Reviewed research article

Paleomagnetic studies on the lava pile between Skálavík and Álftafjörður, Northwest Iceland

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Abstract — *This paper focuses on the lava pile in the westernmost part of the south coast of the Ísafjarðardjúp fjord in the Northwest peninsula of Iceland, between Skálavík and Álftafjörður. New laboratory measurements on the paleomagnetism of over 60 lava flows in four profiles are utilized in the completion of a tentative polarity column for a composite section of 3.4 km thickness along Ísafjarðardjúp. The magnetic results which among other things document the occurrence of several excursions of the geomagnetic field, are consistent with other available data from the area. They also strengthen correlations with a composite section running south from Skálavík to Breiðafjörður. Some relevant previous studies on the Northwest peninsula are reviewed, with emphasis on the question whether the presence of the oldest lignite-containing sediments there is related to major volcano-tectonic events. Judging from the thickness of polarity zones, the rate of buildup of lavas below these sediments seems to have been of similar order of magnitude as elsewhere in Iceland.*

INTRODUCTION: PREVIOUS RESEARCH RELEVANT TO THE GEOLOGY AND PALEOMAGNETISM OF THE NORTHWEST PENINSULA

The lava piles in the older regions of Iceland at the northwestern and eastern coasts of the island are fairly similar in appearance, consisting of sequences of predominantly basaltic lava flows of average thickness 8–10 m. Successive lavas are separated by scoria zones as well as by thin layers of volcanoclastic sediments. The lava pile in the Northwest peninsula (Vestfirðir, Figure 1) is somewhat monotonous compared to that of the eastern fjords, especially away from its eroded central volcanoes. Thus the tectonic tilts are small (mostly < 7°) and rather uniform, there are fewer intrusions or acidic lava flows and tuffs, and alteration minerals such as zeolites are less common. Although more is known of the age and stratigraphy of lavas in the Northwest peninsula than in many other parts of Iceland, much remains to be studied. The project to be described here attempts to fill a few small gaps in our knowledge of the older lava formations of the peninsula. In particular it extends downwards (from Álftafjörður to Skálavík) the geomagnetic polarity column of Kristjánsson and Jóhannesson (1996) for the lava pile on the south side of Ísafjarðardjúp. Some other previously published results are reviewed in the next few sections, especially as regards rates of buildup of the lava pile and the significance of hiatuses in this buildup.

Findings up to 1960

Walker (1959) was able to trace petrographically distinct groups of feldspar-porphyritic or olivine-rich flows for distances up to tens of km in the mostly tholeiitic lava pile of East Iceland, while such grouping seems to be less persistent in the Northwest. On the other hand the Northwest peninsula has some geological features which are almost absent in the East fjords, such as the presence of sediments containing

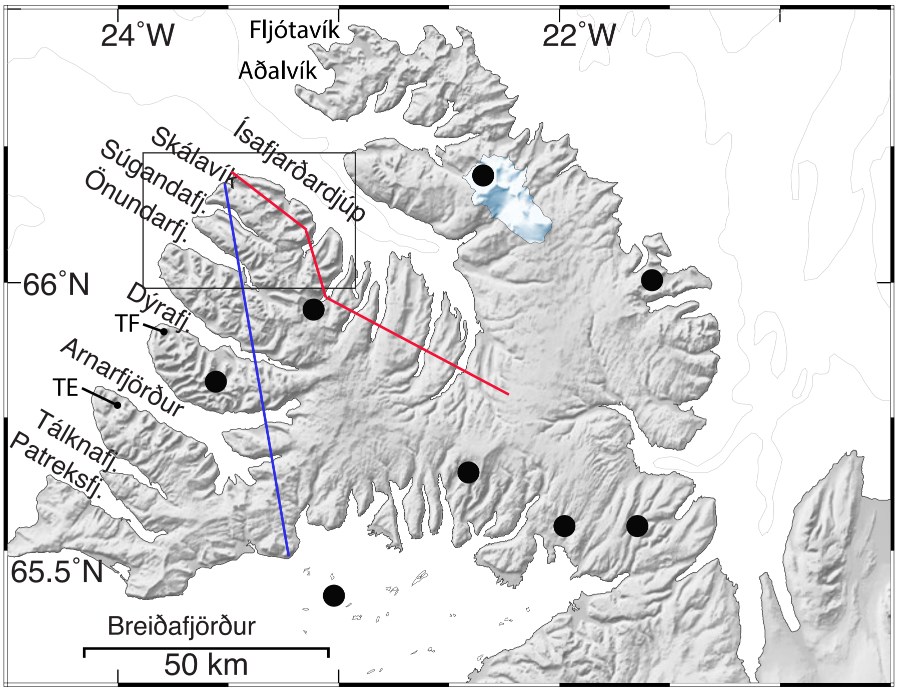

Figure 1. Northwest peninsula of Iceland. Colored lines indicate cross-sections from which the polarity columns in Figure 2 are derived. Box shows location of Figure 3. Black dots mark approximate mid-positions of central-volcano complexes (Jóhannesson and Sæmundsson, 2009). Profiles TF and TE (see text) were sampled by Kristjánsson *et al.* (2003) and Kristjánsson (2009) respectively. – *Vestfirðir. Lituðu línurnar marka samsett jarðlagasnið á 2. mynd, punktarnir marka miðjur megineldstöðva, og kassi sýnir staðsetningu 3. myndar.*

lignite and/or well-preserved impressions of vegetation. These attracted the attention of scientists already in the 18th century. The lignite locations of Northwest-Iceland were by many thought to belong to a single horizon (Thoroddsen, 1896) signifying a hiatus in volcanic activity in the Eocene, or between the Eocene and the Miocene. Bárðarson (1927, p. 146–150) who agreed with the view of a single long hiatus, states that the lava flows below the lignite sediments have suffered considerably more alteration, tilting and intrusion by dikes than those above. No detailed studies have yet been made of the lava pile to establish whether a significant discontinuity in these aspects actually occurs at that level. The view of an Eocene age of the oldest lignites in both Northwest- and East Iceland was supported by studies of fossil pollen (Pflug, 1959), and the dominant view of Iceland's geological history in the first half of the 20th century was one of intermittent (possibly alternating) episodes of volcanism, erosion, and vertical tectonic movements (Bárðarson, 1927; Einarsson, 1960).

Research in 1960–1970

Views of the volcanic and tectonic activity at the Mid-Atlantic Ridge underwent a revolution in the mid- to late 1960s, with the general acceptance of sea floor spreading which among other things introduced the possibility of significant lateral movements of large areas. The picture of Iceland's geology was also changed dramatically, especially due to the research of G.P.L. Walker and his students and collaborators (e.g., Walker, 1959; Watkins and Walker, 1977). This change included recognition of the key role of central-volcano complexes, and replacement of the older view of intermittent volcanic and tectonic episodes by a new vision: continuous volcano-tectonic processes including rifting and subsidence at the active zones passing through Iceland from southwest to northeast.

A further important change of views was brought about by K-Ar age determinations on some of the oldest lava flows in Northwest- and East Iceland (Moorbath *et al.*, 1968) which indicated ages of only 14–16 and 12–13 Ma respectively. It was also suggested tentatively in the late 1960s (Sæmundsson, 1967, p. 158) that a volcanic zone had in the past been active west of the present zone in West Iceland. This is now generally agreed to have been the case, with the activity moving to its current location at around 7 Ma. A similar eastwards jump has been suggested to have occurred at about 15 Ma (Hardarson *et al.*, 1997; Pringle *et al.*, 1999).

The dating by Moorbath *et al.* (1968) in Northwest Iceland was done on material from a single locality at a stratigraphic height of some 500 m above the oldest lignite beds, so that neither the age of the lignites nor of the 300 m thick underlying exposed lava pile was determined. The rate of buildup of the pile was also unknown. In the large 1964–1965 field study in East Iceland summarized by Watkins and Walker (1977), a pile of some 900 lavas (including up to 200 flow units), 8.8 km in total thickness, was inferred to have been built up in a time interval estimated to reach from about 13.5–2 Ma. This translates into an average rate of 0.7–0.8 km per million years or 10 m per 12–14000 years.

In a pilot paleomagnetic project on lava flows around six outcrops of the oldest lignite-bearing sediments south of the long fjord Ísafjarðardjúp (Figure 1), Kristjánsson (1967, 1968) found that the sediments tended to be associated with a zone of a few normal-polarity lavas within a thicker reverse zone. This as well as the fact that the lignite sediments are often absent in exposed locations where they could be expected, lent some support to the possibility that the interval represented by the lignite-bearing sediments was relatively short, say of the order of 0.2 M.y. rather than say >2 M.y.

Research in 1970–1985

Few radiometric age studies have been published on Icelandic lavas after 1968, the major contribution being due to I. McDougall of the Australian National University in connection with comprehensive stratigraphic and paleomagnetic mapping efforts in several areas in 1972–1978. In particular, his total of some 180 dates included more than 70 lavas in two composite sections through the west and east coastal regions of the Northwest peninsula (McDougall *et al.*, 1984). The western composite section which ran from Skálavík south to Breiðafjörður (along the blue line of Figure 1), was made up from non-overlapping parts of over 15 hillside profiles, about 450 sampled lava flows. The profiles were correlated by stratigraphic mapping based on tectonic dip, unusually thick sediments, petrographically distinct lava groups, and geomagnetic polarity zones mapped in the field.

The lignite-bearing sediment beds in Northwest-Iceland include laterite, clay, tephra, and sandstone, but the order and proportions of these types vary greatly between outcrops (Sigurðsson and Sæmundsson, 1984). It has not been certain to what extent the lignite beds may be considered as distinct horizons. With the work of McDougall *et al.* (1984) it was established that in the western part of the peninsula there were at least three different sets of relatively thick sediment outcrops. The oldest and best known of these includes occurrences south of Ísafjarðardjúp: in the Skálavík and Bolungarvík inlets, in Súgandafjörður, and in Önundarfjörður. They consist of various altered volcanoclastics, rarely exceeding 15 m in thickness where exposed. It has also always been assumed (Sigurðsson and Sæmundsson, 1984) that outcrops in Aðalvík and Fljótavík north of Ísafjarðardjúp and on the promontories south of Dýrafjörður and Arnarfjörður (Hardarson *et al.*, 1997) belong to the same episode. A second set of sediment outcrops runs from southwest to northeast just east of Patreksfjörður, Tálknafjörður, Arnarfjörður and Dýrafjörður, and a third one with a more east-westerly trend follows the coast of Breiðafjörður (Jóhannesson and Sæmundsson, 2009). Some fossiliferous sediment occurrences may not belong to any of the above three sets. Thus, a well-known plant-fossil locality within profile TE south of Arnarfjörður (Figure 1) lies at least 200 m above a lignite outcrop at the end of that promontory (Figure 3 of Kristjánsson, 2009).

The progression of K-Ar ages obtained by McDougall *et al.* (1984) harmonized broadly with the stratigraphical mapping, and yielded ages from 14 Ma above the oldest lignite sediments south of Súgandafjörður to just less than 12 Ma at the south coast. The pattern of polarities in their 4-km thick western composite section is shown as the right-hand column of Figure 2. The inferred average rate of buildup there was about 1.8 km/M.y., somewhat higher than in East Iceland (see above). McDougall *et al.* (1984) also sampled the lava pile at some distance below the lignite sediments in their profile SK in Skálavík, and their profiles SU, SN south of Súgandafjörður crossed these sediments (Figures 2, 3). There is a slight southeasterly dip (around 1° on average) along Súgandafjörður. In profile SU the sediments are expected to lie between flows 33 and 34 in a thick zone of reverse polarity (flows SU 8 to 49). Samples from flows 32 and 33 had unstable magnetization. In contrast, the lignite sediments in the other profile SN some 9 km downdip (also sampled by Kristjánsson, 1968) are overlain by ten normal-polarity flows. Explanations may include a general down-dip thickening of lava series (cf. Walker, 1959).

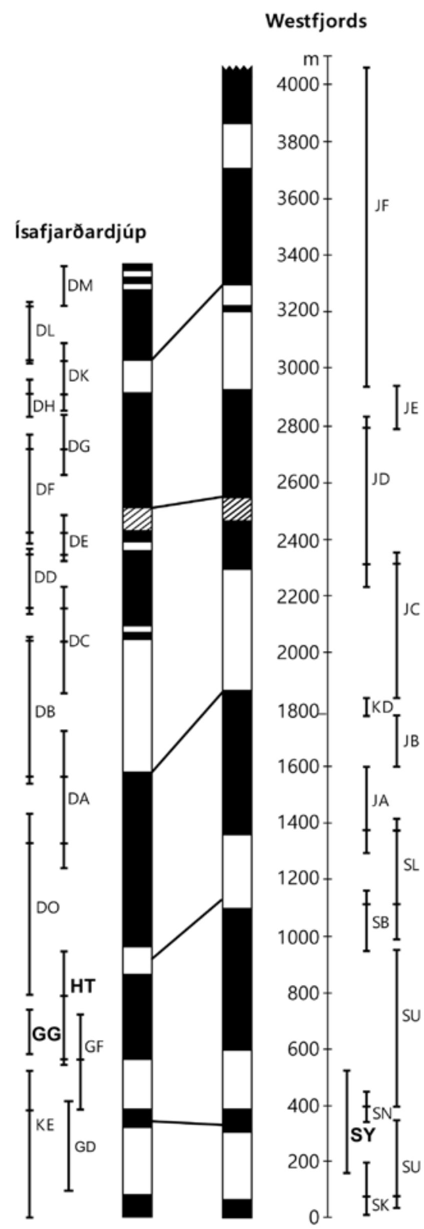

Figure 2. Simplified columns of polarities in two composite sections (Figure 1) through the lava pile of Northwest Iceland. Left: section along the tributary fjords south of Ísafjarðardjúp, from Kristjánsson and Jóhannesson (1996). Right: section from Skálavik to the south coast of the Northwest peninsula, from McDougall *et al.* (1984). Both columns include additions at the base from profiles sampled by Kristjánsson *et al.* (2003), as well from new profiles (in bold). Further information on the profiles is given in the three papers and in the text below. The short bars on some of the vertical lines indicate which portion of that profile was used in the construction of the respective column. Black is normal polarity, hatching denotes an episode of unstable geomagnetic field whose existence has been recently confirmed (Kristjánsson, 2015). The thicknesses of the polarity zones should not be taken to be precise; they vary from place to place. Many thin polarity zones and excursions have been left out. Tentative correlations are shown, from bottom to top: Lignite sediments – compound flows in profiles DO and SB – top of thick normal-polarity zone – field instability – Brjánslækur sediments. – *Helstu syrpur af réttum og öfugum segulstefnum í hraunlagasúlum úr þversniðunum á 1. mynd, ásamt tengingum milli þeirra. Byggt er á gögnum úr fyrri greinum nema í feitletruðu sniðunum neðst.*

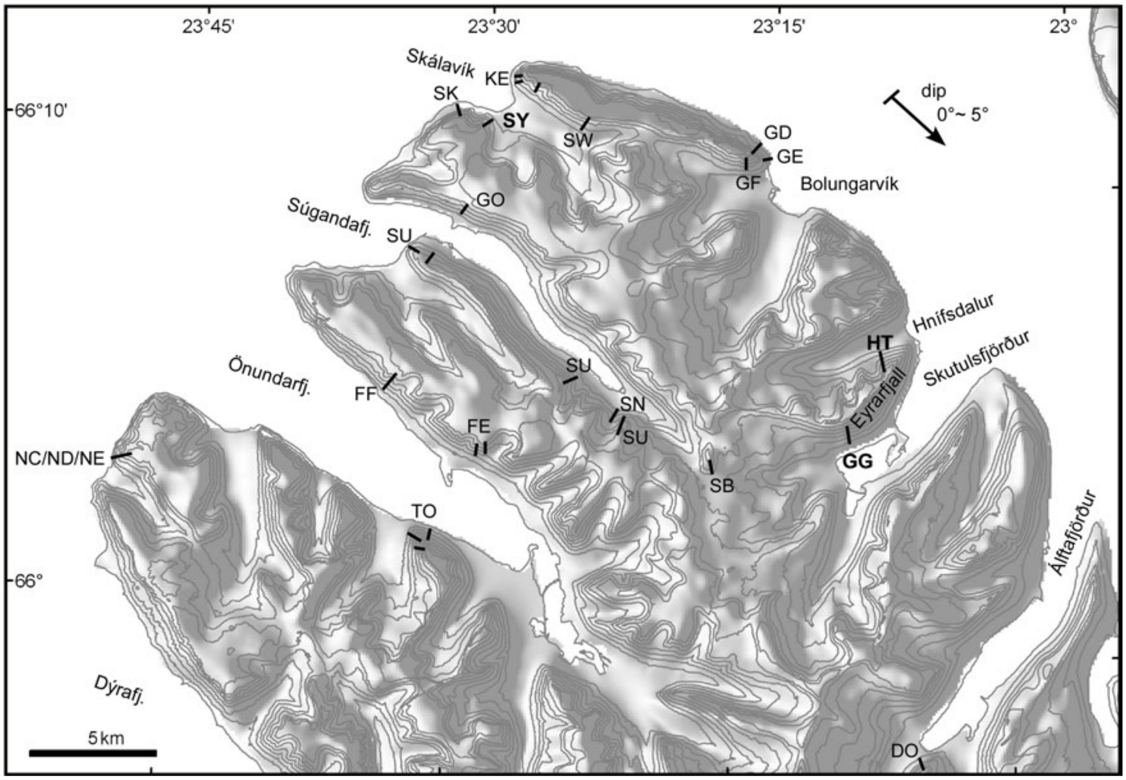

Figure 3. Locations of paleomagnetic sampling profiles SK, SU, SN, SB of McDougall *et al.* (1984), DO of Kristjánsson and Jóhannesson (1996), KE, SW, GD, GE, GF, GO, FF, FE, TO and NC/ND/NE of Kristjánsson *et al.* (2003) and the new profiles SY, HT and GG (in bold). – *Staðsetningar sýnasöfnunarsniða í fyrri greinum, auk þriggja nýrra úr Töflu 1 hér.*

K-Ar dating by McDougall *et al.* (1984) included a determination of a single flow below the oldest lignite sediments, namely SU 10 at 50 m a.s.l. It yielded an age of 15.3 Ma with a small error margin. One should note however, that it is an olivine tholeiite, a type of basalt which is both low in potassium (SU 10 has just about the lowest K-content of all the samples dated in the 1984 paper) and is in general more susceptible to hydrothermal alteration than olivine-free tholeiites. The possibility of systematic error in age here is demonstrated by the fact that the age determined for the flow SU 37 (340 m a.s.l.) is almost 0.9 M.y. younger than that for SU 70 (630 m a.s.l.). Both lie above the lignite sediments and have about four times the potassium content of SU 10. It is therefore doubtful whether the age difference of 2.4 M.y. between SU 10 and SU 37 does reflect any lengthy hiatus at the lignite sediments.

Research in 1985–2000

Guðmundsson (1989) mapped sections through the lava pile of the area between Bolungarvík, Álftafjörður and Önundarfjörður at numerous locations. This mapping which also involved the interpretation of many core logs from drill holes, was commissioned by the Public Roads Administration (Vegagerð ríkisins) as a fundamental part of preparations for the construction of road tunnels from Skutulsfjörður to Önundarfjörður and Súgandafjörður. Guðmundsson (1989) divided the pile above the lignite-bearing sediments into 5–7 main stratigraphic series. These in turn were divided into sub-series which are more or less of lithologically distinct character and of uniform magnetic polarity as determined by fluxgate magnetometer measurements in the field. The succession of lava flows dips towards the southeast, by an amount which may vary with altitude. At the coast of Ísafjarðardjúp it averages of the order of 2° from the western side of Bolungarvík to Álftafjörður, where the stratigraphy becomes complicated due to local buildup of acidic rocks and other central-volcano products.

A few $^{40}Ar/^{39}Ar$ dates from Northwest-Iceland were published by Hardarson *et al.* (1997). A sample from 290 m depth in a borehole situated between the lower and upper parts of McDougall *et al.'s* (1984) profile SU in Súgandafjörður yielded reasonably consistent results of 15.7 Ma. However, the material in the drill hole has suffered severe hydrothermal alteration, possibly due to an intrusive body close to the hole. Its significance is therefore doubtful like the one on SU 10 just mentioned. It should be noted that Hardarson *et al.*'s profile SU is not identical to profile SU of McDougall *et al.* (1984); it appears to be composed of parts of McDougall *et al.*'s SU and SN along with results from additional field mapping. The correlations between Skálavík, Súgandafjörður and Dýrafjörður in Figure 2 of Hardarson *et al.* (1997) were made on the basis of fluxgate measurements of lava polarities in the field. Their normal-polarity zones in flows KE 22–24 in Skálavík, and TF 1 on the south side of Dýrafjörður were later shown to be caused by interfering factors like viscous remanence (Kristjánsson *et al.*, 2003). Hardarson *et al.*'s normal-polarity zone SU 3–5 has not been sampled for laboratory paleomagnetic measurements. Their age determinations on two fresh-looking tholeiites from just above and below a lignite-sediment horizon in profile TF (Figure 1) gave statistically indistinguishable ages of about 14.8 Ma.

Kristjánsson and Jóhannesson (1996) published a stratigraphic/paleomagnetic study on several lava profiles (Figure 2) south of Ísafjarðardjúp, the westernmost (oldest) one being DO of Figure 3. Their composite section (red line, Figure 1) crossed all the tributary fjords to the southeast from Álftafjörður. No radiometric dates are yet available from these profiles, but the authors suggested how they might correlate with the major part of the western composite section of McDougall *et al.* (1984).

Research in 2000–2009

Kristjánsson *et al.* (2003) studied the paleomagnetic directions in several profiles crossing the oldest lignite sediments in Northwest Iceland (Figures 3 and 4). Four of the profiles were in the Aðalvík and Fljótavík inlets (Figure 1) north of Ísafjarðardjúp, and in these a fairly consistent pattern of polarities was observed: the lignite-bearing sediments were near the base of a reverse-polarity zone, with an excursion to low latitudes higher up in at least two profiles and an R to N reversal still higher. See Figure 6 of Kristjánsson and Jónsson (2007). A thin normal-polarity zone, which was originally noted to occur immediately below and/or above the lignite sediments in some profiles south of Ísafjarðardjúp (Kristjánsson, 1967, 1968) appears to thicken farther south, e.g. in profile TF (Figure 1), see Figures 3 and 4 of Kristjánsson *et al.* (2003). If the lignite beds are everywhere of the same age, it is possible that the absence of this normal zone north of Ísafjarðardjúp is due to slower buildup of the lava pile there. Alternatively, a volcanic hiatus in Aðalvík and Fljótavík could have happened in a time period different from that south of Ísafjarðardjúp.

South of Ísafjarðardjúp the polarity pattern below the lignite sediments is broadly similar in several profiles, with evidence of some geomagnetic reversals or major apparent excursions being seen in each. Profile KE on the north side of Skálavík (Kristjánsson *et al.*, 2003) for instance, has an N to R reversal between flows KE 5 and 7, excursions in flows KE 8–10 and 21, and an R to N reversal between flows 26 and 28. The lower reversal was also seen south of Skálavík, between flows SK 10 and 12. It is not seen in profile GD at Bolungarvik which begins an estimated 30 m above sea level. A few excursions also occur here in flows GD 5–6 and GE 3, 5 (the supplementary profile GE filled inaccessible parts of GD), then a normal-polarity flow occurs just below the sediments in GD 19. The same reverse zone is present in profile SW which lies between GD and KE and was sampled up to a scree-covered segment containing the sediments; an excursion occurs in flow SW 11. In the two lowest parts of profile SU, an N to R reversal similarly takes place between flows 7 and 8. Excursions are found in SU 18 and 29, as well as in 33 (resampled in 2011, Table 1). Furthermore, Kristjánsson *et al.* (2003) sampled a profile GO on the north coast of Súgandafjörður. An N to R reversal occurs near the base of that profile, at a gap in exposures between flows GO 2 and 3. Excursions of the geomagnetic pole to mid-latitudes were noted in flows GO 5 and 8; the authors assumed in their Figure 3 that the level of the lignite sediments lay between GO 22 and 23 but according to the author's field notebooks it is more likely that the excursion flow GO 23 is below the sediments (Figure 4). Similarities between all the above profiles also include the frequent occurrence of (usually single) feldspar-porphyritic flows not far below and above the lignite sediments, sometimes with cumulate textures.

Paleomagnetic measurements on the lignite-bearing sediments themselves were made by Kristjánsson *et al.* (2003) in three localities south of Ísafjarðardjúp: in profile SN of McDougall *et al.* (1984), in profile TF of Hardarson *et al.* (1997) and of Kristjánsson *et al.* (2003), and in exposures at road level east of Bolungarvík (cf. Roaldset, 1983). They reveal that in each of these cases the polarity of the sediments is uniform, indicating that their period of emplacement was short.

Guðmundsson (2007) continued his mapping of stratigraphy between Bolungarvík and Skutulsfjörður in the field and in drill cores, again in preparation for the construction of a road tunnel in the area. This extensive study has so far only been described in internal reports, and will not be dealt with in detail here. A brief resumé of some of its findings was presented by Kristjánsson and Guðmundsson (2013), and they have aided in the construction of the lowest part of the Ísafjarðardjúp polarity column of Figure 2.

NEW MAPPING AND PALEOMAGNETIC WORK IN 2010–2012

Methods

New paleomagnetic sampling in Skálavík and Eyrarfjall was undertaken in 2010–2012. The sampling and magnetic measurements was carried out in the same fashion as in other recent surveys in the peninsula. At least four 25-mm diameter core samples were collected from each lava flow with a portable drill. These were generally distributed over a few to several meters laterally but within one meter vertically. Orientation made use of sightings on the Sun or on objects whose position was known from maps or GPS measurements. The sightings as well as measurements of core inclinations were made with a Brunton compass, with an estimated accuracy of the order of 2°. One 21–22 mm long specimen was cut from each sample.

Remanent magnetization vectors were measured with an Institut Dr. Förster four-probe fluxgate magnetometer, before and after stepwise alternating-field (AF) demagnetization at 10, 15, 20, 25 and 30 mT peak fields in a Molspin two-axis tumbler device. Viscous magnetization was generally minor, the directional change after the first AF step being 20° or less in at least 80% of the samples. In successive steps, directional changes were most often only a few degrees, showing that a stable primary remanence component had been isolated. Typical curves of the decay of intensity with increasing field amplitude were similar to those in Figure 5 of Kristjánsson *et al.* (2003) and Figure 5 of Kristjánsson (2015). Traditional statistical procedures (see Kristjánsson *et al.*, 2003) were applied in selecting the optimal estimate of the mean primary remanence direction for each flow. The between-sample agreement was quite satisfactory, with 95% confidence limits on the mean direction being 8° or less in most cases. The positive outcome of this crucial test of consistency makes rock-magnetic studies unnecessary for the purpose of the present project. In particular, the varied shapes of thermomagnetic curves obtained from samples of relatively unaltered Icelandic lavas do not appear to have much relation to the stability or reliability of their primary remanence directions (Kristjánsson *et al.*, 2003; Kristjánsson, 2015).

The demagnetization results indicate that in the area careful field measurements of magnetic polarity in hand samples with a fluxgate magnetometer (Kristjánsson, 1985, p. 129) can generally be trusted, at least above the analcime zeolite zone which reaches to about 100 m altitude according to Figure 3 of McDougall *et al.* (1984). No tectonic tilt correction was applied to the remanence-direction data from profile

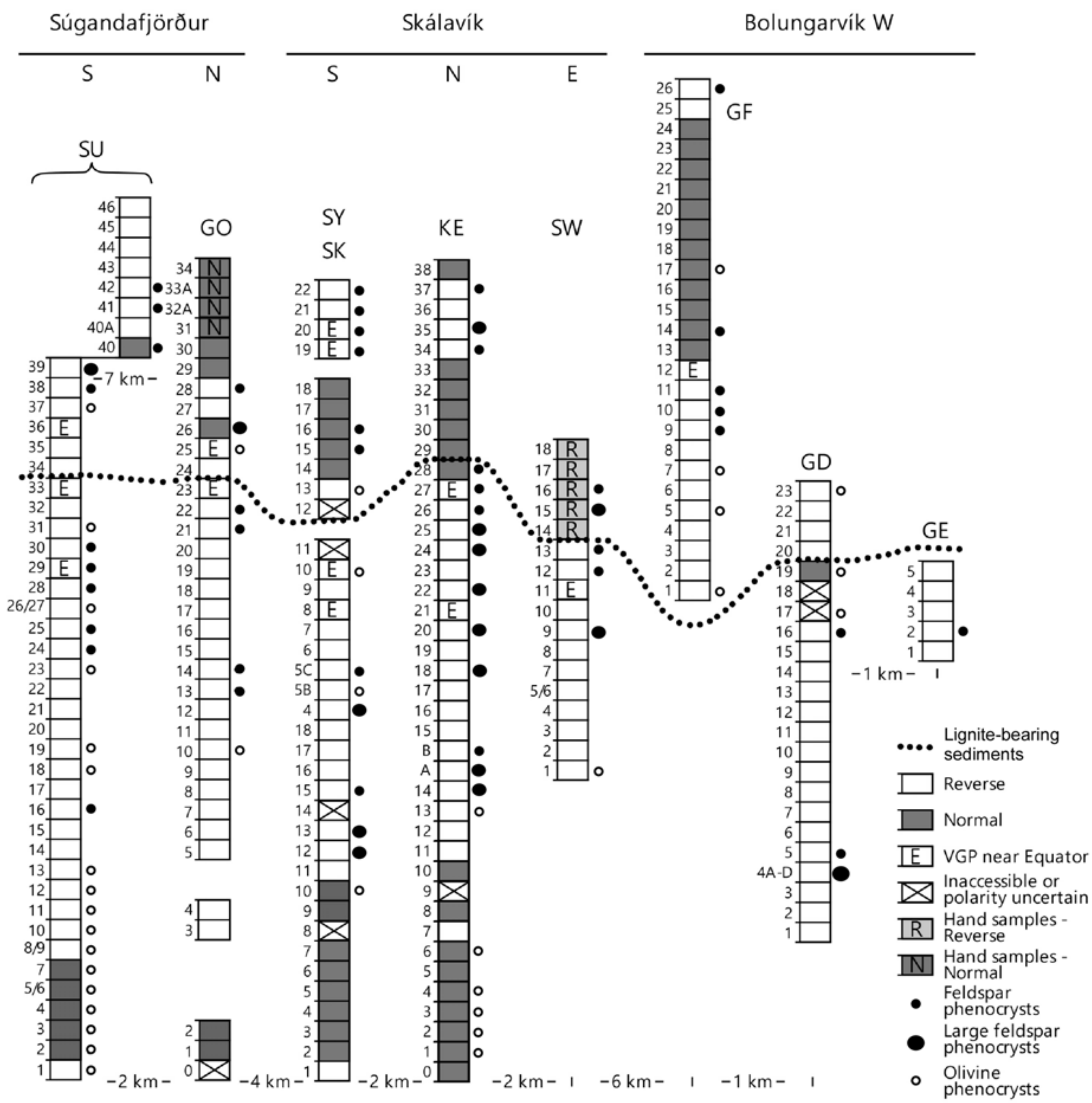

Figure 4. Polarities and lava types in several profiles crossing the level of lignite-bearing sediments, from Súgandafjörður to Ísafjarðardjúp (Figures 1 and 3). The diagram is adapted from Figures 3 and 4 of Kristjánsson *et al.* (2003). – *Berggerðir, réttar og öfugar segulstefnur í sniðum í Súgandafirði, Skálavík og Traðarhyrnu við Bolungarvík.*

Table 1. Paleomagnetic directions and virtual pole positions in Northwest Iceland profiles sampled in 2010–2012. n = number of samples used in averaging. Dec, Inc = declination and inclination of primary remanence direction after tectonic tilt correction. Lon, Lat = east longitude and north latitude of pole. Alf = 95% confidence angle for the mean direction, degrees. J10 = arithmetic average remanence intensity after 10 mT AF treatment, A/m. Pol = polarity: N = normal, R = reverse, T = transitional (Lat. between 10° and 40°), E = equatorial (Lat. below 10°). – *Segulstefnur, staðsetningar sýndarsegulskauta, og styrkur segulmögnunar sýna úr jarðlagasniðum.*

Lava	n	Dec	Inc	Lon	Lat	Alf	J10	Pol
SY SKÁLAVÍK, south side								
SY 0	4	99	-80	111	-62	4	13.66	R
SY 1	4	169	-51	353	-55	1	2.96	R
SY 2	4	97	-82	120	-63	3	16.99	R
SY 3	4	131	-61	49	-54	4	15.51	R
SY 4	4	179	-67	339	-73	6	1.58	R
SY 5B	4	161	-67	17	-71	7	2.63	R
SY 6	4	237	-57	259	-47	3	0.57	R
SY 7	6	175	-33	343	-42	8	0.50	R
SY 8	5	85	-16	75	- 5	8	0.43	E
SY 9	4	193	-81	186	-82	3	3.84	R
SY10	4	298	-18	217	+ 3	5	1.19	E
SY11			Poor exposures – not sampled					
SY12			Poor exposures – not sampled					
SY13	4	104	-75	95	-59	2	7.07	R
SY14	4	38	+83	8	+74	7	2.91	N
SY15	4	8	+86	341	+75	2	4.51	N
SY16	5	327	+78	265	+77	2	6.75	N
SY17	4	358	+58	159	+62	3	2.54	N
SY18	6	324	-17	193	+11	4	0.84	NT
SY19	4	101	+13	54	+ 2	6	0.31	E
SY20	4	100	+ 5	56	- 2	3	1.44	E
SY21	5	197	-70	294	-75	3	1.54	R
SY22	4	185	-64	326	-70	2	3.96	R
HT EYRARFJALL, Hnífsdalur								
HT 1	4	133	-78	89	-72	2	3.72	R
HT 2	4	351	-52	165	- 9	5	1.59	E
HT 3	4	22	+76	74	+80	6	2.51	N
HT 4	4	23	+79	39	+81	2	3.13	N
HT 5	4	5	+85	340	+76	2	7.02	N
HT 6	3	343	+64	190	+68	8	5.58	N
HT 7	4	27	+73	84	+76	2	5.25	N
HT 8	4	70	+71	51	+56	5	1.41	N
HT 9	4	315	+62	226	+57	3	0.84	N
HT10	4	24	-42	135	- 2	4	0.70	E
HT11	4	293	+72	263	+58	7	8.03	N
HT12	4	324	+65	219	+63	4	19.03	N
HT13	5	250	+59	282	+29	7	0.97	NT
HT14	4	21	+79	33	+82	5	2.90	N
HT15	4	23	+72	97	+76	5	1.64	N

Lava	n	Dec	Inc	Lon	Lat	Alf	J10	Pol
HT EYRARFJALL, Hnífsdalur, cont.								
HT16	5	39	+77	51	+74	4	4.07	N
HT17				Inaccessible				
HT18	4	15	+72	112	+79	5	1.92	N
HT19	4	109	+79	12	+53	2	4.92	N
HT19A	5	77	+89	342	+67	3	3.46	N
HT20	4	288	+81	291	+65	5	4.41	N
HT21				Inaccessible				
HT22	4	192	-79	212	-85	2	5.28	R
HT23	4	153	-46	13	-48	8	4.31	R
HT24	4	124	-68	67	-59	2	2.98	R
HT25	4	184	-75	311	-85	11	2.24	R
HT26	4	210	-72	265	-73	2	6.06	R
HT27	4	218	-68	265	-66	3	0.69	R
HT28	5	170	-74	21	-83	3	1.34	R
GG EYRARFJALL, Skutulsfjörður								
GG 1	4	324	+76	253	+75	7	3.77	N
GG 2	4	341	+83	311	+79	4	5.71	N
GG 3	4	47	+67	77	+61	2	7.64	N
GG 4	4	359	+69	160	+76	4	4.62	N
GG 5	5	31	+60	106	+59	2	1.14	N
GG 6	5	41	+57	97	+53	2	0.51	N
GG 7	5	1	+50	155	+55	4	3.84	N
GG 7C	4		Poor exposures, unstable					?
GG 8	4	57	+49	84	+40	4	0.81	N
GG 9	5	73	+33	75	+24	7	0.54	NT
GG10				Inaccessible				
GG11	4	158	+47	356	+ 6	4	4.25	E
GG12	4	125	+71	13	+39	3	5.71	NT
GG13	4	167	+62	347	+19	22	5.66	NT
GG14	4	78	+81	19	+64	7	2.87	N
SU SPILLIR, Súgandafjörður								
SU33	5	346	-42	161	- 1	6	2.59	E
SU34	3	175	-78	91	-88	2	0.93	R
SU37	6	59	-57	109	-23	7	0.19	RT
SU37A	3			Unstable			0.20	R?
SU38	3			Unstable			0.26	R?
SU39A	4	209	-64	284	-64	3	2.51	R

SY, while the tilt in profiles HT and GG was assumed to be 2.5° to the southeast. The directions and virtual geomagnetic pole positions derived from them are presented in Table 1. Figure 5 shows the magnetic polarity of each lava, along with its lithological type based on in-situ appearance and on visual inspection of drill cores.

Skálavík

Sampling in the profile SK south of Skálavík in 1975 (McDougall *et al.*, 1984) ended at flow 20 due to steepness of exposures, while the lignite sediments occur above flow 29 or so. A new profile SY (Figures 3, 4, 5, 6) was therefore mapped and sampled about 1 km to the east-southeast from SK for a paleomagnetic study, to improve knowledge of the stratigraphy in the area. This profile begins in a highly porphyritic flow SY 0 at 66°10.484'N, 23°29.778'W, 120 m altitude; sampling reached up to the base of a thick compound flow SY 22. We correlate SY 0 approximately with SK 15, and SY 4 with SK 19. Like the other profiles in the area described above, the lower part SY 0–10 consists mostly of reversely magnetized lavas, with major excursions in flows 8 and 10. The lignite sediments are thought to lie in a scree-covered interval at 290–340 m a.s.l. along with at least two poorly exposed flows SY 11 and 12 (not sampled). The excursion directions in SY 8 and the olivine tholeiite SY 10 are quite similar to those in respectively GO 23 (as well as KE 21 and SW 11) and the olivine tholeiite GO 25, although GO 25 seems at any rate to be above the expected position of the lignite sediments.

Above the unexposed gap in SY we have the reverse flow 13, normal flows 14–17, and then a transition (also recorded by KE 34) in SY 18–20 to a reverse zone. This along with similarly erratic behavior of remanence directions in lavas both just above and just below the lignite sediments in profiles KE, SU and GO indicates that the geomagnetic field was in a somewhat unsettled regime when these lavas were emplaced. Such behavior also occurs below the sediments in GD/GE and SW, while it is less evident in flows above them in the four profiles of Kristjánsson *et al.* (2003) north of Ísafjarðardjúp, in GD/GF at Bolungarvík, SN in Súgandafjörður, and profiles FE, FF, TO, NE, etc. farther south.

Eyrarfjall and Súgandafjörður

Eyrarfjall, Hnífsdalur. A profile HT of 28 mostly tholeiitic lavas was sampled at the east side of Hnífsdalur. We were unable to continue higher or to sample flows HT 17 and 21, because of steep exposures. The profile starts at 66°06.163'N, 23°08.501'W with a reverse to normal transition at HT 2, the flow HT 1 probably belonging to the same zone of reverse polarity as flows (tested in hand samples) at sea level on the east side of the mountain. A normal-polarity zone HT 3–20 lies at altitudes from 150–450 m and is then overlain by lavas of reverse polarity from HT 22 at least up to the top of our sampling at 560 m. The same normal-to-reverse transition occurs at about 530 m altitude above our profile GG (Guðmundsson, 1989; Á. Guðmundsson, *pers. comm.* 2013). We are assuming that it is also the same as the transition found at about 130 m altitude between flow DO 17 and the 40 m thick reverse compound olivine tholeiite flow DO 18, which is below a minor but conspicuous local unconformity. This would agree roughly with Kristjánsson and Jóhannesson's (1996) correlation of DO 18 with the compound flow SB 24–29 of McDougall *et al.* (1984) whose base is at 700 m. It implies that the tectonic tilt has a mean component of the order of 1–2° along the south-southeasterly direction between GG and DO, within the altitude levels quoted. The reversely magnetized feldsparphyric flows DO 19–24 may correspond to feldsparphyric flows which occur in the sampled reverse series HT 22–28 and above it (S. M. Hreinsdóttir, *pers. comm.* 2012).

Eyrarfjall, Skutulsfjörður. The profile GG starts in a prominent gully above the Grænigarður residence in Ísafjörður town. The position of flow GG 1 is at 66°04.320'N, 23°09.742'W, 150 m altitude. We have sampled the bottom 14 lavas of profile GG, all of normal polarity. Steepness and the presence of a thick dike in the gully prevented further sampling. An excursion of the geomagnetic pole to low latitudes in flows GG 9–13 may correlate with excursions in flows HT 10 and/or HT 12.

Promontory south of Súgandafjörður. A few key flows in profile SU around the estimated level of the lignite-bearing sediments which had given difficulties due to poor within-flow agreement in the study by Mc-

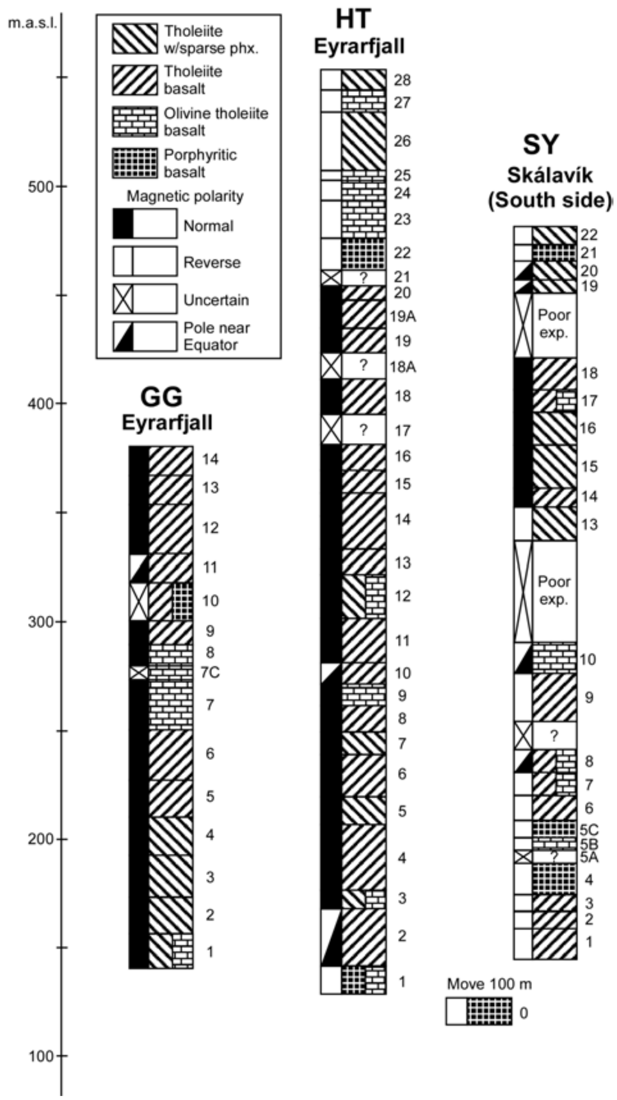

Figure 5. Stratigraphic sketches of those parts of three mountainside profiles which were sampled for paleomagnetic laboratory studies (Table 1). Interbasaltic sediments and some minor unexposed intervals are not shown. Altitudes which were measured with a manual GPS receiver and a digital barometric altimeter, may be uncertain by a few meters. – *Hraunlög og staðsetningar segulskauta í þrem sniðum úr Töflu 1.*

Dougall *et al.* (1984), were resampled. The new measurements were partially successful in isolating stable primary remanence directions.

SUMMARY AND DISCUSSION

The stratigraphic and paleomagnetic study by Kristjánsson and Jóhannesson (1996) in the tributary fjords south of Ísafjarðardjúp enabled correlations to be established between the lava piles in their 2.6 km thick composite section running 45 km southeastwards from profile DO in Álftafjörður, and the major part of McDougall *et al.*'s (1984) 4 km composite section from Skálavík to the south coast of the peninsula (Figures 1,2). The resulting magnetic-polarity columns did not include the oldest parts of the lava pile in these sections, from sea level at Skálavík to Álftafjörður and to the hills southeast of Súgandafjörður respectively. The present paper attempts to fill this gap which is of the order of 0.8 km thickness in both composite sections. Use is made of the paleomagnetic study of Kristjánsson *et al.* (2003) around the oldest lignite-bearing sediments of the peninsula, augmented by new paleomagnetic work on some 60 lava flows (Figure 5, Table 1). Results from Guðmundsson's (1989, 2007) mapping of lava sequences in the Álftafjörður-Önundarfjörður-Bolungarvík area have also been a helpful reference on some aspects of the local stratigraphy. Further geological and paleomagnetic studies would have been desirable in the project reported here, but local conditions for this are rather difficult especially in steep outcrops of thin central-volcano tholeiite lava series such as occur in Skutulsfjörður, Álftafjörður, and Önundarfjörður (cf. profile AJ of Figure 2 in McDougall *et al.* (1984)).

Several geomagnetic excursions have been recorded in the present study, and are useful in short-distance correlations as in previous paleomagnetic surveys in the older parts of the peninsula. Their presence is related to the fact that the general scatter of paleomagnetic poles around the geographic poles was greater at >12 Ma than in younger rocks, cf. Figure 9 of Kristjánsson (2013). An extended episode of geomagnetic instability was recorded in over 15 successive lavas of about 13 Ma age at the eastern end of Ísafjarðardjúp by Kristjánsson and Jóhannesson (1996). The present author (Kristjánsson, 2015, and references therein) who reports new observations on this feature, has not found in rocks of the Northwest peninsula any evidence for other episodes comparable in duration to that one or to the complex 16.7 Ma transition at Steens Mountain in Oregon.

Statistical considerations predict that a very slow rate of eruptions relative to the rate of geomagnetic reversals would result in an average of 2 lavas per polarity zone in the pile. The average number of lavas per polarity zone in the Pliocene and Miocene regions of Iceland is 15–20 (Kristjánsson and Jónsson, 2007), representing a time interval of order 0.2 M.y. and a buildup rate of order 1 km/M.y. Only 0 to 3 reversals are observed to occur in the 10–30 flows between sea level and the lignite sediments, in the profiles of Figure 4 as well as to the north and south, cf. Figures 2 and 4 of Kristjánsson *et al.* (2003). The very slow (<0.3 km/M.y.) rate of emplacement of lavas below these sediments suggested by Pringle *et al.* (1999) therefore does not seem realistic. Hopefully, this question will be resolved by new ^{40}Ar/^{39}Ar age determinations from the Northwest peninsula (Riishuus *et al.*, 2013).

The lithological characteristics of the lava flows below and above the lignite sediments in the area of Figure 3 are fairly similar, as regards for instance the occurrence of flows with large feldspar phenocrysts. This would tend to agree with a small ($\sim$0.2 M.y.) rather than a large (>2 M.y.) age difference between them, especially if lateral movements or other major changes in the mode of volcanism are supposed to have taken place within the latter time gap. It has not yet been established whether for instance removal of a significant thickness of lavas by erosion occurred before the deposition of the sediments. Hydrothermal effects around their level in Skálavík are quite minor, but microscope inspection (M.S. Riishuus, *pers. comm.* 2013) of thin sections indicated somewhat greater alteration of the glassy matrix to clay in two lavas below it (SY 8, KE 23) than in two lavas above it (SY 18, KE 31). Judging from a preliminary analysis of the magnetic behavior of samples in SY and in other profiles around Ísafjarðardjúp (Kristjánsson *et al.*, 2003, section 3.7; Kristjánsson, 2013, p. 547), no major systematic reduction in the overall intensity and stability of remanence occurs below the sediments; these properties are adversely affected by even a moderate rise in the maximum temperature encountered by lavas during burial (Watkins and Walker, 1977, Figure 13; Kristjánsson, 2015). The amount of angular unconformity between the sequences above and below the lignite-bearing sediments is uncertain; published estimates of tectonic tilts in that area are somewhat incongruous and await improvement with the aid of modern techniques. As an example, it has been stated by Hardarson *et al.* (1997) and some subsequent writers that the tectonic tilt below the oldest sediments in the peninsula is about 5° towards northwest or west. This is evidently not the case in our Figure 6; available photographs from the coastline mountainsides in fact reveal no westerly dips between the south side of Dýrafjörður and the north side of Fljótavík.

Figure 6. View across Skálavík from the north, showing the location of flow SY 1. The profile SY runs from there up to near the top of the mountain. Some lava flows and the lignite-bearing sediments are supposedly hidden at the scree-covered bench on both sides of the small corrie. Profile SK (sampled in 1975) starts at sea level near the right-hand side of the photo but its location is not precisely known. Note that the lowest lavas dip slightly inwards along the mountainside which trends about 105° East, while those higher up have no apparent dip. – *Horft yfir Skálavík norðanfrá. Hraunlag SY 1 er sýnt vinstra megin, eldra sýnasöfnunarsnið SK var utarlega hægra megin. Vel sést að neðstu jarðlögin hallast inn eftir, en þau efri ekki merkjanlega.*

It is clear that the buildup process of the Northwest peninsula lava pile varied considerably in space and time. Much additional research on its stratigraphy, age, primary geochemistry, structure, tectonics and hydrothermal alteration is required, giving special attention to the role of the central volcanoes of the peninsula.

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ÁGRIP

Gefið er stutt yfirlit um fyrri rannsóknir á jarðlögum vestantil á Vestfjarðakjálkanum. Síðan er sagt frá nýjum bergsegulmælingum á um 60 hraunlögum við Skutulsfjörð og Skálavík. Ásamt áður birtum gögnum nýtast þær til að fullgera mynstur segulumsnúninga í 3,4 km súlu úr samsettu þversniði gegnum hraunasyrpurnar meðfram Ísafjarðardjúpi að sunnan. Samskonar súla úr þversniði frá Skálavík suður til Breiðafjarðar hefur einnig birst áður, og má tengja þær saman. Bergið er góður efniviður til segulstefnumælinga, jafnvel á handsýnum í mörkinni, en talsvert flókt er á staðsetningum segulskauta eins og þekkt er úr fyrri rannsóknum af hinum eldri svæðum landsins. Jarðlögin undir elstu surtarbrands-setlögum Vestfjarða eru allflest með samskonar („öfuga“) segulstefnu, en það samrýmist ekki vel hugmyndum um að upphleðsla staflans á þeim tíma hafi verið óvenju hæg, Óljóst er enn hvort þau set marka neina meiriháttar atburði í jarðsögu landsins, svo sem langt hlé í eldvirkni eða flutning gosbeltisins til austurs.

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