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Secular variation and reversals in a composite 2.5 km thick lava section in central Western Iceland

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The direction and intensity of primary remanence has been measured in oriented specimens from 367 lava flows of Late Miocene age in Western Iceland. The lavas which were sampled in 8 overlapping profiles, were generally good material for paleomagnetic measurements. In a 2500-m composite section, at least 15 reversals of polarity and several excursions are recorded. The mean remanence direction and other overall paleomagnetic parameters for the present collection of lavas are similar to those found elsewhere in Iceland. The average rate of buildup of this lava pile was rather low and possibly episodic. Hence, correlations to the geomagnetic polarity time scale and to polarity patterns in other composite sections mapped in Iceland are not straightforward.

1. Introduction

1.1 Geological notes

Those parts of Iceland which are older than 3 Ma are mostly composed of flood basalts with minor sedimentary interbeds. They were generated in active zones of rifting, volcanism and subsidence which currently intersect the island from southwest and south to northeast. Most of the production of basalts (as well as of some intermediate and acidic rocks) takes place in so-called central volcano complexes which are commonly of the order of 10 km in size. The basalt lava pile generally dips gently ($<10°$) towards the active rift zone and increases in age away from it. However, there is evidence for large eastwards displacements of the rift zone which have given rise to syncline-anticline structures, unconformities, and crustal fracturing. One such ridge jump in Western Iceland appears to be of similar age as the oldest exposed lavas in the North-western peninsula (about 16 Ma; Hardarson *et al.*, 1997).

Jóhannesson (1980) constructed a diagram showing a 4.5 km composite paleomagnetic polarity column through the lava pile of central Western Iceland. This polarity column was based on field measurements of remanence polarity in hand samples, in profiles situated between the southeastern corner of the North-western peninsula and an area east of Borgarfjördur (Fig. 1(a)). Jóhannesson's paper also includes a description of a synclinal structure in the lava pile in Western Iceland which is thought to mark the position of a former rift axis. The syncline (S in Fig. 1(a)) crosses Snæfellsnes peninsula from southwest to northeast; east of this syncline the age of the lava pile increases towards the currently active volcanic zones. Until recently, the only available radiometric age determination on extrusives from this area was 6.7 ± 0.4 Ma (Moorbath *et al.*, 1968; 6.9 Ma using current decay constants), obtained from one of the youngest units at the axis of the Snæfellsnes syncline. It has therefore been considered that the jump of the spreading axis from the Snæfellsnes syncline to its present position took place at around 7 Ma.

Aided by the above K-Ar age and by paleomagnetic and age data from the work of McDougall *et al.* (1977), Jóhannesson correlated his composite column of polarity zones in central Western Iceland with the geomagnetic polarity time scale of Labrecque *et al.* (1977) between ages of 4 and 10 Ma. In particular, an unusually thick normal-polarity zone (at least 800 m) at the base of the column was correlated with the long normal-polarity chron thought to correspond to the mid-ocean ridge lineation "Anomaly 5". A thick zone of normal polarity has also been found at a similar stratigraphic level in the North-western peninsula (McDougall *et al.*, 1984) as well as in central northern and eastern parts of the island; however, it is not yet clear whether all these occurrences date from the same geomagnetic chron.

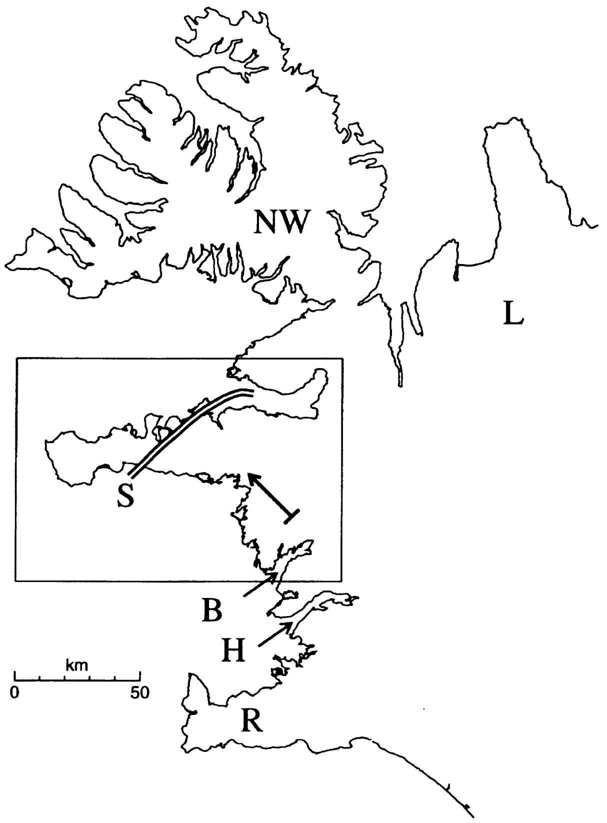
Recent work by Pringle *et al.* (1997) has shown that activity in the Snæfellsnes volcanic zone may have lasted until 5 Ma, i.e. almost 2 Ma longer than suggested by the age determination of Moorbath *et al.* (1968). When it became extinct, activity shifted to the east where a new rift zone was established, the forerunner to the currently active spreading zone of South-western Iceland. A study of magnetic anomaly lineations in Western Iceland and offshore by Kristjánsson and Jónsson (1998) has supported previous suggestions that in this case the lateral movement of the spreading axis took place by a "propagating rift" mechanism but much additional work is needed to clarify details of its timing and of the associated tectonic processes.

The present study area is situated between the Snæfellsnes syncline (Fig. 1(a)) to the northwest and an anticline on the north shore of Borgarfjördur to the southeast. At about 2 Ma activity was resumed in this area and along the Snæfellsnes peninsula but its tectonic setting and petrochemistry of the volcanics were different. The younger sequence is transitional to alkaline in composition and the trend of the volcanic fissures is WNW-ESE in contrast to the NE-SW trend of the Miocene volcanism.

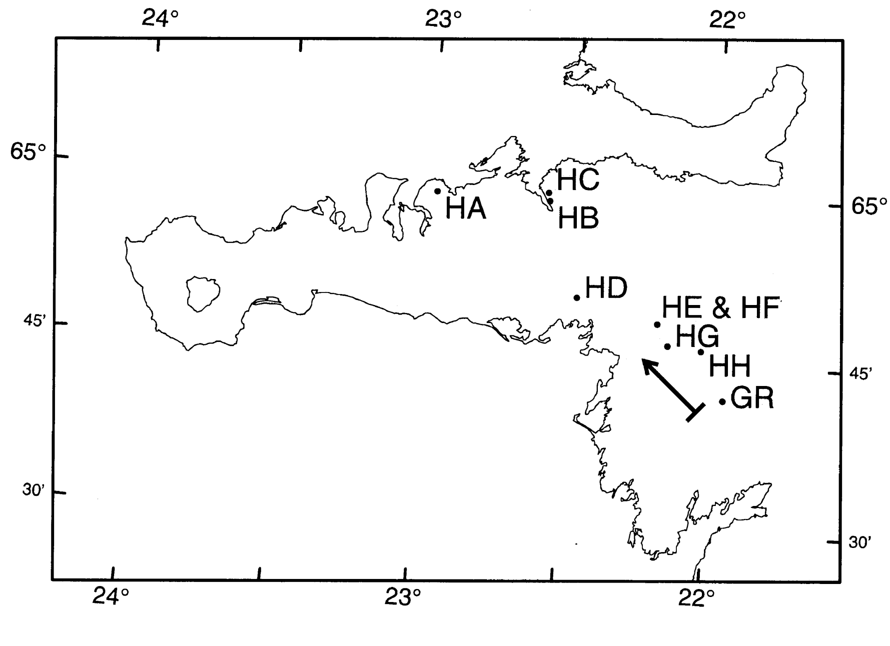
1.2 Previous paleomagnetic work in Western Iceland

Lava sequences so far sampled in Iceland have been shown to be excellent material for paleomagnetic studies, and they have since the early 1950's provided significant information on the history of the geomagnetic field (see review by Kristjánsson, 1993). Good exposures of the lava pile may be found in steep eroded mountain sides and along streams. A mountain profile usually contains 50–80 lavas of about 8 m average thickness. Kristjánsson and McDougall (1982) estimated that the average time interval between successive lavas in typical sampling profiles in Iceland (excluding series of thin "flow units" commonly found near the volcanic centers) is of the order of 10 ka.

Six paleomagnetic studies on more than 300 lavas each have been published from Western Iceland (Fig. 1(a)), as well as a number of smaller surveys. The first large study (Wilson *et al.*, 1972; Dagley and Lawley, 1974) included 329 lava flows in ten profiles of ages between 0 and 5 Ma around the fjord of Hvalfjördur. Numerous geomagnetic excursions and reversals were recorded by these lavas. Only a limited part of the paleomagnetic results was published and the general stratigraphy of the volcanics in the area has not been described in detail in the literature. McDougall *et al.* (1977) and Watkins *et al.* (1977) published paleomagnetic results on 362 lavas of 1.5–7 Ma age in a composite 3.5 km thick section northeast of Borgarfjördur, along with much stratigraphic and K-Ar age dating information. Some ad-



(a)



(b)

Fig. 1. (a) Index map of Western Iceland. Box indicates the area of Fig. 1(b). H: Hvalfjördur fjord. B: Borgarfjördur fjord. L: Langidalur valley. S: syncline crossing the Snæfellsnes peninsula. NW: North-western peninsula. R: Reykjanes peninsula, site of currently active spreading. Arrow: down-dip direction at most of the profiles sampled. (b) Approximate locations of sampling profiles in Western Iceland. See Fig. 2, Table 1 and Appendix. GR: Mt. Grímsstadamúli.

ditions and corrections to this paleomagnetic data set have been made (L. Kristjánsson, unpublished). Kristjánsson *et al.* (1980) measured the paleomagnetism of 353 lavas in a 2.1 km composite section of approximately 2–4 Ma age at the western end of Hvalfjördur, overlapping to some extent with the study by Wilson *et al.* (1972). McDougall *et al.* (1984) gave paleomagnetic results from 1261 lavas in two dated sections of about 7–16 Ma age and 7.2 km combined thickness in the North-western peninsula. Kristjánsson *et al.* (1993) published data from 303 lavas of around 8 Ma age in the Langidalur valley, and Kristjánsson and Jóhannesson (1996) described results from 307 lavas of about 13 Ma age in the North-western peninsula.

Correlations between these sequences and others covering the same age range elsewhere in Iceland are not yet certain. This is partly due to a paucity of K-Ar dates and in some cases to alteration problems affecting the quality of the dating results. Partly it is also due to various stratigraphic and tectonic complexities including variable rates of buildup of the lava pile as well as the occasional large lateral movements of the active volcanic zones mentioned above (Jóhannesson, 1980). Correlation of polarity zones in the Icelandic lava sections with published geomagnetic polarity time scales has also been uncertain, for similar reasons.

1.3 Purpose of the present project

The present research project had various initial aims. With regard to the detailed geology of the area, it was intended to establish a reference section with which other outcrops in the area and neighboring areas might be correlated. For this it was essential to include laboratory paleomagnetic measurements on oriented cores, in order to eliminate spurious polarity reversals which may appear when only field measurements on lava hand samples are available. With regard to the secular variation of the paleomagnetic field, it was of interest to study its characteristics in a sizable collection of lava flows in this region for comparison to those in previous collections from Iceland. New radiometric dating would add much to the overall importance of the project such as the possibility of assigning ages to particular polarity zone boundaries, volcanic and tectonic events, and local anomaly lineations. Even in the absence of new radiometric dates, convincing correlations with the geomagnetic polarity time scale might allow estimation of the rate of volcanic buildup in the area.

2. Sampling and Magnetic Measurements

2.1 Geological field methods and stratigraphy

Eight well-exposed mountainside profiles, forming a single composite section, were selected for our paleomagnetic sampling after reconnaissance mapping of many such profiles in the area. Approximate locations of the selected profiles are shown in Fig. 1(b). Their coordinates are listed at the end of Table 1, and a short description of each location is given in an Appendix. In order of increasing age the profiles were named HA, HC, HB, HD, HE, HF, HG and HH, comprising 387 lavas of total thickness 3215 m including interbeds. The mapping involved definition of lava types, measurements of the thickness of individual lava flows and sedimentary beds, estimation of magnetic polarity by portable fluxgate magnetometer and determination of strike and dip. The lava flows were classified according to Walker's (1959, 1971) classification scheme. The rock types of that scheme are as follows: tholeiite, olivine basalt (single flows), compound flows (lava shields), basaltic andesite (i.e. basaltic icelandite), andesite (i.e. icelandite), dacite and rhyolite. Ignimbrites are classified separately. The lavas often have scoriaceous margins and are separated by sediments, commonly thin red beds believed to be paleosoil, lake sediments (mostly siltstones) and occasional conglomerates. The sedimentary beds are usually a few tens of cm thick but may be up to tens of meters. Detailed diagrams of the stratigraphy of each profile are shown in Fig. 2, indicating lava types, sediments and other information. The exposed lavas in the present section are all basalts except HA 35, 36, 39, 53, 54 (andesite or rhyolite) and HH 28 (ignimbrite). In general the secondary regional alteration in our profiles was minor, with most of the lavas being either zeolite-free or lying within the chabazite-thomsonite zeolite zone. The lowermost parts of some profiles extend into the mesolite-scolecite zone. It is unlikely that regional temperatures of secondary heating in any of these exceeded 100°C (see Alt, 1999, section 6.9).

The section was intended to cover a time interval from below the presumed "Anomaly 5" polarity zone of Jóhannesson (1980) up to the youngest rocks at the core of the Snæfellsnes syncline. The correlation between profiles was based on petrographic characteristics of lava groups and paleomagnetic polarity. In most cases correlations were straightforward but structural complexities and local alteration occasionally created difficulties. Stratigraphic ties between the profile diagrams of Fig. 2 include: HH 80 = HG 2; HF 19/20 = HD 25/26; HD 97/98 = HB 7/8; HC 6/7 = HA 16/17.

The tectonic dip in our profiles is generally to the northwest and ranges from about 2° to 15°, increasing with profile age. Not far from the profiles HA, HB and HC are two central volcanoes, the Setberg volcano west of profile HA and the Hrappsey volcano to the north of HB, HC (see Jóhannesson, 1980). Their main influence on our section is in HA which lies on the outer flank of the Setberg volcano. The region of Fig. 1(b) is intensely faulted. The profiles HD to HH are within the Snæfellsnes Fracture Zone which is characterized by a complicated pattern of NE-SW, N-S and WNW-ESE trending normal and strike-slip faults. Profiles HA, HB and HC are within the fault and dike swarms of the two central volcanoes just mentioned.

2.2 Paleomagnetic sample collection

Four core samples were generally collected from each lava flow with a portable drill, and oriented by geographic sightings or sun compass. The total number of units thus sampled in profiles HA through HH is 367. These are all listed in Table 1, along with a few flows in profile HH where only one sample was obtained. Several of the numbered lava flows were not sampled, mostly because the exposures were steep, very thin, crumbly, or close to dikes. In some cases of compound flows or multiple "flow units" which judging from field evidence were erupted in rapid succession, one unit near the bottom was sampled and sometimes also another one (labelled with a capital suffix in Table 1) higher up. Such units are found in HA 18; HB 4, 8–13, 15; HC 1–2, 7–8; HD 23, 49, 64, 95–97; HE 10, 12–14; HF 8, 19, cf. Fig. 2. Units within flow-unit series in Iceland generally

Table 1. Paleomagnetic directions, virtual pole positions and intensities for lava flows in central Western Iceland profiles. N: number of samples collected from each lava flow, n: number of samples discarded before computation of mean remanence direction, D, I: declination (east) and inclination (down) of best mean remanence direction, after correction for tectonic tilt, Lon., Lat.: longitude and latitude of virtual geomagnetic pole corresponding to the mean remanence direction, Alf: α_{95}, i.e. the 95% confidence angle of the mean direction in degrees, J_{100}: mean remanence intensity of the samples from each flow after 10 mT (100 Oe) alternating field treatment, in A/m, Pol.: magnetic polarity: normal (N) if Lat. > 10°, T if the numerical value of Lat. is between 10° and 40°, E if it is <10°, * if Alf > 20.5°. Values of tectonic tilt (degrees) and downdip direction (east of true north) are at the end of the Table, as well as approximate site coordinates.

Lava	N	n	D	I	Lon.	Lat.	Alf	J_{100}	Pol.
HA Bjarnarhafnarfjall									
HA 1	4		78	−55	94	−27	35	0.14	RT*
HA 2	4		33	60	103	60	3	0.97	N
HA 3	4		62	66	64	53	18	1.04	N
HA 4	4		25	−39	134	1	36	0.53	E*
HA 5A	4		37	−30	121	4	8	0.64	E
HA 6	5		37	−18	120	11	10	1.22	NT
HA 6A	9		Scattered				>60	4.21	(?)
HA 7	9		36	62	97	60	7	1.36	N
HA 7B	3		22	61	117	64	6	4.93	N
HA 8	4		33	58	105	57	2	0.98	N
HA 9	4		28	58	112	60	2	1.46	N
HA 11	4		29	59	109	60	2	1.22	N
HA 13	6	1	22	63	115	66	6	1.09	N
HA 14	6	1	34	58	105	57	8	0.87	N
HA 15	5	1	69	61	63	46	9	0.84	N
HA 16	7	1	72	62	60	46	9	0.87	N
HA 17	6		40	−22	118	8	13	0.83	E
HA 18	8	1	107	−29	58	−21	24	0.26	RT*
HA18D	4		72	27	77	21	4	1.05	NT
HA18E	4	1	186	−64	325	−70	12	3.60	R
HA18F	5	1	96	63	39	37	8	0.57	NT
HA 19	4		194	−73	287	−81	3	8.53	R
HA 20	4		185	−73	314	−84	5	3.14	R
HA 21	4		82	−83	130	−60	4	1.68	R
HA 22	4		329	−80	172	−47	9	1.61	R
HA 23	4		312	−76	185	−43	10	6.31	R
HA 24	4		188	−66	319	−73	3	2.63	R
HA 25	4		179	−68	339	−75	4	1.45	R
HA 26	4		237	−66	248	−56	9	1.82	R
HA 27	4		234	−72	238	−64	18	0.34	R
HA 28	5	1	74	−76	115	−49	7	0.23	R
HA 29	4		235	−80	209	−69	23	0.19	R*
HA 30	4		206	−75	253	−78	4	2.27	R
HA 31	4		211	−75	246	−76	3	2.50	R
HA 32	4		215	−74	249	−73	4	3.45	R
HA 33	4		210	−79	220	−78	3	5.79	R
HA 34	4		257	−53	243	−36	27	0.62	RT*
HA 35	5		157	−81	121	−79	12	0.52	R
HA 36	4		Scattered				>60	0.31	(?)
HA 37	4		359	−75	158	−37	11	1.08	RT
HA 38	4		110	−57	68	−42	13	1.17	R
HA 39	4		269	−70	217	−48	8	1.38	R
HA 40	4		211	−83	186	−75	6	3.24	R
HA 41	4		223	−74	242	−70	6	1.74	R
HA 42	4		192	−57	316	−62	6	4.23	R
HA 43	4		197	−60	307	−64	3	2.83	R
HA 44	4		193	−53	317	−57	6	4.70	R
HA 45	4		166	−77	71	−84	3	2.40	R
HA 46	4		223	−77	229	−72	4	4.39	R
HA 47	4		171	−62	354	−67	8	1.27	R
HA 48	4	1	119	−80	110	−68	18	(73.70)	R
HA 49	4		158	−76	71	−80	5	2.90	R
HA 50	4		268	−82	191	−61	9	5.69	R
HA 51	4		250	−84	184	−66	5	4.15	R
HA 52	4		154	−70	39	−73	5	7.07	R
HA 53	4		126	−69	68	−60	8	6.42	R
HA 54	4		202	−65	293	−68	5	1.83	R
HB Eyrarfjall Álftafjördur									
HB 1	4		25	71	92	75	2	1.73	N
HB 2	4		6	66	144	73	5	3.86	N
HB 3	5	1	87	80	19	59	5	1.41	N
HB 4	4		144	−56	32	−54	3	1.59	R
HB 4G	4		148	−71	52	−72	8	2.73	R
HB 5	4		170	−79	117	−84	4	6.00	R
HB 6	4		164	−78	94	−83	7	5.39	R
HB 7	4		154	−76	68	−78	2	10.54	R
HB 8	4		304	71	256	62	4	0.19	N
HB 8F	3		312	65	236	59	5	0.37	N
HB 9	4		156	68	354	27	5	1.66	NT
HB 10	4		328	77	263	77	5	8.55	N
HB 11	4		41	−68	129	−30	2	1.73	RT
HB 12	4		334	−63	177	−21	8	1.74	RT
HB12G	3		324	−63	185	−23	6	3.58	RT
HB 13	4		204	−66	287	−69	3	2.78	R
HB 14	4		168	−74	29	−82	3	1.98	R
HB 15	4		178	−81	153	−83	3	2.21	R
HB 16	5		292	69	260	54	5	2.51	N
HC Eyrarfjall Álftafjördur									
HC 1	4		303	67	248	57	4	1.79	N
HC 2	4		349	76	241	85	3	1.46	N
HC 3	4		358	78	319	88	3	5.06	N
HC 4	4	1	150	78	353	43	4	2.10	N
HC 5	4		314	58	226	52	8	3.87	N
HC 6	4		76	80	21	63	6	3.60	N
HC 7	4		67	−65	108	−33	8	0.13	RT
HC 8	4		278	−62	220	−35	2	2.45	RT
HC 8G	3		278	−56	223	−30	5	0.47	RT
HC 9	4		254	−76	215	−60	4	1.56	R
HC 10	4		162	−65	15	−70	3	1.52	R
HC 11	4		154	−63	26	−65	5	1.55	R
HC 12	4		198	−71	288	−77	4	3.30	R
HC 13	3		191	−56	319	−61	26	2.66	R*
HC 14	4		189	−52	323	−57	4	2.02	R
HC 15	4		178	−79	149	−86	4	1.83	R
HC 16	4	1	190	−79	201	−85	6	1.78	R
HC 17	4		195	−81	187	−81	5	1.75	R
HC 18	5		192	−78	214	−84	7	5.59	R
HC 19	3		Orientation incomplete					0.89	(R?)
HC 20	4		196	−78	223	−83	11	9.02	R
HC 21	4		Two N, two R: near dike					0.84	(?)
HC 22	4		34	−57	130	−16	6	0.94	RT
HC 23	4		258	−74	217	−56	4	1.64	R
HC 24	4		96	−82	121	−62	3	1.66	R
HC 25	4		225	−83	190	−72	5	5.78	R
HC 26	4		219	−77	229	−74	4	11.86	R
HC 27	4		135	−81	114	−73	9	2.50	R
HC 28	4		87	−83	127	−61	5	0.94	R
HC 29	4		102	−74	97	−56	4	(4.37)	R
HC 30	4		97	−82	122	−63	4	(10.24)	R
HD Hafursfell									
HD 1	6	1	101	−19	62	−13	10	0.12	RT
HD 2	4		194	−67	305	−74	3	1.47	R
HD 3	6		161	−66	19	−71	5	0.31	R
HD 4	4		158	−54	11	−57	10	1.32	R
HD 5	5		216	−74	249	−73	3	3.72	R
HD 6	6		152	−53	19	−54	9	2.78	R
HD 7	4		162	−59	8	−63	9	2.11	R
HD 9	4		178	−74	346	−85	8	3.75	R
HD 10	3		168	−74	35	−83	3	8.61	R
HD 11	3		223	−69	256	−66	6	3.69	R
HD 12	5	1	217	−71	257	−70	3	2.17	R
HD 13	6		123	30	31	2	11	0.40	E
HD 14	5		126	1	34	−14	8	0.57	RT
HD 15	9		Scattered, R/RT				>60	0.61	(RT?)
HD 16	9		Scattered, NT/RT				>60	0.66	(NT?)
HD 17	9		Scattered, NT/R				>60	0.64	(?)
HD 18	9		129	−16	34	−23	13	0.78	RT
HD 19	9		142	−55	34	−54	20	0.94	R
HD 20	4		114	−86	138	−67	8	1.86	R
HD 21	4		201	−83	181	−77	9	1.26	R
HD 22	5		153	−76	74	−78	11	1.30	R
HD 23	4		223	−87	167	−68	3	0.60	R
HD 24	5		115	−86	139	−67	8	1.70	R
HD 25	3		128	−75	82	−67	10	0.63	R
HD 26	4		354	69	175	77	6	0.91	N
HD 27	4		309	77	271	69	5	2.71	N
HD 28	4		20	72	98	78	3	1.11	N
HD 30	4		30	79	36	78	3	1.32	N
HD 34	4		22	72	91	77	8	3.66	N
HD 35	3		37	69	83	68	4	1.94	N
HD 37	4		320	69	234	66	4	2.64	N
HD 39	4		290	79	287	63	4	4.12	N
HD 42	4		265	68	280	43	5	2.51	N
HD 44	4		297	65	250	52	4	3.42	N
HD 45	4		337	64	203	67	7	5.04	N
HD 47	4		2	65	154	72	2	4.92	N
HD 49	5		359	63	161	70	5	2.84	N
HD49E	3		5	62	148	69	12	3.81	N
HD 50	4		Scattered N/NT				>60	2.21	(N?)
HD 51	4		17	84	352	76	2	6.82	N
HD 52	4		350	86	332	73	5	3.11	N
HD 53	4		321	80	286	74	5	4.73	N
HD 54	3		350	74	204	83	3	3.32	N
HD 55	3		4	63	150	69	11	1.13	N
HD 56	3		10	68	132	76	12	2.26	N
HD 57	4		320	67	231	65	4	4.71	N
HD 59	3		303	77	274	66	4	1.62	N
HD 60	4		340	77	263	82	7	1.58	N
HD 61	4		320	82	301	74	4	12.77	N
HD 63	5		38	71	77	69	2	1.84	N
HD 64	3		300	78	279	66	7	0.82	N
HD 65	3		351	75	212	84	6	2.31	N
HD 66	3		355	75	202	87	3	2.94	N
HD 67	3		345	80	304	81	16	8.20	N
HD 68	4		64	64	65	51	5	1.96	N
HD 69	3		64	71	53	59	4	4.54	N
HD 70	3		343	64	192	68	6	1.45	N
HD 71	3		338	65	203	69	4	1.74	N
HD 72	4		329	76	257	77	3	3.12	N
HD 73	4		15	76	79	83	4	2.95	N
HD 74	4		8	68	137	75	5	13.80	N
HD 75	4		22	75	74	80	5	3.13	N
HD 76	3		346	46	178	51	5	2.35	N
HD 78	4		350	53	174	59	7	3.70	N
HD 79	4	1	343	53	185	57	4	(3.58)	N
HD 80	4		342	46	183	51	5	6.12	N
HD 81	4		357	78	314	87	3	5.53	N
HD 83	4		357	76	192	88	7	5.05	N
HD 84	3		29	77	53	78	4	3.39	N
HD 85	3		19	77	54	82	6	2.70	N
HD 87	4		336	73	231	77	3	3.84	N
HD 88	4	1	21	65	115	68	24	2.79	N*
HD 89	4		Scattered N/NT				>60	(2.83)	(N?)
HD 90	4		22	83	2	77	6	3.15	N
HD 91	4		348	77	256	85	3	4.70	N
HD 92	5		350	83	327	78	5	6.24	N
HD 93	4		9	78	29	86	2	3.93	N
HD 94	4		352	76	231	86	5	3.96	N
HD 95	4		192	−74	285	−82	3	3.73	R

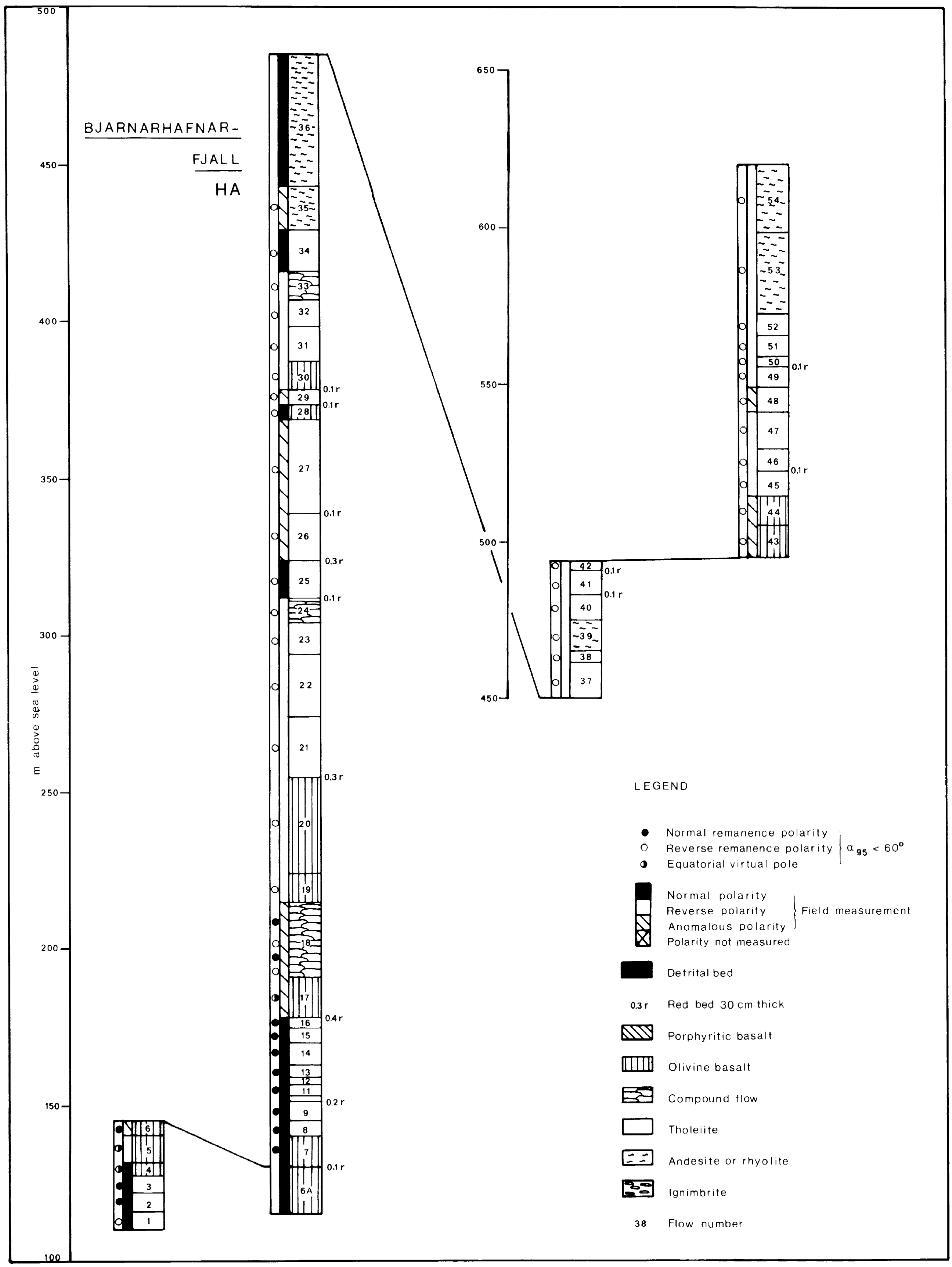
Table 1. (continued).

Lava	N	n	D	I	Lon.	Lat.	Alf	J_{100}	Pol.
HD95F	3		175	−73	359	−83	4	3.72	R
HD 96	3		189	−56	322	−61	4	2.37	R
HD96F	3		190	−61	318	−66	8	5.42	R
HD 97	4		201	−67	291	−72	7	16.20	R
HD 98	3		230	79	314	49	29	0.08	N*
HD 99	4		138	65	8	26	18	0.31	NT
HD100	4		292	80	290	65	5	0.84	N
HD101	4		264	81	302	58	9	0.84	N
HD102	3		313	83	303	72	6	0.64	N
HD103	4		339	77	261	81	4	0.66	N
HD104	4		335	74	240	78	5	0.59	N
HD105	4		293	76	275	62	5	0.56	N
HD107	4		301	78	278	66	7	0.88	N
HD108	4		308	73	258	66	6	0.77	N
HD109	4		Scattered N/NT				>60	0.69	(N?)
HD110	4	1	288	45	243	32	6	(2.15)	NT
HD111	4		321	62	221	59	11	(1.96)	N
HD112	4	1	128	68	13	33	13	(2.89)	NT
HD113	4		30	71	88	72	5	1.73	N
HD114	4		293	55	244	42	4	2.09	N
HE Tröllakirkja									
HE 1	4		18	66	120	71	5	0.49	N
HE 2	4		35	65	95	64	8	4.03	N
HE 3	4		163	−68	18	−73	4	4.83	R
HE 4	4		166	−66	9	−72	11	2.76	R
HE 5	4		132	−73	75	−67	3	6.10	R
HE 6	4	1	288	−82	185	−57	11	0.30	R
HE 7	4	1	202	−64	294	−68	8	0.42	R
HE 8	4		147	−64	37	−64	11	0.38	R
HE 9	4	1	169	−66	2	−73	6	0.68	R
HE 10	4		338	74	232	79	4	0.41	N
HE 11	4		305	77	273	67	3	3.87	N
HE 12	5		1	75	143	87	5	13.76	N
HE 13	4		339	78	276	81	3	1.86	N
HE 14	4		316	63	229	59	15	0.11	N
HF Kolbeinsstadafjall									
HF 1	4		344	38	179	45	1	2.63	N
HF 2	5		89	56	51	34	5	0.30	NT
HF 3	4		358	59	161	64	4	0.90	N
HF 4	4		299	79	285	66	5	1.28	N
HF 5	5		4	67	147	75	2	0.93	N
HF 6	5		345	59	183	64	8	2.64	N
HF 7	4		28	86	349	71	12	0.21	N
HF 8	4		324	73	243	72	3	2.52	N
HF 9	4		7	71	136	80	4	2.14	N
HF 10	4		3	−74	156	−35	5	1.60	RT
HF 11	4		24	40	126	45	3	0.64	N
HF 12	4		19	47	130	52	8	0.71	N
HF 13	4		336	62	202	64	6	0.89	N
HF 14	4		50	53	89	47	6	0.36	N
HF 15	4		231	−78	221	−69	2	1.94	R
HF 16	5		186	−77	242	−87	3	0.99	R
HF 17	4		197	−48	313	−53	3	0.50	R
HF 18	5		352	−84	161	−52	4	0.50	R
HF 19	4		172	−62	354	−68	3	1.70	R
HF 20	5		263	84	311	61	10	(2.89)	N
HF 21	4		223	72	311	36	6	0.40	NT
HF 22	4		346	86	331	73	5	1.70	N
HF 23	4		11	75	97	84	8	4.26	N
HF 24	4		37	78	43	75	4	4.79	N
HG Fagraskógarfjall									
HG 1	4		343	71	206	77	5	1.24	N
HG 2	4		325	70	234	70	7	2.29	N
HG 3	4		339	72	220	77	3	1.13	N
HG 4	4		329	71	229	72	3	0.89	N
HG 5	4		331	57	203	58	5	4.14	N
HG 6	4	1	341	56	189	60	5	1.11	N
HG 7	4		346	66	189	72	4	1.63	N
HG 8	4		17	76	69	83	3	2.89	N
HG 9	4		17	80	20	82	5	4.06	N
HG 10	4		310	65	238	58	3	5.67	N
HG 11	4		103	84	3	59	5	1.82	N
HG 12	4		93	83	6	61	2	7.62	N
HG 13	4		71	85	2	66	2	8.27	N
HG 14	4		19	79	32	82	6	4.07	N
HG 15	8	2	350	67	182	74	5	3.24	N
HG 16	4		Scattered, N and R				>60	0.84	(?)
HG 18	4		Scattered, N and R				>60	0.30	(?)
HG 19	4		302	77	275	66	12	0.24	N
HG 20	4		332	37	195	42	10	0.43	N
HG 21	4		104	68	30	40	4	0.41	N
HG 22	4		185	50	334	6	5	1.25	E
HG 23	4		192	53	328	9	4	1.70	E
HG 24	4		225	17	292	−9	18	0.44	E
HG 25	4		28	38	121	43	7	1.53	N
HG 26	4	1	44	35	104	36	8	1.21	NT
HG 27	4		42	72	68	69	11	1.79	N
HG 28	4		35	72	75	72	7	1.18	N
HG 29	4		11	68	129	75	4	0.99	N
HG 30	4		29	51	116	52	4	1.80	N
HG 31	4		2	82	341	80	5	2.79	N
HG 32	4		16	79	35	83	3	3.90	N
HG 33	4		296	63	249	50	6	1.21	N
HG 34	4		331	75	251	77	6	2.66	N
HG 35	5	1	319	72	246	69	7	2.13	N
HG 36	4		312	79	279	71	3	2.72	N
HG 37	5		351	65	178	72	3	1.60	N
HG 38	5	1	0	72	158	82	3	1.26	N
HG 39	4		354	68	172	76	6	2.03	N
HG 40	4		12	65	131	71	11	3.16	N
HG 41	4		40	73	69	70	1	7.83	N

Lava	N	n	D	I	Lon.	Lat.	Alf	J_{100}	Pol.
HG42	4		349	85	331	75	4	2.99	N
HG43	4		326	68	227	68	6	1.18	N
HG44	4		49	76	48	69	3	4.42	N
HG45	4		268	62	272	38	24	0.51	NT*
HG46	4		240	53	289	19	26	1.42	NT*
HG47	4		226	34	294	1	20	0.20	E
HG48	4		39	72	74	70	5	0.42	N
HG49	4		18	70	110	75	4	10.99	N
HG50	4		345	73	215	81	6	1.42	N
HG51	4		343	65	193	70	10	3.35	N
HG52	4		312	68	242	62	7	5.91	N
HG53	4		17	89	340	68	7	13.59	N
HG54	4		7	78	41	87	7	5.62	N
HG55	4		359	73	164	84	3	0.91	N
HH Dagmálafjall									
HH 1	4		46	82	18	72	6	1.36	N
HH 2	4		350	72	195	81	6	1.12	N
HH 3	4		335	66	209	68	8	0.71	N
HH 4	5		321	66	228	63	3	1.33	N
HH 5	4		264	69	281	44	12	0.39	N
HH 6	4		106	81	9	56	12	1.07	N
HH 7	5		191	73	331	34	5	4.10	NT
HH 8	4		343	65	195	70	8	3.51	N
HH 9	4		287	78	287	62	14	0.52	N
HH10	4		311	64	237	58	6	1.49	N
HH11	4	1	257	63	280	34	17	2.70	NT
HH12	5		328	71	234	72	12	1.68	N
HH13	4	1	355	64	169	71	6	1.87	N
HH14	4		318	74	256	71	15	1.07	N
HH15	4		199	−78	227	−82	2	3.20	R
HH16	4		283	−75	202	−49	11	1.66	R
HH17	1		Thin flow, stable					8.16	(R)
HH18	4		174	−66	352	−73	6	1.86	R
HH19	4		169	−65	1	−71	3	4.48	R
HH20	4		178	−69	344	−78	4	3.77	R
HH21	4		169	−76	53	−85	4	6.62	R
HH22	4		172	−79	125	−85	4	3.60	R
HH23	4	1	192	−73	291	−82	13	0.84	R
HH24	4		131	−73	76	−67	36	2.60	R*
HH25	5		184	−72	320	−83	3	3.53	R
HH26	4		186	−73	312	−83	4	5.95	R
HH27	4	1	172	−72	9	−82	4	4.31	R
HH28	5		205	−78	226	−80	18	0.48	R
HH29	4		166	−60	4	−64	5	1.51	R
HH30	4		163	−66	15	−71	4	1.41	R
HH31	4		131	−66	60	−60	3	2.56	R
HH32	5		155	−75	67	−79	5	0.93	R
HH34	4		191	−66	313	−72	8	1.12	R
HH35	4		199	−61	304	−65	7	2.14	R
HH36	4		173	−66	354	−73	3	6.43	R
HH37	5		170	−64	359	−70	4	3.48	R
HH38	1		Thin flow, stable					1.18	(R)
HH39	4		246	−38	260	−29	12	0.38	RT
HH40	4		234	44	291	10	44	0.32	E*
HH41	4		242	54	287	20	40	0.34	NT*
HH42	4		243	59	289	26	4	0.78	NT
HH44	4	1	275	68	273	47	7	1.01	N
HH45	4		276	69	273	48	17	0.87	N
HH46	4		277	62	264	41	4	1.04	N
HH47	4		274	67	272	45	4	1.20	N
HH48	5		281	72	273	53	11	0.71	N
HH49	4		298	77	279	65	5	1.09	N
HH51	4		272	89	334	65	6	1.25	N
HH52	5		320	81	294	74	2	2.77	N
HH54	4		244	65	292	32	10	0.38	NT
HH55	4		338	53	192	56	11	0.21	N
HH57	4		67	34	81	27	10	0.68	NT
HH58	5		50	57	87	50	16	0.41	N
HH59	1		Thin flow, unstable					0.07	(?)
HH60	5		Two N, two R, one unstable					0.19	(?)
HH61	4		220	−44	285	−43	6	2.83	R
HH62	5		157	−80	115	−80	5	2.42	R
HH63	5		35	−56	130	−15	9	0.62	RT
HH64	5		356	−12	162	19	43	0.33	NT*
HH65	5		9	−63	152	−20	6	0.27	RT
HH66	5		296	−89	162	−64	3	12.32	R
HH67	4		293	−85	177	−59	3	2.59	R
HH68	5		232	−78	217	−69	5	0.49	R
HH69	1		Thin flow, stable					0.80	(R)
HH70	4		165	−55	2	−59	9	1.83	R
HH71	4		356	71	172	81	4	1.20	N
HH72	1		Thin flow, stable					8.28	(N)
HH73	5		26	74	80	77	5	0.83	N
HH74	4		224	53	302	14	3	(1.53)	NT
HH75	4		359	83	336	78	5	0.49	N
HH76	4		70	−53	100	−22	6	0.27	RT
HH77	4		285	−83	185	−58	5	2.16	R
HH78	5		170	−54	353	−59	1	1.24	R
HH79	4	1	191	4	326	−23	26	(4.54)	RT*
HH80	5		15	70	115	77	7	(0.93)	N

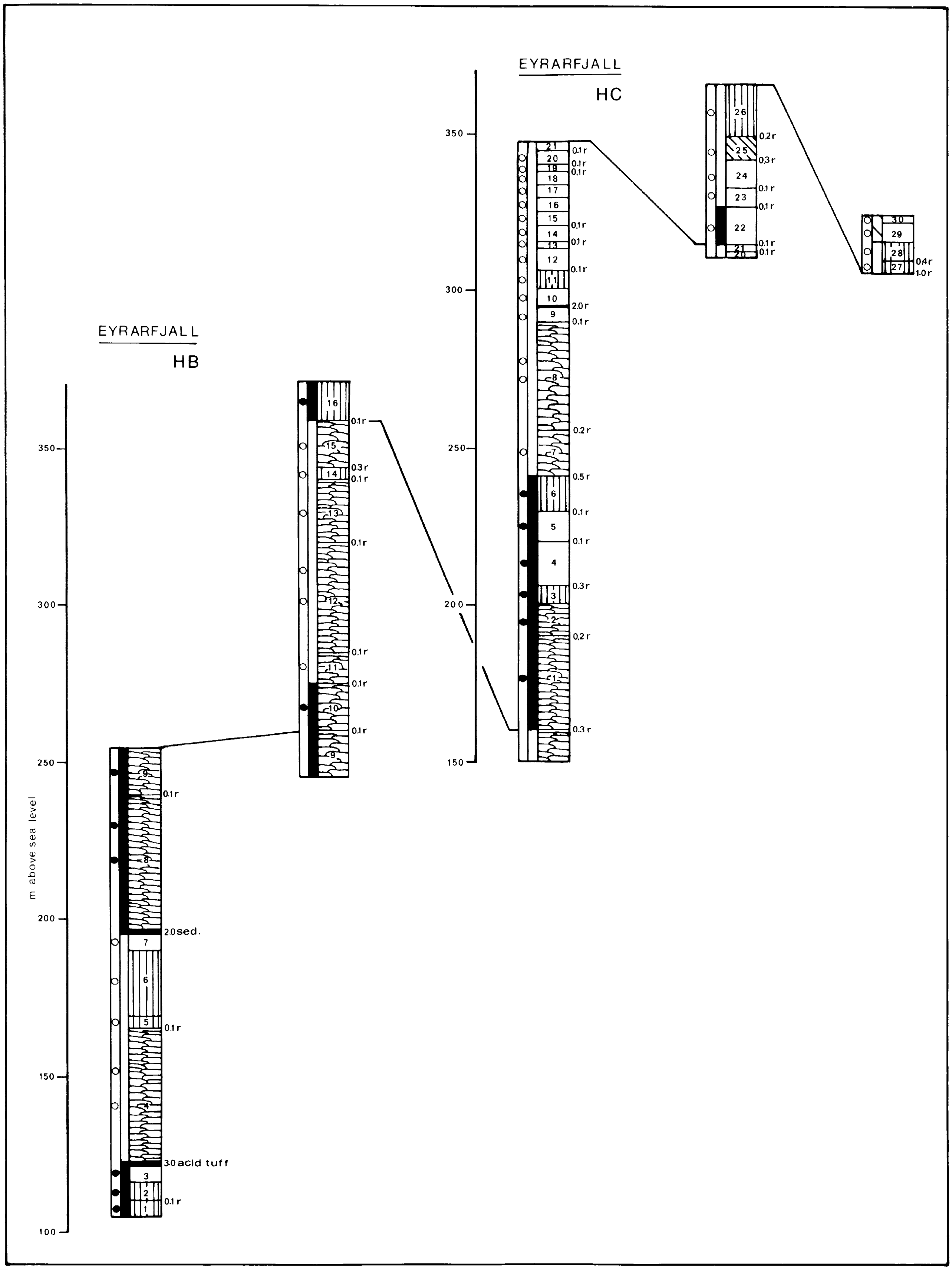
Coordinates and tilt corrections, W-Iceland

Prof.	Lat.	Lon.	Dip		Downdip
HA	64.98	337.02	3 bot.	1 top	315
HB	64.99	337.41	3 bot.	2 top	145
HC	65.00	337.40	3 bot.	1 top	145
HD	64.84	337.51	6 bot.	2 top	325
HE	64.82	337.82	4 bot.	3 top	325
HF	64.81	337.82	6 bot.	3 top	310
HG	64.78	337.86	12 bot.	6 top	310
HH	64.79	337.99	14 bot.	8 top	320



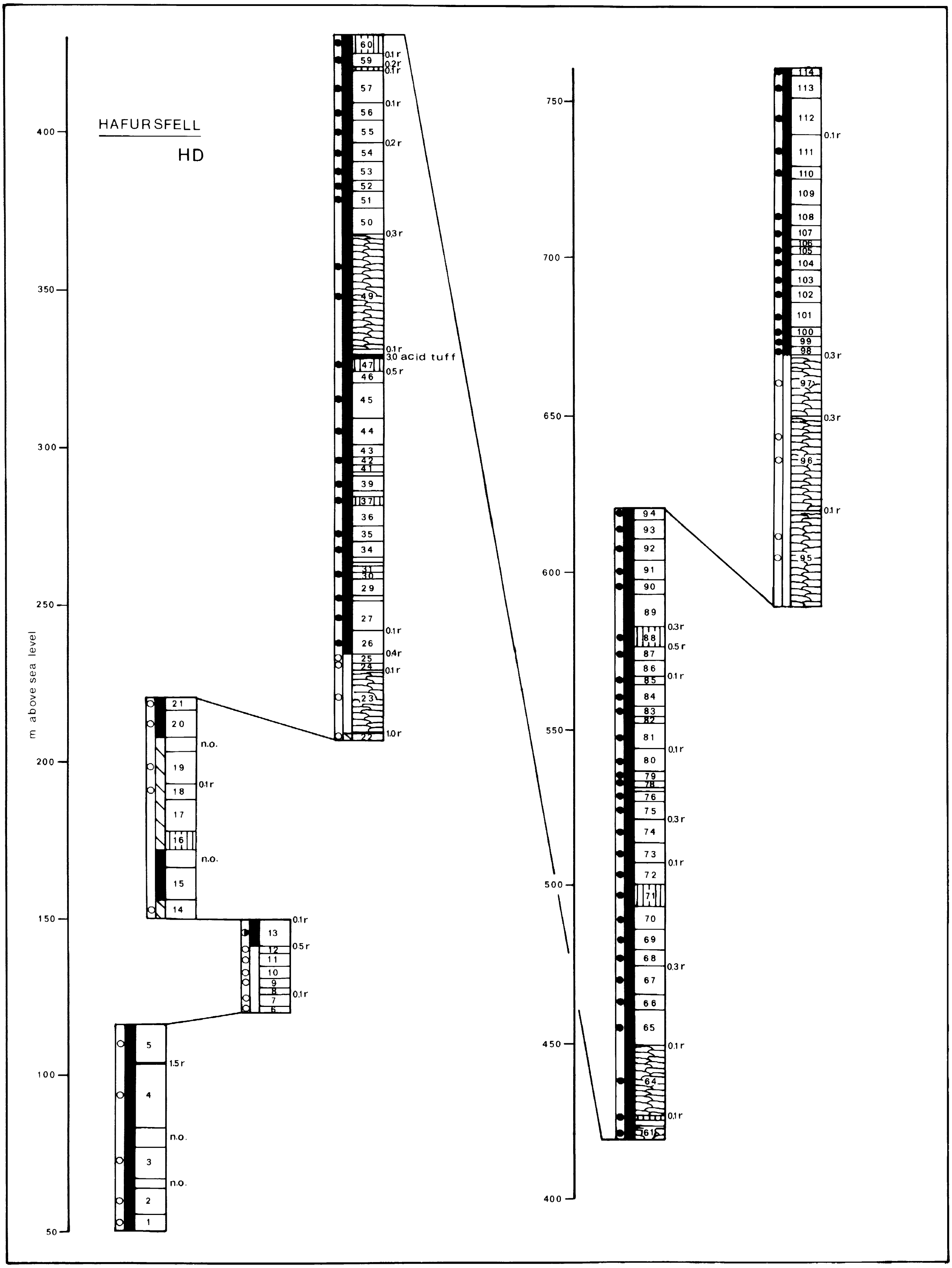
(a)

Fig. 2. Detailed stratigraphy of the eight sampling profiles, showing lava types and thicknesses, sediments, and magnetic polarity (both field and laboratory measurements). n.o.: no outcrop.



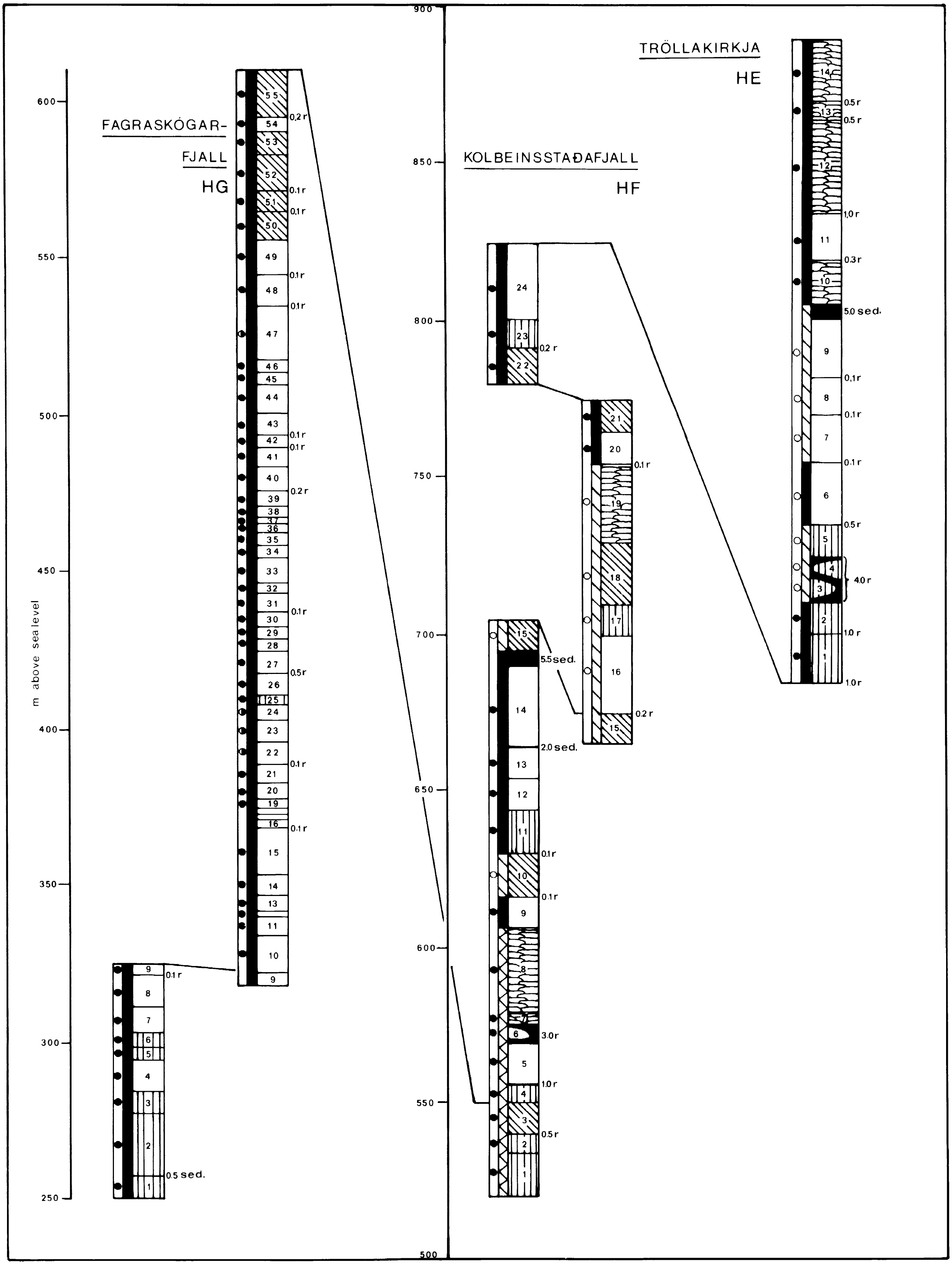
(b)

Fig. 2. (continued).



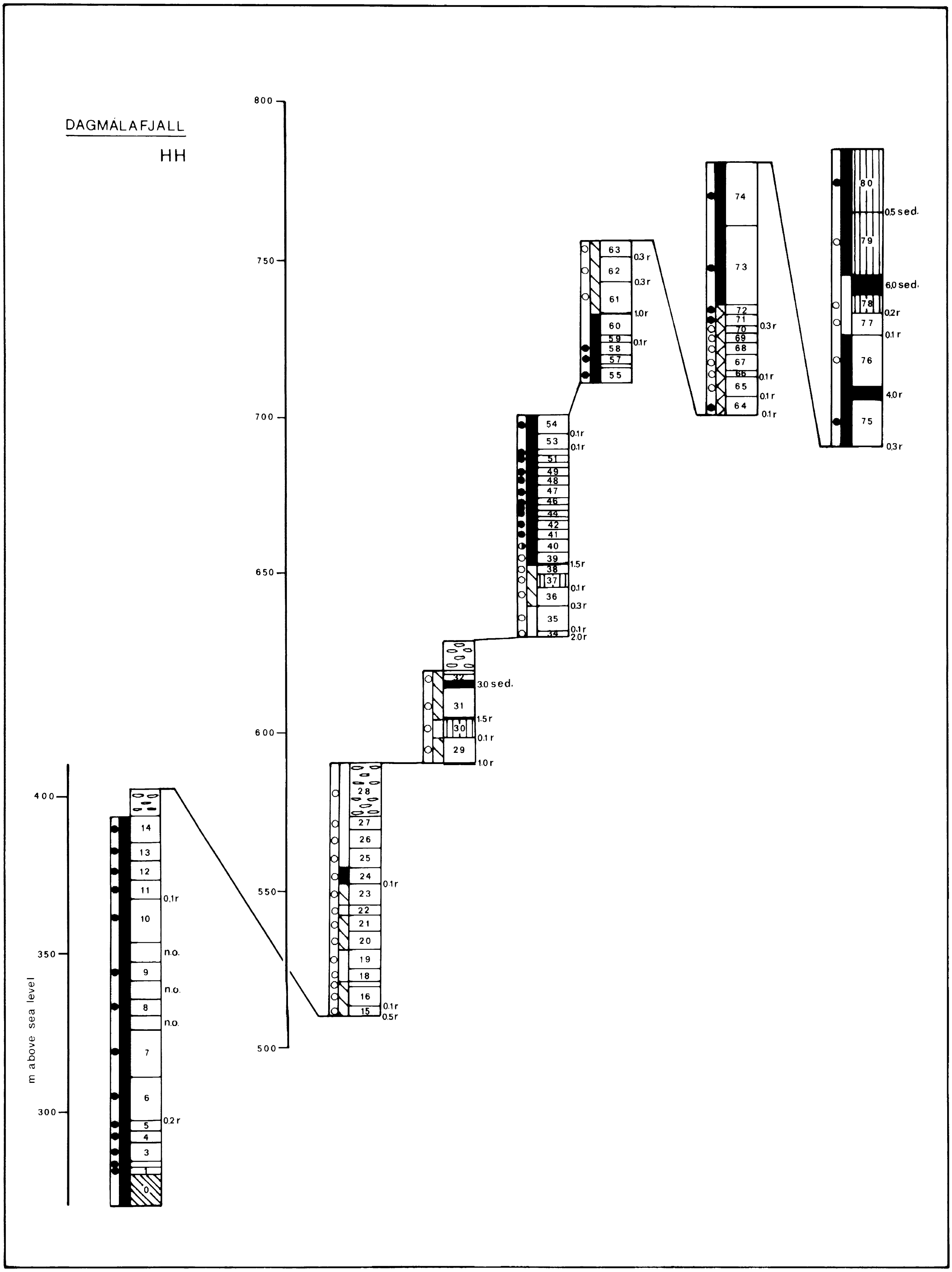
(c)

Fig. 2. (continued).



(d)

Fig. 2. (continued).



(e)

Fig. 2. (continued).

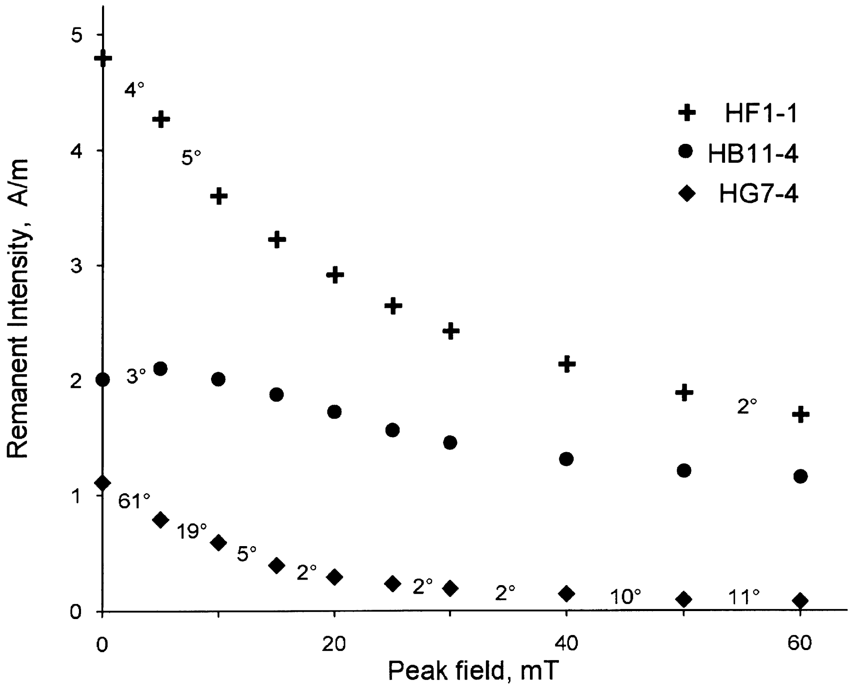


Fig. 3. Remanence intensity during extensive AF demagnetization of three fairly typical specimens from the collection. Direction changes between steps are indicated when they exceed 1.5°. For sample HG 7-4, each treatment from 30 mT (when the intensity had fallen to 0.2 A/m) upwards was performed twice and the direction results were averaged.

record similar remanence directions, as may be seen in Table 1 for example in HC 8 and HD 96. However, an exception occurs in the present work in the series HA 18, see below.

2.3 Magnetic measurements and quality criteria

Magnetic remanence measurements were made at the University of Iceland using an "Institut Dr. Förster" static fluxgate meter and a two-axis tumbler device for alternating field (AF) demagnetization. The response of these samples to the AF treatment is similar to that in other lava series from Iceland of comparable age and alteration state, and may be described as follows.

(i) Initial AF treatment removes mostly Brunhes age viscous remanence (VRM) but also some of the primary remanence. The incidence of this VRM in our samples is in general inversely correlated with their intensity of primary remanence. In many of the samples there is negligible VRM, notably in those cored from oxidized (reddish) zones within a lava flow. The removal of VRM is often characterized by a change in the direction (even by up to 90° or more) of the magnetic moment of a sample. Most of the VRM is generally removed by treatment with a 10 mT peak field, and only in exceptional cases is more than 20 mT needed.

(ii) After removal of the VRM, the remanence is generally stable or very stable in direction to AF treatment in increasing fields. The remanence intensity decreases smoothly, and the direction changes seen are small and random.

(iii) At alternating fields exceeding some critical peak value, usually $\geq$30 mT, those samples carrying a relatively soft (and weak, of the order of 0.3 A/m or less after 10 mT treatment) primary remanence may exhibit increasing random changes in direction. These changes will also occur after repeated treatment at a single peak field. They may be due to minor anhysteretic remanence, or to new viscous magnetization picked up on the way from the demagnetizer to the magnetometer.

Some of these features are illustrated in Fig. 3 which shows results from three samples. In samples HF 1-1 and HB 11-4 the VRM is small compared to the primary remanence, and the direction change on initial treatment is also small. In the latter sample the remanence intensity is slightly increased at the 5 mT step. This behavior is quite common in reversely magnetized rocks but the increase rarely persists beyond the 10 mT step. In the sample HG 7-4 where the primary remanence is weak and rather soft, the direction is changing systematically up to 20 mT but from there on the changes are random.

These results are the basis for the general demagnetization treatment for the present collection. The remanence of all samples was measured before any treatment and after 10, 15 and 20 mT. If a systematic direction change exceeding 3–4° occurred at the last step, the treatment was extended to 25 or 30 mT as necessary. If a random direction change exceeding 3–4° occurred at the 20 mT step or later steps, the treatment was usually repeated and the results were averaged. In one sample from every flow, remanence measurements were also done routinely after 5 and 25 mT.

The mean remanence direction listed in Table 1 is that which yielded the best within-flow agreement, generally using the same field for all samples. If two treatments gave equally good results (the 95% confidence angles α_{95} for the unit differing by less than 10%) the mean direction obtained at the higher field was selected.

The incidence of isothermal remanence attributable to lightning effects is more common in the present survey than in most previous paleomagnetic studies in Iceland. Lava flows where one or more samples were thus affected are HA 48; HC 29, 30; HD 79, 89, 110–112; HF 20; HH 74, 79, 80. The mean remanence intensities for these flows in Table 1 are in brackets. The lightning-induced component was sometimes not entirely removed by 30 mT demagnetization.

Agreement between primary remanence directions in samples within each lava of our Western Iceland profiles is generally good. Occasionally, one of the samples from a unit might yield a severely discordant direction, possibly due e.g. to orientation errors; reheating by overlying units, small intrusions, or drilling equipment; outcrop movement; or lightning, cf. the previous paragraph. In some other samples the primary remanence was weak and/or magnetically soft, so that most of it is removed with the VRM at 10 or 15 mT. In these, the critical peak field for the primary remanence mentioned in (iii) above may be 20 mT or less, making their "window of directional stability" narrow or non-existent. Both these types of single samples have been left out of the calculations of directional averages, as indicated in Table 1. Some units with high α_{95}-values were resampled in a later field season, when possible at a spot more than 10 meters from the original one.

The remanence of several lavas in two segments of our profiles exhibited unsatisfactory stability during AF treatment, namely in HA 1–18F and HD 1–19. These segments are at low altitudes, and their magnetic instability is probably connected with local hydrothermal alteration affecting relatively unoxidized titanomagnetite as carrier of the primary remanence. Resampling at both segments resulted in reduced angular uncertainties for direction means in some cases, but in other units it only yielded additional unstable samples.

Altogether 12 flows were discarded as giving completely unreliable mean directions (the angle α_{95} being greater than 60°), and orientation data from one flow was lost. In some of these flows, however, the paleomagnetic polarity is fairly certain and is included in Table 1. In another 14 lavas, the α_{95}-value is between 60° and 20.5°, in which case the polarity is marked with an asterisk in Table 1. These flows have not been used in the calculation of mean paleomagnetic directions for the collection. The root-mean-square value of α_{95} in the remaining 340 flows is about 7°.

All directions have been corrected for tectonic tilt, estimated from measurements at or close to each profile. Values are given at the end of Table 1. The tilt decreases gradually with altitude. The uncertainty in the tilt correction vectors may reach 2° of arc.

Remanence intensities measured after 10 mT AF treatment are on average of the order of 3 A/m. This value is similar to those previously reported from Icelandic lavas (e.g., Kristjánsson, 1984). Magnetic susceptibility measurements were made on one specimen from each lava flow in our profiles, yielding an average value of about 0.03 in SI units (i.e. $2.4 \cdot 10^{-3}$ cgs units). Both in these flows and in others of similar age from Eastern and Northern Iceland (Kristjánsson, 1984, 1999), there is no overall correlation between remanence intensity and susceptibility.

3. Paleomagnetic Results

3.1 Composite polarity column

Considerable overlap was included in our sampling profiles (Fig. 4), altogether about 90 flows. In particular, all of profile HC is essentially an overlap with the lower half of HA, and the lower part of profile HD is also thought to cover all the time interval represented by HE.

The pattern of paleomagnetic polarity zones generally agreed with other stratigraphic ties. However, it must be kept in mind that in this respect it is only a qualitative indicator; uncertainties are introduced by a general thickening of the lava pile in Iceland in the down-dip direction (Walker, 1959) as well as by irregular temporal and lateral variations in its rate of buildup (cf. below). Thus, the 100 m thick zone of normal magnetization seen around the boundary of profiles HF and HE only corresponds to a zone of shallow and unstable directions in HD 13–18. This mismatch may be related to the fact that the stratigraphic position of these flows is close to the Hredavatn unconformity mapped by Jóhannesson (1980) elsewhere in this region.

A single composite stratigraphic column of 2500 m thickness is presented in Fig. 4, consisting of the flows (in ascending order) HH 1–80, HG 1–55, HF 4–24, HE 1–9, HD 26–94, HB 4–15 and HA 2–54, see Fig. 2. At least 15 reversals occur in this composite section. On the right-hand side of Fig. 4 we have indicated one tentative correlation with the geomagnetic polarity time scale of Cande and Kent (1995), assigning the thick normal-polarity zone of profiles HG and HF to chrons C5n.1n and C5n.2n. In the present section the polarity vs. time pattern will not be reflected faithfully in the polarity vs. thickness pattern if aggregate lava thickness is not strictly proportional with time. For instance, the lava pile of Fig. 2 includes several thick series which may have been emplaced during short periods. Thus, sediments are very thin or absent in the bottom 200 m of profile HH, and the 80-m reverse zone near top of HD consists mostly of "flow units". Conversely, it is possible that long periods (exceeding 100 or even 200 ka) occasionally elapsed between successive flows in the section. For instance, the polarity changes five times in profile HB and the lower half of HC even if this part of the lava pile is also mostly composed of "flow units". Such probable time gaps are, however, not marked by distinct unconformities, evidence of local erosion, or unusually thick sediments.

For the above reasons we hesitate to correlate other details of our composite polarity column with the geomagnetic polarity time scale until comprehensive dating results from the area become available. Problems due to variable rates of emplacement are also encountered if one attempts to correlate the polarity pattern of Fig. 4 with those from other areas of similar age in Iceland such as the east coast of the North-western peninsula (figure 5 of McDougall *et al.*, 1984) or central Northern Iceland (figure 4 of Sæmundsson *et al.*, 1980). The most likely correlation again involves the thick normal-polarity zone in HG and HF. Within that zone, individual excursions such as that recorded in flow HF 10, may coincide with reversal events previously found to occur within the corresponding thick normal-polarity zone in the other areas.

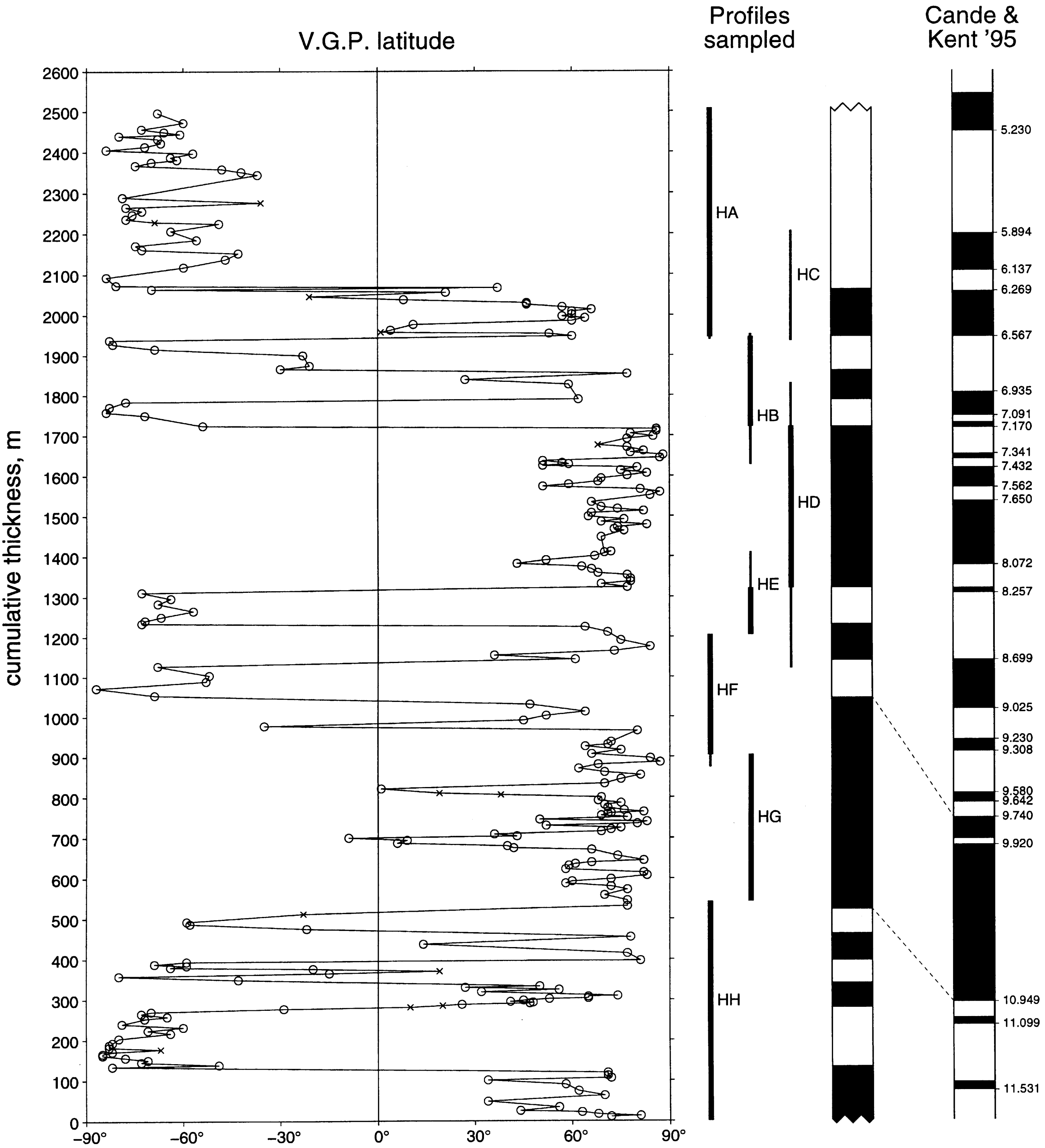
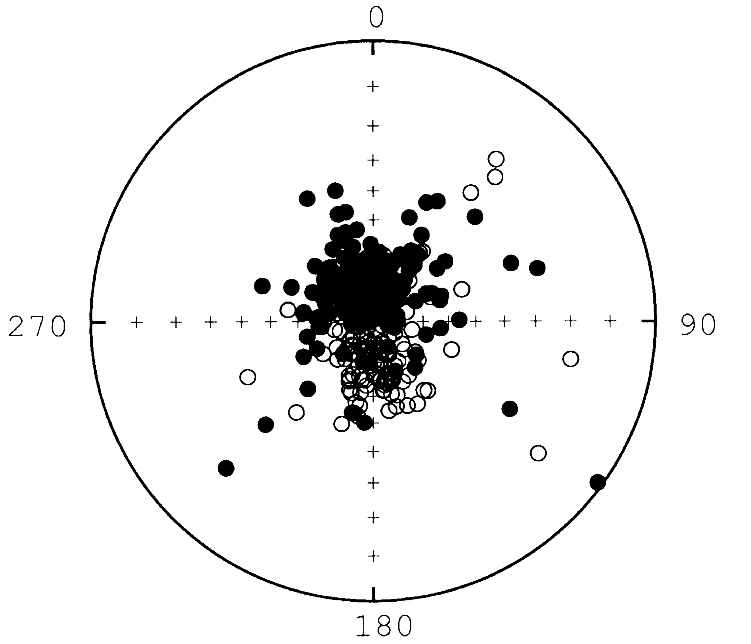


Fig. 4. Polarity column for the composite section from profiles HH to HA. Black: normal polarity. Virtual geomagnetic pole latitudes are plotted as a function of cumulative thickness above the base of HH. Mean remanence directions in lavas marked "x" have α_{95}-values greater than 20.5°. Thick vertical lines indicate those parts of profiles which were used in the composite section. Broken lines indicate tentative correlation with the geomagnetic polarity intervals C5n.1n and C5n.2n of Cande and Kent's (1995) time scale. Reversal ages (in Ma) on the right-hand side.

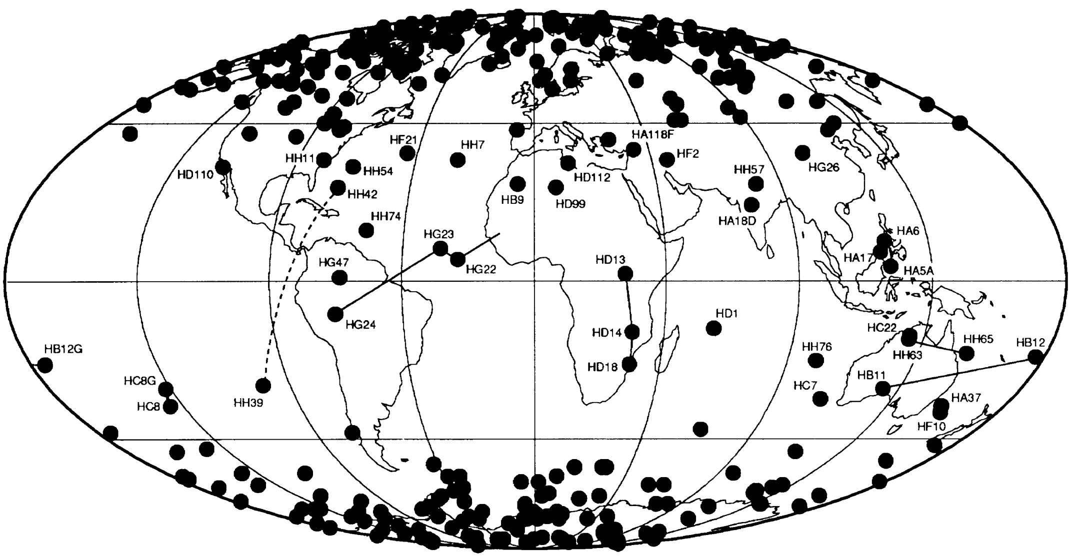
3.2 Mean field direction and overall scatter

Paleomagnetic average directions and statistical parameter values should preferably be obtained from collections consisting of at least 2–300 data points. Each collection should cover several geomagnetic chrons and exhibit little serial correlation between successive flow directions. Remanence directions from the present study are shown in Fig. 5(a), which illustrates the advantage of large paleomagnetic collections. Directions which in small data sets (<50 units, say) would be looked upon as isolated "outliers", turn out to belong to a continuous distribution. This is still more evident when sets of thousands of units are considered together (see Kristjánsson, 1985).

The mean remanence directions and virtual poles in our lava collections are given in Table 2 along with relevant statistical parameters. Sets of paleomagnetic directions having



(a)



(b)

Fig. 5. (a) Stereographic projection of all paleomagnetic directions from profiles HH through HA (Table 1) where the within-flow α_{95} was less than 20.5°. Solid circles: directions pointing downwards. (b) Virtual geomagnetic poles corresponding to the directions of Fig. 5(a). All poles below 40°N or S latitude are numbered for reference, and lines are drawn to indicate some poles occurring in succession.

significantly "far-sided" and/or "right-handed" mean poles with respect to the geographic pole were found in some earlier studies on Icelandic lavas (see Watkins *et al.*, 1977; Kristjánsson and McDougall, 1982). In the present study and other recent work (e.g., Kristjánsson and Jóhannesson, 1996) such deviations are less apparent. The angular separation between the mean field direction for normally magnetized lavas (i.e., those yielding virtual geomagnetic poles north of the Equator) and that for reversely magnetized lavas (after inversion) is only around 1°, and the statistical parameters for the two groups are also similar. The results are affected to a very minor extent by rejection criteria.

As is the case in other collections from Icelandic lavas, virtual geomagnetic poles at low and middle latitudes make up a significant proportion of our results. In the present data set, the number of reliable virtual poles below 40°N or S latitude is 40, i.e. over 11% of the 340 lavas having directional α_{95}-values less than 20.5°. These are all numbered

Table 2. Mean paleomagnetic directions and virtual poles, for all units with α_{95} less than 20.5°. c.s.d.: circular (angular) standard deviation of each group of N unit vectors, obtained using the approximation $\arccos((R-1)/(N-1))$ where R is the length of their resultant.

		Directions				Poles		
	N	Decl.	Incl.	c.s.d.	α_{95}	Lon.	Lat.	c.s.d.
Normal	202	356°	75.9°	22.9°	2.9°	251°	87.5°	32.0°
Reverse	138	358°	76.7°	21.8°	3.3°	328°	88.3°	31.2°
Both	340	357°	76.2°	22.4°	2.2°	273°	88.2°	31.7°

in Fig. 5(b), which also indicates some instances when low- or mid-latitude poles in successive lavas lie close to each other.

Kristjánsson and Jóhannesson (1989) and Kristjánsson (1995, 1999) included the data presented in this study, in their compilations. They discussed various aspects of the geomagnetic field dispersion such as the distribution of transitional geomagnetic poles in latitude and longitude. They also suggested a possible long-term temporal trend in the amplitude of the secular variation. Kristjánsson (1995) confirmed previous conclusions (e.g., from Dagley and Lawley, 1974; Kristjánsson and McDougall, 1982) that low- and mid-latitude virtual poles obtained from Icelandic lavas are not found preferentially in any particular longitude intervals. The numerical excess of normal over reverse directions in the present study (Table 2) appears to be fortuitous, as it is similar to the number of lavas sampled in the thickest polarity zone of our composite section which happens to be of normal polarity. When still longer time intervals are considered, no significant differences have been noted between normally and reversely magnetized lavas in Iceland, neither in their relative abundance, the distribution of paleomagnetic directions, or remanence intensity values (Kristjánsson, 1995).

3.3 Geomagnetic excursions

Not all of the "transitional" or low-latitude geomagnetic poles displayed in Fig. 5(b) occur at boundaries between normal and reverse zones. A number of apparent excursions and periods of large erratic pole movements during otherwise quiescent behavior of the geomagnetic field may also be seen in our data. This is in agreement with the model of Kristjánsson (1985, section 4) which describes the movement of the virtual pole in latitude as a biased random walk process. Such excursions include flows HG 20–26 and 45–47, HF 10, HC 22, (probably) HA 1–6 and 17–18F of Fig. 2. The sampled exposures of the last two groups are separated laterally by a few hundred meters, but it appears that the pattern of magnetic field variations is repeated to some extent; however, we have ascertained in the field that this repetition is not due to faulting.

Some stages of a reverse to normal polarity transition seem to be recorded in flows HH 39–48, but no details of the transition occurring at the base of the presumed Anomaly 5 normal-polarity zone in central Northern Iceland (Sæmundsson *et al.*, 1980, flows PB 23–30; L. Kristjánsson, unpublished measurements, 1984) are reliably recorded in the present profiles. Kristjánsson and Jóhannesson (1989, 1996) provide examples of possible extended periods of instability of the field.

3.4 Sampling in Mt. Grímsstadamúli

We attempted to extend the composite section downwards in the mountain Grímsstadamúli at 64.7°N, 21.9°W (GR in Fig. 1(b)). There is a stratigraphic gap of unknown magnitude between the top of Grímsstadamúli and the base of our profile HH. The lava pile in this mountain is considerably faulted, and tilts 14° towards 300° ETN. The lava flows are mostly thin tholeiites without traceable interbeds. Field mapping of polarities had indicated the presence of polarity zone boundaries which could be used for correlation across the faults.

Altogether 108 lava flows were sampled in 8 short overlapping profiles on the west and southwest slopes. It turned out that the apparent polarity boundaries were mostly due to viscous and unstable magnetization components. Only six lava flows were normally magnetized, and a few others gave virtual geomagnetic poles in low latitudes. The available information was insufficient to establish a composite stratigraphic column at this locality. Therefore, data from Grímsstadamúli have not been included in Table 1 or Figs. 4 and 5. In the Cande and Kent (1995) polarity time scale, reverse polarities occupy most of the time interval between 11 and 12 Ma, so the age of Grímsstadamúli may fall within this interval.

4. Conclusions

As our composite 2500 m section in Western Iceland appears to span the age range from at least 11.4 Ma to about 5 Ma (Pringle *et al.*, 1997), the overall rate of buildup of this section is of the order of 400 m/Ma. A similar figure is obtained by correlating the 520 m thick normally magnetized zone in profiles HG and HF with the 1.2 Ma interval covered by chrons C5n.1n and C5n.2n. This rate is much lower than those reported by McDougall *et al.* (1984) from the lava pile of the North-western peninsula, generated in the same volcanic zone. It must be kept in mind that these results are qualitative, as the inferred "rate of buildup" depends on variables such the altitude of the profiles and their distance from central-volcano complexes. However, it seems clear (Pringle *et al.*, 1997) that activity in the Snæfellsnes spreading zone was decreasing through the period 15–5 Ma.

At least 15 unambiguous reversals of paleomagnetic polarity are recorded in the composite section (Fig. 4). Additionally, there are in the profiles (Table 1) at least 12 excursions reaching latitudes less than 40°, and some of these are likely to be parts of unrecorded polarity transitions. Even so, this would be a relatively small number of reversals for the 6 Ma interval covered by our section (Pringle *et al.*, 1997). Composite sections in Iceland previously dated by the K-Ar method have recorded of the order of 5–7 reversals/Ma, from which Kristjánsson and McDougall (1982) concluded that the actual rate of geomagnetic polarity reversals was at least 8/Ma in the last 15 Ma (including short events).

If our mapping and the age data quoted above are correct, the apparently low overall rate of lava buildup and of polarity reversals in the lava pile must mean that extrusive activity in central Western Iceland was quite intermittent. This may limit the potential of central Western Iceland as regards accurate radiometric dating of individual geomagnetic reversals and excursions.

The 500 m thick normal-polarity zone in profiles HG and HF seems to be spatially correlated with "Anomaly 5" west of Iceland and its onshore continuation (Jóhannesson, 1980; Kristjánsson and Jónsson, 1998) but anomaly lineations over formations of 9 to 5 Ma age in Western Iceland are narrow and indistinct.

Paleomagnetic direction vectors from the 367 lavas sampled in this study are distributed in a similar way as those from comparable paleomagnetic collections already investigated from the Neogene lava pile of Iceland. In particular, a significant proportion of these directions (over 10%) corresponds to virtual geomagnetic poles below 40°N or S latitude. The distribution of poles is a smooth function of latitude, indicating that a distinction sometimes attempted in the literature between "ordinary" secular variation and transitional/excursion states of the field is artificial. This distinction has often been used as a reason for rejecting low-latitude poles from statistical analyses, leading to inadequate models of the field variations. The distribution of low- and mid-latitude virtual poles in longitude is uniform when this and other surveys in Iceland are analyzed together (Kristjánsson, 1995). Similarly, the fact that the number of normally magnetized lava flows in the present collection is somewhat greater than that of reverse flows, appears to be due to chance.

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Appendix. Short Description of Profile Locations

HH: Mt. Dagmálafjall north of the Sléttaskard pass. HG: Mt. Fagraskógarfjall north of the Grettisbæli hyaloclastite mound. HF: East side of Mt. Kolbeinsstadafjall. Figure 1 of Kristjánsson (1993) shows the west side of this mountain. HE: East side of Tröllakirkja peak. HD: Mt. Hafursfell west of Södulsholt farm. HB, HC: Mt. Eyrarfjall east of Álftafjördur fjord. HA: East slope of Mt. Bjarnarhafnarfjall. Flows 6A and up are on the south side of the Fagridalur corrie, flows 1–6 are a few hundred meters farther south.

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