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Stratigraphy and Paleomagnetism of the Esja, Eyrarfjall and Akrafjall Mountains, SW-Iceland

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Abstract. Detailed geological and magnetic mapping in an area of Pliocene and Plio-Pleistocene volcanic rocks in Southwestern Iceland has enabled us to correlate a 2,100-m-thick lava succession with similar dated sequences in Iceland and with the ocean-floor geomagnetic polarity time scale. This correlation, supported by additional K-Ar dating, implies (1) that the succession is between 4.2 and 1.8 Ma in age, (2) that at least 13 glaciations occurred in Western and Southwestern Iceland between 3.1 and 1.8 Ma ago, and (3) that at least two geomagnetic events are present in the Lower Matuyama epoch.

Paleomagnetic results from 353 igneous units, mostly basalt lavas, are tabulated. Analysis of directions from 258 of these shows them to possess some serial correlation; their mean is very close to a central axial dipole field value, but explanations are proposed for observed systematic departures from this field in other Icelandic paleomagnetic survey results.

Key words: Paleomagnetism – Basalt lavas – Stratigraphy – Glaciations – Geomagnetic time scale – Iceland.

1. Introduction

The area around Hvalfjördur, (Fig. 1) is mostly built up of basalt lavas, and belongs to the uppermost part of the 'plateau basalt' succession of Western Iceland. Regional stratigraphic mapping in the area was initiated by Einarsson (1957) who successfully employed field measurements of remanence polarity in lavas to distinguish and correlate age groups. Further stratigraphic work in the Hvalfjördur area, as well as in the rest of Iceland, has continued to depend heavily on magnetic polarity mapping, and laboratory studies (Sigurgeirsson, 1957; Wilson et al., 1972) have confirmed Einarsson's polarity results in the area.

A few early K-Ar dates from the south shore of the fjord have been reviewed by Pálmason and Sæmundsson (1974); their reliability is low due to the high atmospheric argon content. Piper (1971) first suggested how Einarsson's local polarity groups might be correlated with the geomagnetic polarity time scale then available from dated formations (Cox, 1969). His interpretation included Einarsson's reversed groups R2 and R3 being equivalent to the lower Matuyama epoch. Fridleifsson (1973) and Fridleifsson

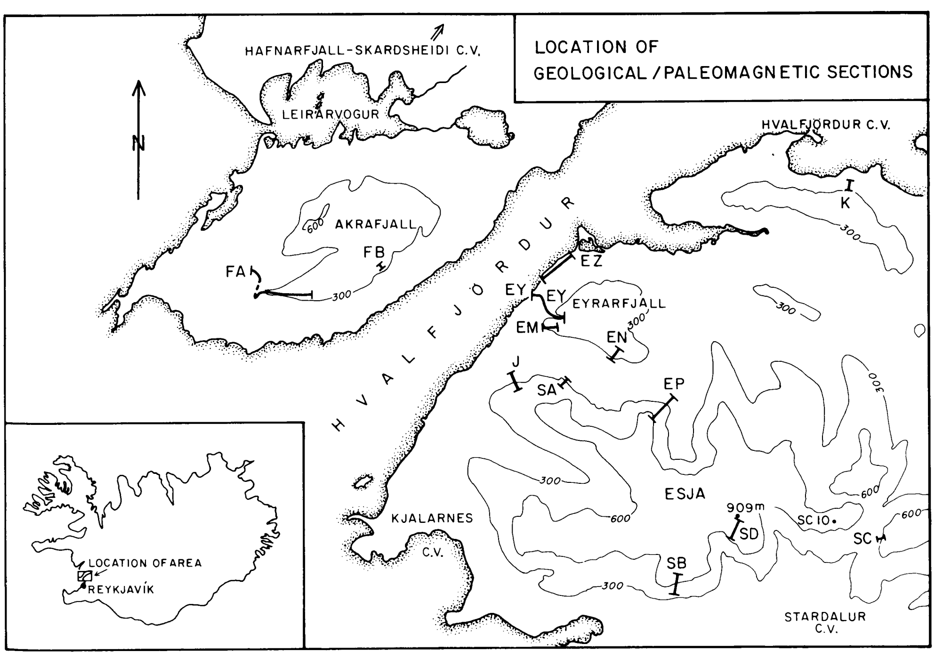

Fig. 1. Location of stratigraphic/paleomagnetic sections in Esja, Eyrarfjall, and Akrafjall. Sections *J*, *K* of Wilson et al. (1972) are also included

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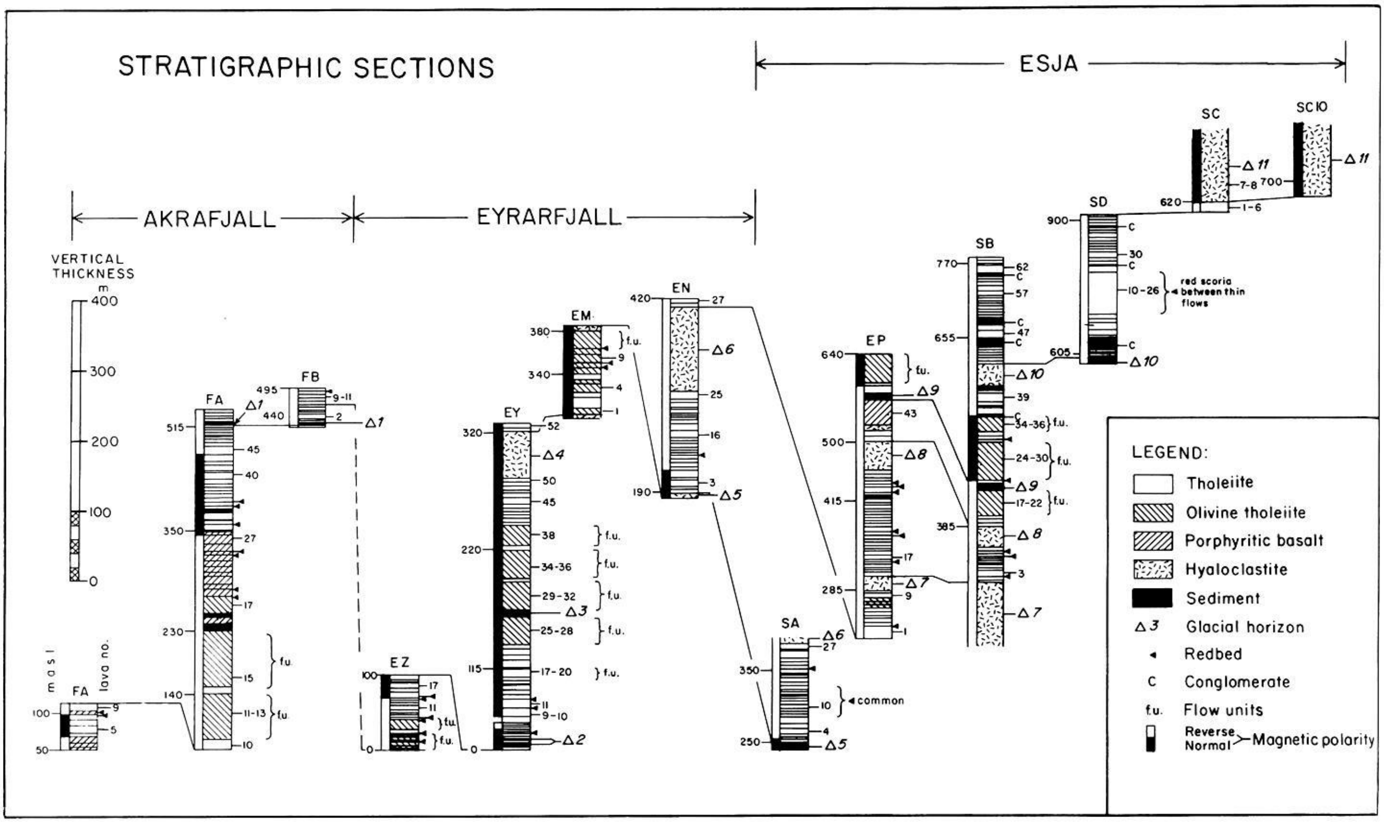

Fig. 2. Stratigraphy of each sampled section, showing lava types and polarities, formations of glacial origin, sediments, and stratigraphic ties between sections. Occasional numbers to the left of the columns are barometric altitudes

and Kristjansson (1972) subsequently assumed the thin group N3 in the Esja area to belong to the Olduvai event and N2, occurring at the top of the Esja volcanics, to belong to the Gilsá event.

In the course of detailed geological mapping of the Esja area (Fridleifsson, 1973) it appeared that a third event of normal magnetization might be present in continuously exposed cliff sections in the area. Sampling for laboratory measurements in Esja was therefore initiated by us in 1973 (Sect. SA, SB, SC), to help clarify the much disputed problem of the time intervals covered respectively by the Gilsá, Olduvai and Reunion events. AF treatment of samples showed, however, that the normal polarity remanence of the lowest event (lavas SB 1–5) was of secondary origin.

After these results were obtained it was decided to extend sampling to obtain a complete profile down to the oldest lavas exposed on the south shore of Hvalfjördur, interpreted as reaching into the middle Gauss epoch. Sections SD, EP, EM, EY, and EZ were therefore cored in 1974–1976, as well as section EN to replace badly altered lavas of section SA. Sections FA and FB on the northern side of the fjord were added in 1977.

2. Geology

2.1. Geological Setting

The research area (Fig. 1) lies 10–40 km west of the active Reykjanes-Langjökull volcanic zone. The rocks dip 5–8° southeastwards. Geological mapping suggests continuous volcanic activity within this segment of the zone since about 7 Ma to the present (Fridleifsson, 1973; Franzson, 1978; McDougall et al., 1977). The rate of volcanism was, however, not uniform as four central volcanoes were active in the vicinity of our cross section during the growth of the strata described here, and these are characterised by a very high extrusion rate. Our area lies 15–20 km S and SW of the Hafnarfjall-Skardsheidi and Hvalfjördur central volcanoes, and about 1–10 km north of the Kjalarnes and Stardalur central volcanoes (Fig. 1).

The area is bisected by a major fjord, Hvalfjördur, and the correlation across it is by no means certain. The geological mapping north of the fjord (Sect. FA, FB) was originally conducted by Franzson (1978) but our work south of the fjord is based on mapping of Eyrarfjall by students at the University of Iceland under the supervision of Dr. K. Saemundsson (Jonasson et al., 1973; Sects. EZ, EY, EM, EN) and on mapping of Esja by Fridleifsson (1973; Sects. SA, EP, SB, SC, SD).

All the sections were, however, selected and described specially as a part of the present study (Fig. 2). They are mostly in steep slopes with nearly complete outcrops. Farther east along the fjord, considerable mapping and sampling work has been carried out by Einarsson (1957), Piper (1971), Wilson et al. (1972) and by students; the latter work is not yet completed (K. Saemundsson, 1979, personal communication) and will not be discussed here.

2.2 Pliocene Strata

The profile starts in the mountain of Akrafjall, where Franzson (1978) interpreted the short normal polarity event of lavas FA 4–7 as belonging to the Nunivak event, and this view is maintained here. Franzson found the Cochiti event missing both in Akrafjall and in the Hafnarfjall-Skardsheidi region farther north. McDougall et al. (1977) suggested that these two events were recorded as one in their Borgarfjördur profile.

The profile up to FA 51 is a typical Tertiary lava sequence with basaltic lavas (tholeiites, olivine tholeiites, and plagioclase-phyric tholeiites) separated by thin red partings. Two thick olivine tholeiite compound lavas occur. There are several thin sedimentary layers and one thick fluviatile conglomerate horizon (7–34 m, FA 15–16); it thickens eastwards and may represent a river bed.

Section FA begins in the sequence belonging to the last volcanic phase of the Hafnarfjall-Skardsheidi central volcano (Heidarhorn phase of Franzson, 1978). Section FA ends in, and FB is within, lavas that correspond to the onset of the Hvalfjördur central volcano (Heidarhorn tholeiite series of Franzson, 1978).

2.3 Plio-Pleistocene Strata

After the onset of glaciations, the character of the volcanic pile changed markedly. Instead of the relatively uniform lava sequence in the Pliocene part of the lava pile, the glaciations left their marks in the lava sequences in the form of widespread coarse conglomerate horizons (tillites) and more spectacularly by thick hyaloclasitite sequences which form by volcanic eruptions under ice sheets. After a glaciation, hyaloclastite ridges (with a pillow lava core enveloped by pillow breccias and tuffaceous hyaloclastites) with steep slopes are the dominant features of the topography. In subsequent volcanic eruptions, lava flows bank up against the hyaloclastites or flow down their slopes depending on the eruptive site. The lava may fill the valleys between the hyaloclastites and eventually bury them. Due to the rugged topography after a glaciation, valleys, a short distance apart, may be physically isolated from one another. Thus, an absence of volcanism in one valley may allow the development of aprons of sediment spreading out over the lava plains at the feet of the easily eroded hyaloclastite mountains, while simultaneous active volcanism in an adjacent valley may give rise to a pile of lavas with no sedimentary intercalations (Fridleifsson, 1973). One has therefore to be even more careful than in Pliocene strata in connecting profiles far apart. For this reason it was deemed necessary to let the paleomagnetic profiles overlap considerably with one another.

Glacial Horizon 1 The first major conglomerate horizon (5–22 m) is found between lavas FA 51–52 and FB 0–1. In western Akrafjall the lowest part of the horizon is a grey, ill sorted conglomerate with boulders up to 1.5 m i. d. (Franzson, 1978). It is found both in Akrafjall and Skardsheidi and occurs one to three lava flows above the lower boundary of what are interpreted as Mammoth event lavas (Franzson, 1978). This horizon has also been found in upper Borgarfjördur where glacial striations are found on the underlying basalt flow (Saemundsson and Noll, 1974). This is thought to be the lowest tillite horizon in western Iceland and has been dated at about 3.1 Ma (McDougall et al., 1977). A similar age was found for the lowermost tillite in NE Iceland (McDougall and Wensink, 1966), but there is evidence for even earlier cool-climate deposits in other parts of the country (McDougall et al., 1976; Johannesson, 1975; Albertsson, 1976).

Glacial Horizon 2. Coarse conglomerate, fluviatile sediment and siltstone, 10 m thick, occur between lavas EY 1–3. Striations are seen on the boulders (Jonasson et al., 1973). In the lava sequence between glacial horizons 2 and 3 there are two sediment horizons (2 m each) both of which have small pebbles of basalt and rhyolite (above EY 14 and EY 20).

Glacial Horizon 3. Coarse conglomerate with pebbles and boulders up to 30 cm set in a grey matrix, 5 m thick with 5 m of finer grained sediment above, lying between lavas EY 28–29.

Glacial Horizon 4. Fluviatile sediment with a conglomerate horizon (15–20 m) overlain by a hyaloclastite sequence (tuffaceous hyaloclastite, pillow breccia and pillow lava) 40–200 m thick, which thickens towards the Kjalarnes central volcano. It lies between lavas EY 50–51. The underlying tholeiite lavas are thought to represent the first volcanic phase of the Kjalarnes central volcano (Esja unit 3, Fridleifsson 1973).

Glacial Horizon 5. Tuffaceous hyaloclastite, pillow breccia and pillow lava, 10–200 m thick, between lavas EM 11–EN 1. It thickens towards the Kjalarnes central volcano. (Esja unit 7).

Glacial Horizon 6. Tuffaceous hyaloclastite, pillow lava and pillow breccia, 25–200 m thick, with a thin sedimentary base, lying between EN 25–26, right above SA 27, right under EP 1. (Esja unit 10).

Glacial Horizon 7. Tuffaceous hyaloclastite, pillow breccia and pillow lava, 20–300 m thick, underlain by conglomerate in SE-Esja, and occuring between EP 10–11, right under SB 1. (Esja unit 12, considered uppermost hyaloclastite belonging to the Kjalarnes central volcano).

Glacial Horizon 8. Tuffaceous hyaloclastite, pillow breccia and pillow lava, 10–200 m thick, succeeded by a 10 m grey, ill sorted conglomerate in N-Esja. (Esja unit 15). It occurs between EP 40–41 and SB 12–14.

Glacial Horizon 9. Tuffaceous hyaloclastite, pillow breccia and pillow lava in E-Esja, brown and grey, ill sorted conglomerates with pebbles up to 20 cm in W-Esja. Thickness ranges from 5–300 m. (Esja unit 18; forms the base of the Stardalur central volcano).

Glacial Horizon 10. Grey ill sorted conglomerate blanket with boulders commonly 20–30 cm and sometimes over 100 cm, about 20 m in W-Esja and over 100 m in E-Esja where it interfingers with up to 240 m-thick hyaloclastite sequence of basalt and basaltic andesite compositions with a minor rhyolite. This unit was formed after the collapse of the Stardalur caldera. (Esja unit 23). It lies between lavas SB 40–41, and right under SD 1. This major glacial horizon was noted by Pjeturss (1910), and Rutten (1958) referred to it as the morainic horizon at the base of the 'Graue Stufe', and drew the Tertiary-Pleistocene boundary at the base of the conglomerates.

The conglomerate horizon between lavas SB 36–37 could possibly represent a separate glaciation. Above Glacial horizon 10 there are similarly three major sediment/conglomerate horizons in profile SB, all of which are characterized by coarse conglomerate (with pebbles up to 20 cm and more rarely 50 cm) at the base, overlain by gravel and finer sediment. These are between SB 46–47 (15 m), SB 48–49 (10 m), and SB 61–62 (5 m). The thickness varies considerably along strike. In Sect. SD there are also three horizons with the same characteristics between lavas SD 3–4 (15 m), SD 27–28 (1.5 m), and SD 38–39 (3 m). The most likely correlation of the conglomerates between the two sections is

Table 1. K-Ar ages of two rhyolite samples (from I. McDougall)

Lab. no.	Field no.	K (wt.%)	Rad. ^{40}Ar 10^{-12} mol/g	$\frac{100 \cdot \text{Rad. } ^{40}\text{Ar}}{\text{Total } ^{40}\text{Ar}}$	calc. age Ma ± 2S.D.
73-1483	SC 10A	2.369, 2.362	7.96	11.5	1.89 ± 0.08
73-1484	SC 10B	2.350, 2.372	7.49	20.1	1.78 ± 0.04
			7.76	5.6	1.85 ± 0.18

SB 46–47 ≙ SD 3–4, SB 61 ≙ SD 27–28, which indicates the presence of four conglomerate horizons between what is termed here Glacial horizons 10–11 But as no volcanic hyaloclastites were found associated with the conglomerate horizons in spite of the high volcanicity, the horizons are considered to be of a local nature rather than representing major glaciations. More detailed work on these might alter that view.

Glacial Horizon 11 Basaltic and rhyolitic hyaloclastites at the top of the present profile, with thickness over 100 m. SC 7 and SC 8 are feeder plugs within the basaltic hyaloclastite, but SC 10 is the feeder dyke of the rhyolite hyaloclastite. The rhyolite was erupted on an arched sheet just outside the Stardalur caldera fault during the final volcanic phase of the Stardalur central volcano (Esja units 25 and 26).

2.4. Potassium-Argon Dates, Correlation of Glaciations

Dr. I. McDougall of the Australian National University in 1973 collected samples from sections SA, SB, SC to investigate their suitability for K-Ar dating. No useful basalt samples were found, but Dr. McDougall has obtained, and kindly allowed us to quote, the results from two samples of the rhyolite unit SC 10 (Table 1). Both samples are composed mainly of spherulitic cryptocrystalline feldspathic material rather than glass, with minor dark altered areas.

The decay constants are the same as those used by McDougall et al. (1977). If the recently recommended decay constants for ^{40}K (Steiger and Jäger, 1977) are used, these (and other ages mentioned in the present paper) will increase by 2.67%.

In the profile presented here there are signs of a least 11 and possibly 16 glaciations. The lower part of the sequence overlaps in time with the Husafell area 60 km further NE which is set in the same configuration with respect to the Reykjanes-Langjökull volcanic zone. There, Saemundsson and Noll have mapped 8 glacial horizons in strata dating from the Mammoth event to just above the transition Gauss/Matuyama (Saemundsson and Noll, 1974, McDougall et al., 1977). The first two glacial horizons of Saemundsson and Noll (1974) are represented in the present profiles, but out of their five glacial horizons, 3 to 7, in the uppermost part of the Gauss epoch only three are present here (3 to 5). There may thus be signs of 13 and possibly 18 glaciations in the volcanic strata of western Iceland dating from the Mammoth event (~3.1 Ma) to the uppermost glacial unit in Esja, the rhyolite SC 10. According to the new K-Ar dates just tabulated, this normally magnetized unit is more likely to belong to the Olduvai than to the Gilsá geomagnetic event.

2.5 Rock Alteration

Secondary alteration in the study area has been found (Fridleifsson, 1973; Franzson, 1978) to follow generally the zonal pattern demonstrated by Walker (1960) for the Tertiary basalts of eastern Iceland. The profile FA in Akrafjall starts near the top of the mesolite-scolecite zone; the tops of sections FA and FB are zeolite-free. In Esja and Eyrarfjall the profiles also start in the mesolite-scolecite zone which extends up to about 300 m elevation. Above 700 m zeolites are rare except in Sect. SC, which is just outside the thermal aureole associated with the Stardalur central volcano.

3. Paleomagnetic Sampling and Measurement

A total of 353 units were sampled in 11 sections. All were lava flows except SC 7–11 (intrusions), and SB 13, SA 28–30 (hyaloclastites). In case of multiple pahoehoe 'flow units' or composite flows, only one flow unit was sampled, and some very thin or poorly preserved flows were left out, e.g., in EZ and SA. Flows having an A or B suffix were located after the original mapping and numbering took place. In all sections, numbering begins at the bottom.

Three or more 2.5-cm cores were drilled from each unit and orientated in place by geographic sightings. One specimen of 2.2-cm length was cut from each core for remanence measurements, which were made at the University of Rhode Island using spinner magnetometers, and at the Universities in Munich and Reykjavik using mostly Institut Dr. Förster static fluxgate magnetometers. Remanence intensity and direction was measured both at the total N.R.M. level and after treatment in 100 and 200 Oe peak alternating fields (1 Oe = 10^{-4} T). In the poorly stable flows EN 1–15, 150 Oe treatment was also applied, flows EP 36, SD 42–44 have been affected by lightning, and some samples from these were demagnetized to 300 Oe.

Direction data obtained at Rhode Island were averaged within each unit using the minimum-scatter criterion used by Watkins et al. (1977); in other units, the more internally consistent of the results after 100 or 200 Oe was selected for use in subsequent analysis. The difference between these techniques is generally small here.

Random errors in the orientation and marking of a core may be of the order of 3°, and random errors in magnetic direction measurement on a stable specimen may amount to 2° Table 2 shows the mean field direction obtained from each unit after tectonic tilt correction. It also gives the within-unit 95% confidence angle for the field direction, a virtual geomagnetic pole position and an arithmetic mean remanence intensity in volume units after 100 Oe demagnetization.

When α_{95} exceeds 60° (Vincenz and Bruckshaw, 1960), we consider the computed average field direction to be meaningless and it is not given in Table 2; however, this is often due to anomalous behaviour in one sample, and the polarity of the other two then agrees with that of adjacent units. Units marked with a small a in Table 2 have α_{95}-values exceeding 23.5° (i.e., a vector sum R less than 2.93 if $N = 3$), and these have been excluded from computation of mean magnetic properties in the collection.

Table 2

No.	*N*	*D*	*I*	*Lon*	*Lat*	alf	*J*	pol
FA Akrafjall								
FA 01	3	108	−68	83	−52	28	2.2	R[a]
FA 02	3	164	−52	4	−57	7	1.1	R
FA 03	3	161	−45	5	−51	18	0.9	R
FA 04	4	348	+86	333	+72	20	3.3	N
FA 05	3	12	+76	71	+85	10	0.7	N
FA 06	4	340	+68	208	+73	6	1.0	N
FA 07	3	48	+77	44	+70	6	0.7	N
FA 08	3	191	−64	314	−71	3	2.2	R
FA 09	3	204	−70	277	−74	11	1.0	R
FA 10	3	197	−85	170	−74	13	0.7	R
FA 12	3	140	−53	36	−51	5	4.2	R
FA 14	3	190	−65	316	−72	4	1.7	R
FA 15	3	206	−79	212	−79	2	0.8	R
FA 16	3	152	−61	27	−63	5	1.1	R
FA 17	3	102	−34	66	−22	3	0.6	RT
FA 18	3	346	−81	164	−48	6	2.0	R
FA 19	3	148	−78	93	−77	3	7.6	R
FA 20	3	184	−71	323	−81	5	5.4	R
FA 21	3	205	−67	282	−71	8	3.8	R
FA 22	3	172	−75	43	−86	5	8.9	R
FA 23	3	202	−71	276	−76	7	7.4	R
FA 24	3	210	−79	218	−78	4	8.1	R
FA 25	3	164	−57	5	−62	11	0.9	R
FA 26	4	209	−70	268	−73	14	0.7	R
FA 27	3	235	−78	217	−68	6	1.0	R
FA 29	3	108	+78	15	+51	15	1.0	N
FA 30	3	354	+75	213	+87	1	6.3	N
FA 31	3	347	+64	186	+70	10	3.8	N
FA 32	4	359	+78	333	+87	4	2.7	N
FA 33	3	76	+74	38	+57	5	1.1	N
FA 34	3	47	+79	34	+71	5	9.9	N
FA 35	3	101	+71	29	+44	19	3.5	N
FA 36	3	83	+66	48	+45	6	8.2	N
FA 37	3	87	+68	42	+46	7	7.6	N
FA 38	3	85	+71	38	+50	3	3.3	N
FA 39	3	310	+70	251	+64	5	2.9	N
FA 40	3	30	+48	115	+50	2	6.1	N
FA 41	3	346	+76	246	+83	4	5.2	N
FA 42	3	11	+73	110	+82	6	1.9	N
FA 43	3	20	+77	54	+81	4	6.9	N
FA 44	3	6	+66	143	+74	5	1.5	N
FA 45	3	13	−51	147	−7	12	0.5	E
FA 46	3	32	−59	133	−17	6	0.6	RT
FA 47	3	36	−57	129	−15	5	0.6	RT
FA 48	3	26	−50	135	−7	9	0.5	E
FA 49	3	199	−63	300	−68	2	5.8	R
FA 50	3	196	−62	307	−67	5	6.9	R
FA 51	4	179	−83	156	−79	3	5.6	R
FA 52	3	287	−73	202	−44	9	3.1	R
FB Kuludalur								
FB 00	3	20	+16	135	+32	20	2.1	NT
FB 01	3	200	−55	305	−60	3	2.1	R
FB 02	3	128	+60	18	+23	8	1.0	NT
FB 03	3	221	−57	276	−54	4	3.9	R
FB 04	3	234	−69	245	−60	5	3.5	R
FB 05	3	239	−78	214	−66	3	3.8	R
FB 06	3	233	−74	234	−65	5	4.2	R
FB 07	3	220	−69	260	−67	2	4.7	R
FB 08	3	122	−57	58	−47	1	1 7	R
FB 10	3	151	−60	27	−62	7	2.8	R
FB 11	3	149	−60	30	−60	5	3.3	R
FB 12	3	181	−72	334	−82	2	3.4	R
FB 13	3	209	−81	197	−77	4	4.5	R
EZ Hvalfjardareyri								
EZ 03	3	141	−72	66	−70	6	1.5	R
EZ 05	3	186	−76	276	−87	5	2.3	R
EZ 08	3	191	−61	318	−67	14	1.8	R
EZ 12	3	186	−68	322	−77	4	5.4	R
EZ 14	3	190	−74	285	−84	6	1.3	R
EZ 15	3	5	+59	149	+66	3	1.9	N
EZ 16	3	11	+75	89	+85	5	9.2	N
EZ 17	3	354	+69	177	+77	4	2.7	N
EZ 18	3	0	+71	157	+81	4	8.9	N
EZ 19	3	336	+69	217	+74	9	2.9	N
EZ 20	3	356	+67	167	+75	3	6.8	N
EY Fossardalur								
EY 01	4	340	+59	193	+63	26	0.2	N[a]
EY 02	4	67	+79	30	+64	2	2.2	N
EY 03	3	328	+74	248	+75	3	1.5	N
EY 04	3	27	+72	85	+75	5	1.3	N
EY 05	4	50	+69	69	+62	34	0.5	N[a]
EY 06	3	310	+70	250	+64	4	1.2	N
EY 07	5	170	−53	355	−58	4	0.5	R
EY 08	3	177	−47	342	−54	12	1.4	R
EY 08 A	4	170	−58	356	−63	3	1.5	R
EY 08 B	3	163	−56	7	−61	5	2.7	R
EY 09	3	137	+88	345	+61	12	1.4	N
EY 10	3	169	+84	342	+51	4	4.5	N
EY 11	3	4	+77	47	+88	6	2.2	N
EY 12	3	345	+71	205	+78	3	17.2	N
EY 13	4	16	+71	110	+77	12	3.3	N
EY 14	3	10	+70	128	+78	4	12.2	N
EY 15	3	351	+72	192	+81	2	2.8	N
EY 16	3	307	+66	243	+57	4	1.7	N
EY 17	3	308	+67	245	+59	2	6.5	N
EY 18	3	296	+65	253	+52	3	2.6	N
EY 19	3	303	+65	247	+55	2	3.3	N
EY 20	3	314	+76	267	+70	5	0.6	N
EY 21	4	58	+76	44	+65	8	0.8	N
EY 22	3	8	+71	131	+80	8	0.5	N
EY 23	3	11	+66	132	+73	3	2.5	N
EY 24	3	15	+71	111	+79	5	3.3	N
EY 25	3	13	+72	112	+80	4	7.7	N
EY 26	3	23	+74	78	+79	3	8.1	N
EY 27	3	7	+74	120	+85	6	8.7	N
EY 28	3	18	+76	64	+82	3	2.5	N
EY 29	3	44	+78	41	+72	6	3.3	N
EY 30	3	50	+81	24	+71	2	1.5	N
EY 31	4	26	+81	16	+78	3	2.7	N
EY 32 A	3	58	+81	22	+68	4	5.5	N

Table 2 (Continued)

No.	*N*	*D*	*I*	*Lon*	*Lat*	alf	*J*	pol
EY Fossardalur								
EY 32B	3	52	+81	25	+70	7	3.6	N
EY 33	3	209	+82	326	+50	5	3.1	N
EY 34	3	207	+75	322	+37	2	3.0	NT
EY 35	3	201	+77	327	+40	4	2.2	N
EY 36	3	212	+75	320	+38	3	3.7	NT
EY 37	3	52	+81	24	+70	6	2.8	N
EY 38	3	333	+84	319	+74	3	2.9	N
EY 39	3	6	+64	144	+72	1	6.0	N
EY 40	3	343	+79	293	+82	4	6.1	N
EY 41	4	4	+79	354	+85	2	5.7	N
EY 42	4	354	+80	318	+84	5	3.0	N
EY 43	4	25	+77	49	+79	7	2.5	N
EY 44	3	294	+77	281	+63	4	3.1	N
EY 45	3	65	+57	70	+44	8	0.5	N
EY 46	3	103	−41	67	−27	12	2.2	RT
EY 47	3	105	−39	65	−26	13	2.2	RT
EY 48	3	109	−32	59	−24	10	5.2	RT
EY 49	3	94	+ 1	65	− 1	53	0.5	E[a]
EY 50	3	102	−38	67	−24	13	1.2	RT
EY 51	3	346	+71	204	+79	8	6.7	N
EY 52	3	15	+75	85	+82	5	7.8	N
EY 53	3	113	+80	8	+53	9	2.9	N
EM Morastadir								
EM 01	3	27	+72	84	+76	7	7.6	N
EM 02	3	37	+74	64	+72	1	9.3	N
EM 03	3	54	+70	63	+62	13	2.0	N
EM 04	4	19	+61	123	+65	8	4.7	N
EM 05	4	31	+71	85	+72	8	2.9	N
EM 06	3	354	+68	174	+76	3	3.0	N
EM 07	3	353	+83	330	+78	7	1.1	N
EM 08	3	4	+79	2	+86	5	1.6	N
EM 09	3	8	+70	136	+78	5	3.8	N
EM 10	4	8	+72	126	+81	6	8.2	N
EM 11	3	81	−35	85	−13	6	0.7	RT
EN Middalur								
EN 02	3	34	+66	92	+66	3	0.9	N
EN 03	3	21	+68	109	+73	9	1.3	N
EN 04	3	39	+83	9	+73	9	2.4	N
EN 05	3	112	+85	355	+60	6	1.9	N
EN 06	3	136	−57	43	−53	6	0.4	R
EN 08	3	232	+17	286	− 7	7	0.6	E
EN 10	3	86	+ 4	71	+ 3	10	0.5	E
EN 11	3	92	+13	64	+ 5	31	0.4	E[a]
EN 12	3	80	+38	68	+23	7	1.2	NT
EN 13	3	143	−63	43	−61	11	0.9	R
EN 14	3	212	+16	305	−14	45	0.5	RT[a]
EN 15	3	75	−69	108	−40	16	0.3	R
EN 16	3	96	−75	103	−54	13	0.6	R
EN 17	3	178	−75	5	−88	8	1.7	R
EN 18	3	172	−52	352	−58	6	2.9	R
EN 19	3	181	−66	335	−74	7	2.4	R
EN 20	3	181	−76	273	−89	12	5.6	R
EN 21	2	170	−68	5	−76	11	2.1	R
EN 22	3	173	−74	21	−85	8	3.9	R
EN 23	4	177	−72	349	−83	8	1.2	R
EN 24	3	175	−69	353	−78	6	2.2	R
EN 25	3	173	−58	350	−64	21	0.9	R
EN 26	3	80	−72	108	−46	18	0.7	R
EN 27	3	97	−71	96	−51	9	1.9	R
SA Kerlingargil								
SA 01	3	46	+69	74	+63	9	2.6	N
SA 02	3	229	−47	274	−42	20	2.5	R
SA 05	3	181	−72	332	−82	32	1.2	R[a]
SA 06	3	227	−10	286	−22	41	0.4	RT[a]
SA 07	3	232	−36	275	−34	29	0.6	RT[a]
SA 08	3	217	−65	271	−64	23	0.4	R
SA 09	3	232	−45	271	−40	30	0.3	RT[a]
SA 10	3	267	+20	255	+ 8	27	0.3	E[a]
SA 12	3	63	+47	80	+37	8	1.1	NT
SA 13	3	89	+36	60	+19	5	1.5	NT
SA 14	3	266	−61	230	−39	28	0.3	RT[a]
SA 15	3	211	−46	295	−48	50	0.7	R[a]
SA 16	3	198	−40	314	−47	36	0.5	R[a]
SA 20	3	110	−75	97	−60	3	0.9	R
SA 21	3	28	−87	152	−58	20	1.4	R
SA 22	3	140	−82	123	−73	24	4.0	R[a]
SA 23	3	180	−71	338	−82	12	3.5	R
SA 24	3	180	−75	343	−87	11	2.2	R
SA 25	3	220	−62	272	−59	25	1.6	R[a]
SA 26	3	157	−63	22	−67	23	2.3	R
SA 27	3	192	−76	250	−85	9	5.0	R
SA 28	3	177	−51	344	−57	5	14.0	R
SA 30	4	249	−86	179	−66	5	5.2	R
EP Thornyjartindur								
EP 01	3	171	−61	355	−67	5	6.4	R
EP 02	3	162	−55	7	−59	6	2.7	R
EP 03	3	158	−59	16	−63	5	3.8	R
EP 04	3	161	−56	10	−60	2	2.0	R
EP 05	3	164	−53	4	−58	10	1.7	R
EP 06	3	146	−74	68	−74	3	3.3	R
EP 07	3	120	−74	88	−63	4	3.0	R
EP 09	3	175	−78	126	−86	13	5.9	R
EP 10	3	180	−76	341	−89	5	3.8	R
EP 11	3	196	−68	298	−74	8	8.8	R
EP 12	3	190	−78	205	−85	9	4.8	R
EP 13	3	199	−74	266	−80	4	7.1	R
EP 14	3	171	−81	139	−82	9	5.2	R
EP 15	3	249	−71	231	−56	8	5.0	R
EP 16	3	238	−67	246	−57	3	9.6	R
EP 17	3	242	−73	230	−61	5	7.8	R
EP 18	3	218	−73	248	−71	8	6.3	R
EP 19	3	240	−70	239	−59	5	7.6	R
EP 20	3	236	−74	231	−64	2	6.3	R
EP 21	3	239	−72	235	−61	7	6.0	R
EP 22	3	218	−77	230	−74	10	6.0	R
EP 23	3	225	−75	234	−70	5	5.4	R
EP 24	3	193	−82	176	−79	2	7.8	R
EP 25	3	138	−88	152	−67	5	7.9	R

Table 2 (Continued)

No.	*N*	*D*	*I*	*Lon*	*Lat*	alf	*J*	pol
EP Thornyjartindur								
EP 26	3	158	−84	140	−75	5	7.5	R
EP 27	3	157	−82	132	−77	1	6.7	R
EP 28	3	177	−78	139	−87	6	4.2	R
EP 29	4	186	−76	270	−87	5	7.6	R
EP 30	3	206	−70	276	−73	6	5.6	R
EP 31	3	177	−74	357	−85	6	6.4	R
EP 32	3	160	−69	29	−74	10	3.7	R
EP 33	3	181	−75	326	−88	7	7.9	R
EP 34	3	172	−74	22	−84	10	7.1	R
EP 35	4	154	−56	20	−58	5	3.7	R
EP 36	3	166	−66	9	−72	8	(2.3)	R
EP 37	3	168	−75	42	−84	10	1.3	R
EP 38	3	169	−69	9	−77	12	1.0	R
EP 39	3	161	−76	70	−82	5	3.7	R
EP 40	3	198	−76	243	−82	10	4.8	R
EP 41	3	132	−86	139	−69	1	11.0	R
EP 42	3	194	−62	311	−67	8	7.3	R
EP 43	3	219	−75	240	−72	5	3.8	R
EP 43 A	3	187	−63	325	−69	13	4.8	R
EP 44	3	274	−63	222	−37	13	2.5	RT
EP 45	3	349	+68	188	+76	4	1.5	N
SB Kistufell								
SB 01	3	144	−57	34	−55	3	0.8	R
SB 02	3	163	−53	5	−57	4	2.1	R
SB 03	3	153	−53	19	−55	6	3.0	R
SB 04	3	159	−59	16	−63	5	0.9	R
SB 05	3	216	−77	231	−75	12	1.6	R
SB 06	3	153	−55	21	−56	12	1.4	R
SB 07	3	159	−57	13	−61	9	2.2	R
SB 08	3	155	−56	18	−58	5	1.8	R
SB 09	3	126	−52	51	−44	19	0.5	R
SB 10	3	148	−54	26	−54	14	2.7	R
SB 11	3	165	−58	5	−63	9	0.3	R
SB 12	3	167	−72	26	−81	2	3.4	R
SB 13	4	162	−71	26	−76	11	1.3	R
SB 14	6	147	−74	64	−74	12	0.5	R
SB 15	3	194	−68	302	−75	12	1.8	R
SB 16	3	190	−78	204	−85	5	3.5	R
SB 17	3	243	−76	222	−63	5	4.2	R
SB 18	3	214	−77	230	−76	5	5.1	R
SB 19	3	224	−79	215	−73	2	4.2	R
SB 20	3	234	−81	203	−69	5	3.9	R
SB 21	3	223	−76	229	−72	8	1.9	R
SB 22	3	228	−76	229	−69	2	4.9	R
SB 23	3	276	−71	212	−45	5	1.2	R
SB 24	3	18	+68	116	+73	8	0.7	N
SB 25	3	359	+75	161	+87	12	0.3	N
SB 26	3	20	+70	106	+75	2	0.7	N
SB 27	3	8	+67	139	+74	7	1.2	N
SB 28	3	6	+72	130	+82	7	1.0	N
SB 29	3	50	+72	60	+65	30	0.3	N[a]
SB 30	3	332	+61	208	+63	29	0.9	N[a]
SB 31	3	357	+61	165	+68	21	1.4	N
SB 32	3	49	+68	72	+62	2	5.9	N
SB 33	3	57	+71	59	+61	5	5.8	N
SB 34	3	64	+73	50	+60	2	3.0	N
SB 35	3	70	+73	46	+57	11	1.2	N
SB 38	3	163	−44	3	−50	7	4.3	R
SB 39	3	172	−49	351	−55	4	3.9	R
SB 40	3	152	−57	24	−58	12	3.2	R
SB 41	3	186	−65	326	−73	4	3.4	R
SB 42	3	208	−67	279	−69	9	4.2	R
SB 43	3	209	−73	260	−75	2	4.9	R
SB 44	3	166	−75	50	−83	4	7.9	R
SB 45	3	157	−71	41	−75	7	6.7	R
SB 46	3	172	−70	3	−79	3	5.0	R
SB 47	3	204	−71	274	−75	8	3.0	R
SB 48	3	185	−66	326	−73	14	7.6	R
SB 49	3	146	−65	42	−65	18	1.4	R
SB 50	3	208	−55	294	−57	6	1.9	R
SB 51	3	182	−71	330	−82	4	4.1	R
SB 52	3	151	−62	30	−63	4	6.3	R
SB 54	3	156	−61	22	−64	5	3.8	R
SB 55	3	211	−81	199	−76	14	2.6	R
SB 56	3	204	−69	282	−73	9	6.1	R
SB 57	3	142	−79	103	−74	3	3.3	R
SB 58	3	155	−74	58	−77	13	3.3	R
SB 60	3	197	−72	282	−79	7	3.3	R
SB 61	3	182	−69	332	−79	6	1.4	R
SD Grafardalur-Hatindur								
SD 01	3	189	−76	250	−86	7	4.3	R
SD 03	3	196	−79	207	−82	2	1.5	R
SD 04	3	237	−73	235	−63	2	1.4	R
SD 05	3	228	−74	236	−68	5	5.7	R
SD 06	3	214	−73	252	−73	4	7.9	R
SD 07	3	223	−82	198	−73	4	4.3	R
SD 08	3	233	−82	198	−70	12	4.6	R
SD 09	3	282	−83	184	−59	2	1.7	R
SD 10	3	163	−79	112	−82	7	3.1	R
SD 11	3	178	−75	2	−88	5	2.2	R
SD 12	3	155	−73	52	−77	3	2.0	R
SD 13	3	70	−76	121	−48	4	2.4	R
SD 14	3	78	−74	112	−47	5	3.3	R
SD 15	3	102	−77	105	−58	6	2.5	R
SD 16	3	111	−73	92	−58	7	2.3	R
SD 17	3	182	−85	160	−75	6	2.8	R
SD 18	3	276	−83	188	−59	3	3.8	R
SD 19	3	176	−82	153	−79	6	2.5	R
SD 20	3	279	−80	195	−56	6	8.7	R
SD 21	3	28	−87	153	−59	4	5.7	R
SD 22	3	187	−71	313	−81	4	4.1	R
SD 23	3	178	−74	354	−86	5	4.2	R
SD 24	3	181	−84	159	−76	2	10.0	R
SD 25	3	193	−65	310	−71	5	5.4	R
SD 26	3	183	−68	330	−76	5	4.1	R
SD 27	3	201	−63	298	−67	8	11.0	R
SD 28	3	179	−77	135	−89	12	3.0	R
SD 29	3	175	−76	39	−87	5	5.2	R
SD 30	3	184	−74	311	−86	8	4.5	R
SD 31	3	171	−79	118	−85	5	2.2	R
SD 32	3	137	−73	74	−69	35	2.2	R[a]
SD 34	3	197	−81	189	−80	18	2.6	R

Table 2 (Continued)

No.	*N*	*D*	*I*	*Lon*	*Lat*	alf	*J*	pol
SD Grafardalur-Hatindur								
SD 37	3	307	−88	165	−62	6	8.3	R
SD 38	3	35	−85	149	−56	8	2.5	R
SD 39	4	134	−85	139	−70	5	2.6	R
SD 40	3	82	−73	108	−47	16	3.1	R
SD 41	3	177	−74	5	−86	12	3.1	R
SD 42	4	191	−75	267	−85	6	(3.8)	R
SD 43	3	194	−77	226	−84	3	(3.4)	R
SD 44	4	202	−76	239	−81	6	(3.5)	R
SC Svinaskard								
SC 01	2	271	−71	216	−47	(9)	3.3	R
SC 02	3	274	−73	211	−49	11	1.3	R
SC 03	3	96	−85	133	−63	27	3.0	R[a]
SC 04	3	166	−71	22	−78	10	0.4	R
SC 05	3	138	−16	26	−27	27	0.3	RT[a]
SC 07	4	177	+78	340	+42	6	2.8	N
SC 08	5	91	+84	4	+62	5	4.7	N
SC 09	7	25	+78	39	+80	20	1.4	N
SC 10	4	128	+61	18	+24	18	1.4	NT
SC 11	4	62	+84	9	+68	4	5.3	N
Mean direction not significant (alf > 60)								
FA 28	3	Poor stability					0.1	(?)
EZ 01	3	Scattered-near dyke					2.5	(?)
EN 01	5	Scattered-near dyke					0.8	(?)
EN 07	5	Poor stability					0.5	(R?)
EN 09	5	Poor stability					1.2	(?)
SA 03	3	Two N, one unstable					2.7	(N?)
SA 11	3	Scattered					0.6	(?)
SA 17	3	Scattered R/RT					1.1	(RT?)
SB 36	3	Scattered N/NT					1.8	(N?)
SB 37	3	Two R, one NT					1.5	(R?)
SB 53	3	Two R, one E					4.4	(R?)
SB 59	3	Two R, one NT					3.8	(R?)
SD 02	3	Two R, one N					3.0	(R?)
SD 36	3	Two R, one N					3.3	(R?)

List of all units sampled for magnetic measurements
N = Number of samples per flow
D, *I* = Declination and inclination of best mean field after tectonic tilt correction
Lon, *Lat* = Coordinates of virtual geomagnetic pole
alf = α_{95} of mean field
J = Mean remanence intensity after 100 Oe, in amperes/m
pol = Magnetic polarity of unit
[a] If alf > 23.5°, *T* if |Lat| < 40°, *E* if |Lat| < 10°

From geological correlations, 77 sampled units are considered to overlap in time with sampled units in other sections of the composite profile, although they are very unlikely to be identically the same as any of those. The overlaps are as follows: FB 0–2 overlap with the top flows of FA; FB 8–13 overlap with EZ; EY 51–53 overlap with the bottom flows of EM; SA 1–30 overlap with EN; EP 41–45 overlap with SB above SB 13; SB 1–13 and 47–61 overlap with EP and SD, respectively; SD 1–3 overlap with SB below SB 47; SC 9 and 11. Omitting these and all units with $\alpha_{95} > 60°$, we are left with 268 in our main composite profile shown in Fig. 3, where computed geomagnetic pole latitudes are plotted against stratigraphic height. In this figure, each major hyaloclastite sequence has been reduced to one tenth of its maximum recorded thickness, to allow for the fact that it would have taken on very different dimensions in a subaerial environment.

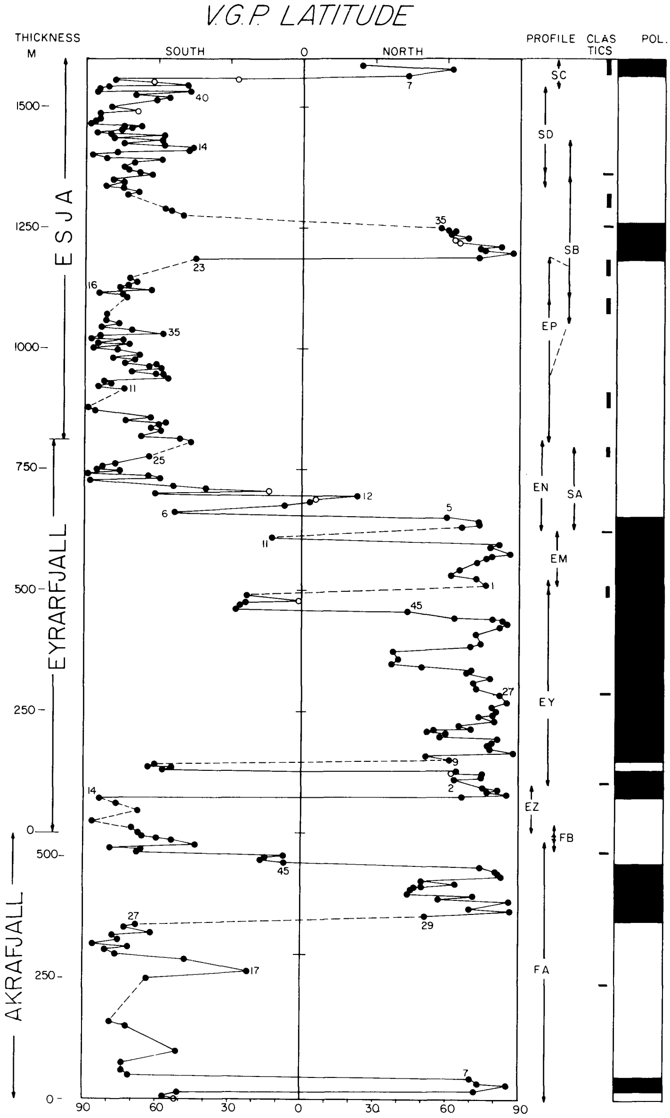

Fig. 3. Plot of virtual geomagnetic pole latitude versus stratigraphic thickness for a composite profile through area of Fig. 1. Some lavas numbered to aid comparison with Fig. 2 and Table 2. *Open circles* are lavas where field direction has α_{95} exceeding 23.5°. *Broken lines* indicate minor gaps, uncertain correlations, or hyaloclastites (see text). *Double arrows in right hand column* show amount of partial overlap between sections. Simplified polarity structure on far right; *black* is normal magnetization

4. Magnetic Stratigraphy and Correlation; Discussion

For lack of dated material in the present sections, their interpretation must be limited for the time being to a straightforward correla-

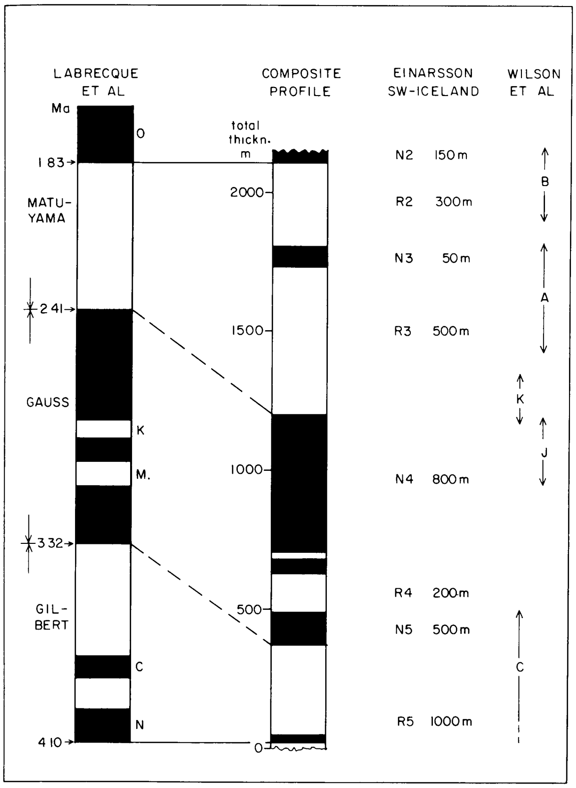

Fig. 4. Polarity column from Fig. 3, showing proposed correlations with the ocean-anomaly geomagnetic time scale of Labrecque et al. (1977) and with the stratigraphic thickness of Einarsson's (1957) polarity groups. Approximate position of some sections sampled by Wilson et al. (1972) shown on the right

tion with one recently proposed global magnetic time scale (Fig. 4) and remarks of mostly local interest.

The Gilbert-Gauss Boundary is represented at most by one flow here (FA 28, unstable), but by several flows in section C of Wilson et al. (1972). The Gauss-Mammoth boundary here includes four transitional flows (FA 45–48) but at most one flow in C or in Borgarfjördur (NT2, not sampled). In general, it appears unlikely that transitional directions will be of use in stratigraphic correlation of lavas in Iceland.

Mammoth and Kaena Events (Einarsson's R 4). The Mammoth event, beginning at FA 45, is here much thicker than the Kaena, which may be due to inclusion of a series of rapidly erupted flows from the Hvalfjördur volcano. Flows younger than Mammoth are not found in Akrafjall (Franzson, 1978). The Kaena comprises only four flows, plus possibly two obscured by soil cover. In section NT of McDougall et al. (1977) a series of 8 thin flows at the presumed upper boundary of the Kaena event have yielded normal poles near 25° N, 100° E; but corresponding transitional directions have not been found south of Hvalfjördur. A suggestion by Kristjansson et al. (1975) that a 'rebound' occurred in this transition, has later turned out to be inapplicable because lavas NT 31–36 are, in fact, repeated by a fault as NT 37–43.

Upper Gauss Epoch, 'Fosså event' The Upper Gauss, termed *N* 4 by Einarsson, is represented by most of our EY and EM sections. It includes five flows of similar, shallow reverse magnetic directions (EY 46–50), noted by Jonasson et al. (1973) and called by them the Fosså event. However, in the absence of any high-latitude poles in this group of flows, we hesitate to designate it to a separate polarity event. The same argument applies to the low-latitude reverse flow EM 11 and to flow FB 2. The paleomagnetic Sect. J of Wilson et al. (1972) similarly belongs to the Upper Gauss epoch, but in their Fig. 1 they have erroneously designated a reversely magnetized sill (J 22) as a separate polarity interval.

Gauss-Matuyama Boundary. In the lower parts of sections EN and SA (EN 2–14; SA 2–16) which are stratigraphically equivalent, we see a similar pattern of rapid polarity fluctuations and transitional directions (Table 2). Although these flows are magnetically the least stable of the present collection, we believe that these fluctuations are real and indicate details of a complex Gauss-Matuyama transition. Such complexities have also been found in sedimentary rocks (Gurariy, 1977). Other details of the Gauss-Matuyama transition may be recorded by Sigurgeirsson (1957), by Wilson et al. (1972) in Sect. K as 12 mostly thin flows with pole positions near the equator at 80° E, and in flows NT 93–97 of McDougall et al. (1977).

Reunion (or Olduvai) Event. At SB 24 there begins a series of 13 normally magnetized flows, belonging to the thin N 3 series of Einarsson (1957). At its lower boundary, Sigurgeirsson (1957) observed a remarkable series of transitional flows, at various localities in the area, later investigated in more detail by Shaw (1975). Only one transitional flow occurs at this reversal in our Sect. SB and EP.

The dating at 1.8 Ma of a normally magnetized series stratigraphically higher than this event, present in our view convincing evidence that at least two separate events occurred in the Lower Matuyama epoch. Therefore, if the Olduvai was the major event in the Matuyama (Labrecque et al., 1977) the N 3 must be identified for the time being with the Reunion event. We do not, however, consider the problem of Matuyama events to be settled, and further sites for the dating of these are being looked for in Iceland.

Brunhes Age Flows. The younges volcanic rocks in the Esja area are the so-called Reykjavik grey or 'dolerite' lavas. These have not been radiometrically dated or mapped in detail by us, but they are generally believed to be of late Brunhes age. Laboratory results by us from samples of 33 'flow units' at 11 sites around Reykjavik confirm the conclusion of Wilson et al. (1972) based on data from one site, that the magnetic directions in these lava flows are quite tightly grouped and hence that most of them may have been emplaced within a short period compared to the time scales of secular variation. Our results, using 4 samples per flow unit, yield a mean field having $D=8.3°$, $I=70.6°$ ($\theta_{63}=10°$, with $N=33$).

5. Mean Paleomagnetic Field and Secular Variation

5.1 Rates of Eruption

In the interpretation of Fig. 4, the present composite profile contains some 300 lavas covering 2.4 Ma in time. Due to uncertainty in translating thicknesses of hyaloclastite sequences into equivalent lava thickness, it is difficult to compare the mean rate of build-up in this pile to data from other studies in Iceland. However, the rate is relatively high, due to the nearness of central volcanoes, and according to Fig. 4, it may increase by a factor of three or more between the bottom (Gilbert) part and the top (Matuyama) part of the profile.

5.2 Serial Correlation

On close inspection of Table 2, a grouping of paleomagnetic directions is commonly seen in 3 to 7 successive lavas. Examples include FA 45–48, EY 16–19, EP 1–5, SB 32–35 and SD 13–16; possibly a third of all lava flows in the Table may belong to such groups. It is mostly likely that these groupings are due to tight grouping of the respective eruptions in time, rather than to chance or to secular variation peculiarities. The observed extent of the serial correlation obviously depends much on circumstances such as the completeness of exposures and the mappers' criteria for distinguishing separate lava flows. However, it is instructive to test whether a serial correlation of this sort might affect statistical properties of the overall data set.

Watson and Beran (1967) suggested a testing method analogous to the autocorrelation function of scalar time series. A simplified statement of this test for a unipolar Fisher's (1953) distribution of N unit vectors X_i is that the mean product

$$S(u)=\sum_{i=1}^{N-u} X_i X_{i+u}/(N-u)$$

at lag $u \neq 0$ should be significantly larger than the value of $(1-1/K)^2$ in case of serial correlation between the vectors. $1-1/K$ is also the value of cos θ_{63} or R/N, if N is large and $K>5$. We have applied this test to three comparable populations of paleomagnetic vectors from long stratigraphic sequences of Icelandic flows; the results are presented in Table 3.

The data from W-Iceland are those of Watkins et al. (1977), with later minor corrections, while those from the north are from a study by Saemundsson et al. (1980). Each includes only non-overlapping units having α_{95} less than 23.5°, with reverse field vectors inverted before computation. It is seen that definite serial correlation exists in all these collections at lags of one and two flows, and it is relatively strongest in Esja.

The above results support the view (Kristjansson, 1968) that it is inadvisable to draw conclusions regarding the geomagnetic or tectonic causes of differences between populations of Icelandic lava flows if N is less than 50 or 100. However, averaging lava directions in smaller groups, e.g., with $N=20$, may help to elucidate some aspects of geomagnetic field behaviour (Watkins et al., 1977; Saemundsson et al., 1980).

5.3 Mean Fields and Systematic Errors

Even in collections of hundreds of magnetically stable flows spanning several geomagnetic reversals, such as the three profiles just referred to, it is not certain that we have obtained a precise and meaningful average geomagnetic field for each area and time interval. Besides the observation that R/N values vary considerably between the three entries above, several systematic sources of errors in the data may not average to zero and it is necessary to estimate their sizes. Among these we shall mention three.

Magnetic anomalies of crustal origin are common over Iceland (Haines et al., 1970), some extending tens of kilometers and amounting to more than 1° in direction at 3 km altitude, especially near the volcanic zones. In the past, such regional anomalies may have caused the geomagnetic field at ground level to deviate systematically by 2° or more from the core-generated field during large parts of geomagnetic epochs.

Tectonic tilt corrections are often uncertain in work on Icelandic lava sequences, especially in gentle stream or hill sections and where the surfaces of lava flows are uneven. Tilts commonly decrease with altitude in the sections sampled, but only an average tilt value is used for correction. This error source may well reach 2° in means of say 50 lava flow directions.

Systematic errors of orientation and measurement include map errors (especially in work in narrow valleys), errors in the measurement of drill core inclination due to loose fitting of the orienting tool, unconscious 'handedness' in marking cores and aligning them for remanence measurement, and so on. The latter types of error will be minimized by coring equally often towards all directions, but in practice the choice of coring direction will be much restricted by the landscape. Thus, in two cases of large paleomagnetic collections in Iceland we have found, from field work notebooks, that about 80% of the cores of each were drilled towards one half of the horizon, mostly at low positive inclinations. Errors from these sources may amount to 2–3°

The above estimates indicate that it should not be surprising to find mean paleomagnetic field directions from different parts of the country deviating from one another by up to 6° of arc, even in large collections of roughly contemporaneous strata.

As an example, it was noted by Watkins et al. (1977) that mean field directions from lavas of similar age in Borgarfjördur and in Eastern Iceland have inclinations that are, respectively, a few degrees lower and a few degrees higher than a central axial dipole field value. On the other hand the mean field from the present collection of 258 lavas all having an internal α_{95} value of 23.5° or less, is $D=3.4°$, $I=76.8°$, which is within one degree of the expected dipole field values $D=0°$, $I=76.5°$ ($\theta_{63}=18.8°$, $\alpha_{95}=2.1°$). We thus see that allowing for the presence of systematic errors in mean paleomagnetic field directions may explain minor observed differences between them, so that recourse to physically improbable tectonic or geomagnetic scenarios, as discussed by Watkins et al. (1977), is avoided.

Further statistical analysis of the present collection of paleomagnetic data is being published elsewhere (Saemundsson et al., 1980) along with results from Northern Iceland lava flows.

Table 3. Qualitative test for serial correlation in three populations of Icelandic paleomagnetic vectors

Area	N	$S(u)$					$(R/N)^2$
		$u=0$	1	2	3	4–9 (av.)	
W-Iceland	325	1.0	0.887	0.877	0.874	0.868	0.867
N-Iceland	292	1.0	0.846	0.809	0.794	0.794	0.789
Esja etc.	258	1.0	0.944	0.918	0.905	0.898	0.896

6. Conclusions

Recent detailed geological studies in the area of the Esja, Eyrarfjall, and Akrafjall mountains by the authors and others have confirmed the local magnetic polarity stratigraphy of Einarsson (1957) and its correlation with geomagnetic time scale by Piper (1971). Some new detail has been added, such as the demonstration of two separate magnetic events in Gauss epoch lavas in Eyrarfjall, and it now appears that the two normal Lower Matuyama series in Esja may belong to the Reunion and Olduvai events rather than to the Olduvai and Gilsá.

As remarked by Piper (1973), there is fairly good correspondence between the magnetic polarity of outcropping basalt sequences in the Hvalfjördur area and the polarity of low-altitude aeromagnetic anomalies (Sigurgeirsson, 1970) in the area. The anomaly trend is also similar to the general geological strike direction, although the linearity of these magnetic anomalies is not as persistent as it is over mid-ocean ridges near Iceland. For instance, a prominent positive anomaly correlated with the Gauss age rocks of Eyrarfjall may peter out towards southwest (Kristjansson, 1978).

Hyaloclastites and conglomerate horizons of glacial origin are common in the area and are first observed in strata of Lower Mammoth age. Their presence complicates stratigraphic considerations, but also enables correlations to be made with dated sequences of lavas elsewhere. By correlating with other dated sequences in western Iceland (Saemundsson and Noll, 1974; McDougall et al., 1977) we conclude that at least 13 glaciations occurred in Western and Southwestern Iceland between 3.1 and 1.8 Ma ago.

A mean paleomagnetic direction, computed from 258 lava flows with good internal consistency in non-overlapping parts of 11 sections in the lava pile, is very close to the local value of the central axial dipole field. Possible sources of systematic direction errors in large paleomagnetic collections of Icelandic lava flows are discussed, and it is concluded that minor differences between means of these need not be significant. Due to serial correlation between adjacent lavas and to unpredictable features of the paleomagnetic field, it is also increasingly evident that differences in statistical properties of the field are not eliminated between groups of 20–30 or even of 200–300 flows, when all valid data including low-latitude poles are included. This conclusion reduces the confidence with which tectonic and geomagnetic inferences can be drawn from paleomagnetic data in other regions.

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