbly or possibly out-of-place outcrops were not sampled. A complete one-to-one correspondence between remanence directions in the temporally overlapping parts of these profiles is therefore not to be expected. However, one finds excellent agreement in several pairs of sites. Thus, the directions in flows DT 4, 5, 6, 7, 9, 10, 12, 13 and 14 are all within 6° of those in DU 1, 2, 3, 4, 5, 6, 8, 9 and 10 respectively. Some of these correlations, which also agree with the lithological types of the outcrops, are shown in Fig. 4. One assumes that the three flows sampled above DU 10 belong to a thicker normal-polarity zone.

Remanence directions also furnish a definite correlation between profiles DT and DV. Thus, the transitional directions in the units DV 7, 7A are within 6° of those in DT 1, 1A; both belong to olivine tholeiite compound flows of relatively rare occurrence. Further, the quite different direction in the overlying tholeiite flow DV 8 is identical to that in DT 3. The base of profile DV similarly has a solid correlation to profile DX in Mjóifjörður, as the remanence directions in the transitional flows DV 1 and DX 4 are only a few degrees apart. The same applies to flows DV 2 and DX 5. The VGPs of non-overlapping parts of the profiles are shown in Fig. 7, connected by imaginary paths.

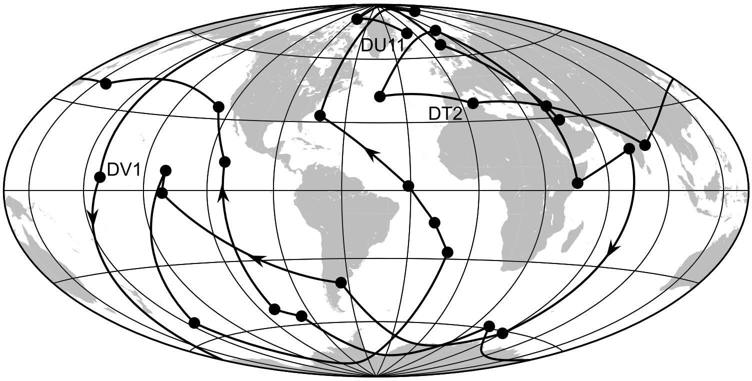

Fig. 7. Map of virtual geomagnetic poles (VGPs) in the complex excursion obtained by combining the non-overlapping profile segments DX 1–3, DV 1–7 (incl. DX 6) and DT 2–14. VGPs from the overlying normal-polarity flows DU 11–12A are also shown.

Correlations can also be established with some flows in the three profiles of *Kristjánsson and Jóhannesson (1996)*, as well as between these profiles. However, it appears that they have recorded several details of the excursion which are not found in the new profiles, cf. the directions plotted as small symbols in Fig. 6. This is to be expected, as the lateral extent of flows in Iceland often does not exceed a couple of km when they are 10 m or less in thickness.

4.2. Resampling at profile JD; correlation and ages

In order to exclude the distant possibility that the directional results in profile JD (Fig. 2a) of *McDougall et al. (1984)* were affected by some artifacts (unexposed intrusives, slumping, experimental errors, etc.), resampling of ten lava flows was carried out 100–300 m east of the original profile. Exposures in the new sampling localites were not complete. These excursion flows lie at 350–500 m altitude and have suffered much less secondary alteration than those in our Ísafjarðardjúp profiles. Their primary remanence is therefore generally stable. Measurements on 5–7 samples from each flow were made with the same equipment as already described, yielding similar ranges of k and α_{95} values. Table 2 shows a comparison between directions from *McDougall et al. (1984)* and those from the resampling, confirming the presence of a complex excursion. The VGPs in this excursion are shown in Fig. 8.

As stated above, whole-rock K-Ar age determinations have indicated that the excursion in profile JD and probably also the one in the Ísafjarðardjúp profiles are a little less than 13 Ma old. It is known (*McDougall and Harrison, 1988, p. 29*) that ^{40}Ar/^{39}Ar ages on basalts tend to be slightly older than K-Ar ages. Hence, this episode may perhaps have occurred before 13 Ma; the normal-polarity subchrons in the 13–14 Ma interval according to a recent version of the Geomagnetic Polarity Time Scale (*Ogg, 2012*) are C5AAn at 13.032–13.183 Ma, C5ABn at 13.363–13.608 Ma and C5ACn at 13.739–14.070 Ma.

Table 2. Left: Remanence directions and VGPs in a part of lava profile JD of Table 1A in *McDougall et al. (1984)*, where these vary in an unusual way. **Right:** Results from sites sampled near this profile in 2013–14. Legend as in Table 1. A correction has been applied for 3.5° tectonic dip towards 135°E. Four samples were discarded, all from the new sampling in flow JD 18. The position of the new site in JD 14 is 65°40.126′N, 23°13.026′W, altitude 370 m.

McDougall et al. (1984)							This study						
Lava	*n*	*Dec* [°]	*Inc* [°]	*Lon* [°]	*Lat* [°]	α_{95} [°]	*n*	*Dec* [°]	*Inc* [°]	*Lon* [°]	*Lat* [°]	*k*	α_{95} [°]
JD 12	3	351	+65	175	+70	2							
JD 13	3	105	+67	30	+39	3							
JD 14	3	163	+79	345	+45	14	7	118	+79	7	+51	251	3.8
JD 15	3	328	+80	285	+77	5	5	306	+80	286	+70	791	2.7
JD 16	3	116	–5	43	–13	33	5	112	+17	43	–1	156	6.1
JD 17	3	87	+29	63	+15	5	5	75	+23	76	+17	274	4.6
JD 17A	3	75	+19	77	+15	3	5	77	+20	74	+15	632	2.7
JD 18	3	7	–65	152	–23	27	7	8	–68	151	–26	252	3.8
JD 19	3	311	–71	190	–37	16	5	272	–63	223	–39	182	5.7
JD 19A							5	280	–51	224	–25	141	6.5
JD 20	3	266	–75	211	–55	3							
JD 21	3	199	–79	218	–82	2	6	203	–74	262	–79	878	2.3
JD 22	3	258	–30	251	–20	5							
JD 23	3	327	–55	184	–14	15							
JD 24	3	295	–69	202	–38	7	6	301	–77	189	–47	1023	2.1
JD 25	3	174	+1	343	–24	5							
JD 26	3	87	+62	48	+40	3							
JD 27	3	119	+85	356	+59	8							
JD 28	3	14	+77	61	+84	2							

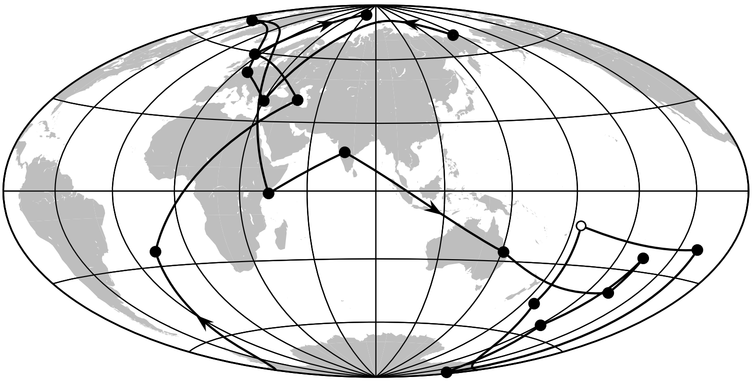

Fig. 8. Map of VGP positions from the profile segment JD 12–28. The directional α_{95} values are 8° or less in all the lavas but one, denoted by open circle.

Improved resolution of the ages of these instability locations will hopefully be attained by a program of ^{40}Ar/^{39}Ar dating in the Northwest peninsula which is currently underway (*R.A. Duncan and M.S. Riishuus, personal communications 2013*).

5. POSSIBLE LONG-DISTANCE CORRELATIONS

5.1. Geomagnetic instability in East Iceland lava sequences

K-Ar ages of up to 13 Ma have been reported from some of the oldest lavas in East Iceland (data in Table 2 of *Watkins and Walker, 1977*, recomputed with current decay constants). Therefore, evidence for the geomagnetic instability episode in Ísafjarðardjúp might possibly be found in East Iceland paleomagnetic profiles. Two published instances come to mind in this context, namely flows G 23–31, H 2–6 at the Gerpir promontory (*Watkins and Walker, 1977*), and the slightly younger flows DB 17–25, TO 1–6 north of the Mjóifjörður fjord (*Kristjánsson et al., 1995*), see Fig. 1. This possibility needs to be followed up by further stratigraphic research, with resampling for paleomagnetic and ^{40}Ar/^{39}Ar work. To date, no definite correlations of geological units from narrow time intervals (for instance, volcanoclastics from major explosive eruptions) have been reported between the areas west and east of Iceland's active volcanic zones. Such correlations could be very helpful in establishing the history of these zones.

5.2. The Gran Canaria and Steens Mountain episodes

Some published studies on Neogene volcanic rocks worldwide have noted occurrences of VGPs moving in an apparently irregular fashion over the globe. The record closest in age to that described in the present paper is probably an R-T-N-T-N transition in the island of Gran Canaria (*Leonhardt et al., 2002*). The central T-N-T part of this transition, which took place at about 14 Ma, comprises some 32 lava units. It is possible that with improved dating techniques, it can be settled whether this event coincides with any instability episode found in Icelandic lava series.

*Watkins (*e.g., *1963, 1969)* reported results from extensive paleomagnetic work in the Steens Mountain area of southeastern Oregon, including a 71-lava section within which the geomagnetic field direction appeared to have varied in an unusually complex fashion. Some 30 lava flows yielding transitional VGPs were found between thick zones of reverse polarity below and normal polarity above. 26 of the transitional lavas belonged to two groups having fairly similar remanence directions, i.e. the flows numbered 30–48 and 49–56 by *Watkins (1969)*. The lava flows of Steens Mountain have subsequently been studied in great detail (*Jarboe et al., 2011*), resulting in the definition of altogether 75 intermediate directions in an R-T-N-T-N-T-R-T-N transition at 16.7 Ma. Evidence suggesting that extremely rapid field changes occurred during a part of this episode (e.g., *Coe et al., 1995*) has recently been shown by *Coe et al. (2014)* to be due to a rock-magnetic artifact. The oldest published K-Ar date on exposed lava flows in Northwest Iceland (*McDougall et al., 1984*) is about 15.4 ± 0.2 Ma, obtained on a K-poor olivine tholeiite at least 50 m above the stratigraphically lowest sea-level outcrops. It is probable that higher ages will be found in the current dating program mentioned above. However, no extended sequence of widely varying transitional VGPs was found in the oldest lava series of Northwest Iceland by *McDougall et al. (1984)* or in a comprehensive survey of these lavas by *Kristjánsson et al. (2003)*.

6. CONCLUSIONS

The question of the character of geomagnetic transitions and excursions has been much debated by paleomagnetists during the last half-century. This debate has involved matters such as the complexity of pole paths, field-intensity variations, possible precursor features, and preferred VGP longitude intervals. The present study has a bearing on some aspects of this question, including time scales and the relative magnitudes of dipole and non-dipole components during intermediate field configurations.

An unusual episode of apparent geomagnetic field instability was found by *Kristjánsson and Jóhannesson (1989, 1996)* in at least 15 successive lavas within three profiles DD, DE, DF in two tributary fjords of Ísafjarðardjúp in the Northwest peninsula of Iceland (Fig. 2b). These authors correlated it with a similar episode in profile JD (Fig. 2a) about 30 km away, sampled by *McDougall et al. (1984)*. The episode occurred within the time interval 12.5–12.9 Ma according to K-Ar dates, an estimate which may be subject to revision when new ^{40}Ar/^{39}Ar age determinations from this area become available. The author felt that a confirmation of its occurrence in Ísafjarðardjúp was needed, in view of somewhat advanced hydrothermal alteration around the excursion profiles and the relatively low primary remanence intensity of the lavas. We have therefore sampled 51 new lava sites in four hillside profiles DT, DU, DV and DX (Fig. 2b, Table 1), the first two of these lying more than 3 km from the previous profiles. According to the local dip and strike, the new profiles were expected to cover the interval of instability. In 2012–14, 5 to 12 core samples were collected at each site, and the number of AF demagnetization steps applied to each sample was at least 5. This may be compared to 4 samples/4 steps by *Kristjánsson and Jóhannesson (1996)*, and 3 samples/2 steps by *McDougall et al. (1984)*.

In the present survey, about 17% of samples were discarded due to weak, discordant and/or poorly stable remanence directions. It is a higher proportion than in other recent collections from the Northwest peninsula; for instance, less than 2% of samples were discarded in the 365-lava study by *Kristjánsson (2009)*. The remaining stable samples however showed excellent within-unit agreement, so that reliable mean remanence directions ($\alpha_{95} < 6°$, Table 1) could be obtained from all but two sites (DT 1B, DV 12).

The results confirm those of *Kristjánsson and Jóhannesson (1989,1996)* and their conclusion that an episode of geomagnetic field instability with highly scattered directions (Fig. 6) is recorded in their profiles. In several cases, individual lava flows can be correlated between the four new profiles (Fig. 4), as well as with flows in the three previous ones. At least 25 successive flows or flow units in the new profiles were erupted during the main episode of field instability, i.e. DX 1–3, DV 1–7 and DT 1A–14 (Fig. 7). The apparent polarity pattern there is N-T-N-T-R-T-N-T-R-T-R-T-N. Some 10 flows in the nearby previously sampled profiles, whose reliably determined VGPs belong to the excursion, also are without counterpart in any particular flow in the new profiles. As the total thickness of the composite sequence of excursion flows in the new profiles is at least 220 m, the duration of the episode may have reached 100 kyr, judging from the overall rate of buildup. This rate was estimated by *McDougall et al. (1984)* to be 180 m/100 kyr (or one lava per 5 kyr) in the western part of the peninsula, and only 70 m/100 kyr in the eastern composite section in Fig. 2a, of 8–12 Ma age.

Partial resampling of profile JD has also confirmed the presence of complex VGP movement in about 12 successive flows (Table 2, Fig. 8). Episodes of this nature may represent an unusually long-lived state of the geomagnetic field, when a weak dipole moment is dominated by variable higher-order components. There is mounting evidence for the occurrence of such episodes, from the available observations in Neogene formations in Iceland and elsewhere pointed out in this paper. This phenomenon should be studied in more detail, and taken into account in for instance geomagnetic polarity time scales and models of the generation of the field.

We propose that an appropriate name for the Ísafjarðardjúp episode is the Kleifakot geomagnetic instability event, after two abandoned small farmsteads not far from the base of profiles DF and DD respectively. There are opportunities for investigating the Kleifakot event further by sampling at locations in the tributary fjords south of Ísafjarðardjúp, as well as in the stratigraphically uncharted area north of that fjord (Fig. 2a), in the highlands of the Northwest peninsula, and along its southwestern coast. New multi-disciplinary research on those profiles of similar age in East Iceland where lavas exhibit erratic paleofield variations, also needs to be carried out to assist in establishing precise correlations across the active volcanic zones.

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