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Paleosecular Variation of Direction and Intensity from Two Pliocene-Pleistocene Lava Sections in Southwestern Iceland

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Two lava sections in southwestern Iceland were revisited; sectoin IG of Kristjánsson *et al.* (1988) of Brunhes chron age and section K of Wilson *et al.* (1972) of early Matuyama chron age. Paleodirections obtained from 22 lavas at the former section do not seem to have averaged out the secular variation completely because of their small angular standard deviation, and this suggests rapid accumulation of the lavas. The latter section consists of 29 lavas and contains the Gauss to Matuyama transition near its base. The time interval during which the lavas at this section were erupted also seems to be short, judging from the small directional dispersion. Thelliers' paleointensity method was also applied to the samples from this section. A characteristic low paleointensity was obtained from the transitional lava flow. However, low paleointensities were also obtained from the lavas which erupted some time after the transition, and which record directions close to those of an axial geomagnetic dipole.

1. Introduction

The remarkable basaltic lava sequences in Iceland have been the subject of many paleomagnetic studies since the pioneering work by Jan Hospers in 1950's (see for example, Irving, 1988; Kristjánsson, 1993). Paleomagnetic expeditions by several research groups since then have made substantial contributions to the study of geomagnetism. Paleomagnetic studies in Iceland are still worthwhile in spite of the largest paleomagnetic database ever obtained on the globe because; 1) previous measurements were often from only two or three samples per lava, 2) reliable paleointensity data are scarce, and 3) some of the lava sequences younger than 2–3 Ma have not been fully investigated.

Most of the paleointensity information from Icelandic lavas are estimates of relative paleointensity; determined by the NRM intensity at a fixed level of AF demagnetization (first by Dagley and Wilson, 1971). The "relative" methods, unlike relative paleointensity methods often applied to sediment sections, do not take any account of magnetic mineral concentration. It is often supposed, however, that the relative paleointensity data from Icelandic lavas still reflect the real paleointensity, partly because the large number of data average out the differences of various rock magnetic factors, and partly because the Icelandic basalt lavas are relatively similar in rock magnetism. The relative paleointensity study gave intriguing results on the relation of pseudo-dipole moment versus VGP latitude, but this does not preclude the importance of the absolute paleointensity data. Early absolute paleointensity studies are due to Smith (1967) and Lawley (1970) in which 13 baked sediments plus 18 lava flows and 27 lava flows, respectively, were studied by the methods of either Wilson (1961) or van Zijl *et al.* (1962). Although it is now generally agreed that these two methods are less reliable than those by Thellier and Thellier (1959) and Shaw (1974) due to the lack of an internal consistency test, the results of Smith (1967) and Lawley (1970) might be fairly reliable because they performed many tests to detect any magnetic alteration during heating. Some of the results of Smith (1967) are from the same section at Mt. Reynivallaháls as this study, and, as we will see later, his result from a lava which records a transitional direction is in good agreement with those obtained in this study. Shaw *et al.* (1982) and Roberts and Shaw (1984) applied the Shaw method to 277 late Tertiary lavas in Eastern Iceland to obtain 106 results, and in the latter paper some asymmetry between normal and reversed polarity data was found. It is noted that generally they obtained data from only one specimen per lava, and the reliability of some of the results, such as some very high paleointensities, is a matter of debate (Kristjánsson, 1985b). Only few paleointensity studies using the Thelliers' method have been reported from Icelandic lavas. Two studies were made with regard to the latest Pleistocene geomagnetic excursion of about 40 ka (Marshall *et al.*, 1988; Levi *et al.*, 1990), and one was on 17 Holocene lavas (Schweitzer and Soffel, 1980). Senanayake *et al.* (1982) obtained eleven late Tertiary paleointensities from one to three specimens per lava.

This study was aimed as a reconnaissance study for future extended works, such as a detailed magnetostratigraphy to establish the polarity time scale in Neogene period from Icelandic lavas which is considered to show more frequent reversals than those from marine magnetic anomalies (Kristjánsson, 1985a), or, thorough paleointensity studies to overcome the unbalanced data numbers between intensity and direction which are essential to establish a statistical model of paleomagnetic field. In this paper, we report on the paleosecular variation from two lava sections of Pliocene to Pleistocene age in southwestern Iceland which were previously studied by Wilson *et al.* (1972) and Kristjánsson *et al.* (1988). Paleointensity experiments using the Thelliers' method was also performed on the samples from one of the sections, which includes the Gauss to Matuyama transition at its base. Special emphasis is put on these paleointensity results in this paper.

2. Lava Sections and Samples

Samples were collected from 29 lavas of section K of Wilson *et al.* (1972) at Mt. Reynivallaháls and 22 lavas of sectoin IG of Kristjánsson *et al.* (1988) at Mt. Ingólfsfjall, which locate about 30 km northeast and about 50 km southeast of Reykjavík, respectively. Both sections comprise a sequence of basaltic lavas, mostly tholeiite type, of typical thickness of 2–20 m, and intermittent occurrence of sediment and hyaloclastite layers are recognized. The former, referred to as section RK in this study, covers the top of N4 and the lowest part of R3 using the polarity groups of Einarsson (1957), and this corresponds to Gauss to Matuyama chrons according to Kristjánsson *et al.* (1980). Section IG (section RG in this study) was assumed to be in the Brunhes chron by Kristjánsson *et al.* (1988), and recently this has been confirmed by K-Ar ages determined by Duncan (personal communication, 1994). He collected one and four samples from sections IE and II, respectively, of Kristjánsson *et al.* (1988). Two normal lavas just above the reverse to normal boundary at the two sections gave 0.71 ± 0.01 Ma and 0.57 ± 0.18 Ma. One reversed lava below the boundary gave 0.83 ± 0.27 Ma, and two lavas from much higher levels gave 0.29 ± 0.03 Ma and 0.54 ± 0.06 Ma. As the polarity boundaries of the two sections correspond to that of section IG because the lava layers are almost horizontal at Mt. Ingólfsfjall, it is concluded that the normal of the section IG is in the Brunhes chron.

Samples were collected using a portable drill. Usually, five cores were drilled from each lava. The core orientations were ascertained by the sun azimuth or geographic sightings. A magnetic compass was also used as a subsidiary orientation method. However, the differences of measured azimuth angle between the magnetic orientation and other two methods varied between less than 5° and more than 25°, indicating that magnetic orientation is often compromised by the magnetization of the rock.

3. Paleomagnetic Results

3.1 Paleodirections

One pilot sample from each lava was subjected to stepwise alternating field (AF) demagnetization, usually up to 80 mT. Stepwise thermal demagnetization was also applied to another pilot sample from each lava. Remanences were usually very stable to AF demagnetization while they were often less stable to thermal demagnetization. Nevertheless, analysis of the stable component on an orthogonal component plot was always straightforward for all samples from both sections RG and RK. Examples of the orthogonal component plot of AF and thermal demagnetization are shown in Fig. 1. As AF demagnetization was found to be more effective, all the remaining samples were cleaned by AF demagnetization at two or three steps up to the optimal level of 15–25 mT. Primary remanence directions were also determined on the orthogonal component plot including the origins. Lava mean paleodirections were determined by combining these specimen directions with those of pilot samples. Lava mean directions and the corresponding VGP positions are summarized in Table 1 for section RG. For section RK, paleodirections are summarized in Table 2 with some paleointensity results which will be discussed later. No tectonic tilt correction was made to the paleodirections at section RG because at the Mt. Ingólfsfjall the lava layers are almost horizontal, while at section RK, an attitude correction was made to all the directions with a representative value (strike = 45°, dip = 4°).

One of the new features of this study is the increased number of 3–5 cores per lava used to

Table 1. Site mean paleodirections from section RG (64.0°N, 21.1°W) in southwestern Iceland.

Lava	Altitude (m)	Inc	Dec	α_{95}	n	Plat (°N)	Plon (°E)	J (A/m)
RG01	138	70.0	28.0	3.9	4	72.7	83.9	4.6 ± 0.4
RG02	139	71.6	27.4	2.9	4	74.6	78.5	4.8 ± 0.5
RG03	140	74.1	26.6	1.1	4	77.2	66.2	4.8 ± 1.0
RG04	142	68.4	29.4	5.9	4	70.4	86.9	6.0 ± 0.4
RG05	143	72.8	24.1	1.6	4	77.1	77.0	3.3 ± 0.3
RG06	148	72.9	27.1	3.2	4	75.9	72.6	4.3 ± 1.2
RG07	150	76.0	26.6	4.5	4	78.3	59.2	5.7 ± 0.4
RG08	152	72.7	14.8	3.2	4	80.8	101.7	6.5 ± 0.4
RG09	154	73.0	20.4	0.8	4	78.9	88.2	6.4 ± 0.8
RG10	156	72.3	19.2	4.2	4	78.7	94.8	4.2 ± 0.8
RG11	160	70.1	26.2	7.4	4	73.5	93.2	7.0 ± 1.3
RG12	163	72.9	24.8	3.2	4	77.0	82.5	8.3 ± 2.2
RG13	167	71.3	20.0	4.0	4	77.3	98.8	7.3 ± 2.9
RG14	176	77.9	341.0	3.3	4	81.6	277.3	8.2 ± 1.0
RG15	200	73.8	351.5	4.6	4	84.3	207.4	6.2 ± 0.9
RG16	203	67.6	352.4	3.0	4	75.9	179.1	6.3 ± 0.9
RG17	210	63.3	9.5	3.6	4	70.1	138.8	5.3 ± 0.6
RG18	213	66.5	2.4	4.5	4	75.0	153.0	4.8 ± 0.4
RG19	216	69.6	350.4	6.8	4	78.3	188.3	4.8 ± 0.6
RG20	220	65.5	5.5	1.2	4	73.4	146.0	3.4 ± 0.2
RG21	230	66.2	6.1	3.5	4	74.2	143.9	7.2 ± 0.7
RG22	235	67.0	16.4	2.7	4	73.2	119.7	10.0 ± 4.5

Note: Inc, Dec, inclination and declination; α_{95}, 95% confidence circle; n, number of samples included in the calculation of the lava mean directions; Plat, Plon, latitude and longitude of the VGP position; J, mean NRM intensity and its standard deviation.

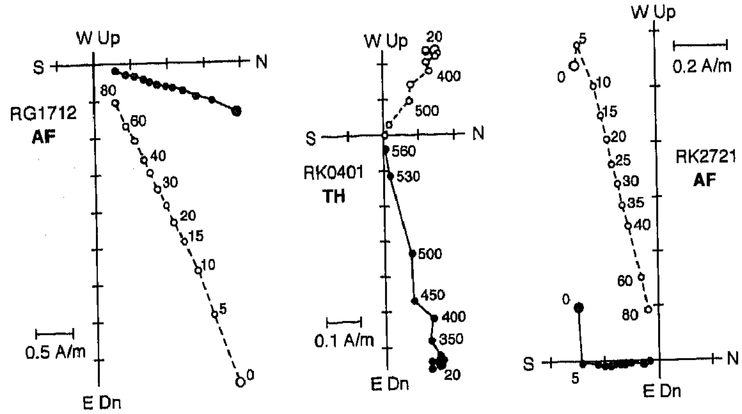


Fig. 1. Representative orthogonal component plots of step-wise demagnetization for the lavas in southwestern Iceland. AF and TH indicate the alternating field and thermal demagnetization, respectively. The polarities of the specimens are, from left to right, normal, transitional, and reversed.

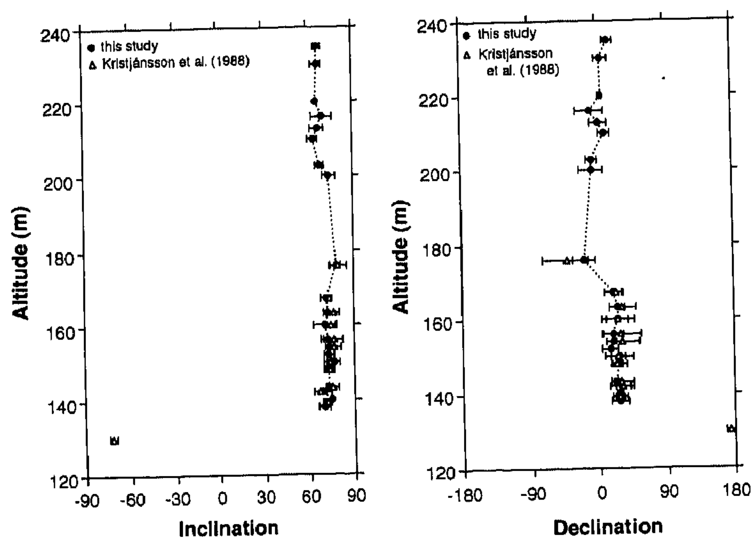


Fig. 2. Variation of paleodirection at section RG of Brunhes chron, and comparison with the previous data by Kristjánsson *et al.* (1988).

obtain the lava mean directions compared to 2–4 cores per lava used in previous studies. When more than one specimen from the same core were demagnetized, the specimen directions were averaged to obtain a sample mean direction. Four sample directions, which usually involved five specimens, were used to calculate lava mean directions in section RG, while in section RK we used three to five sample directions in which those of "NRM" steps in the paleointensity experiment were also included.

Figure 2 compares the lava mean directions of section RG obtained in this study (closed circles) with the results of Kristjánsson *et al.* (1988) (white triangles) who measured three samples per lava. Unfortunately we missed the bottom lava which records a Matuyama reversed direction,

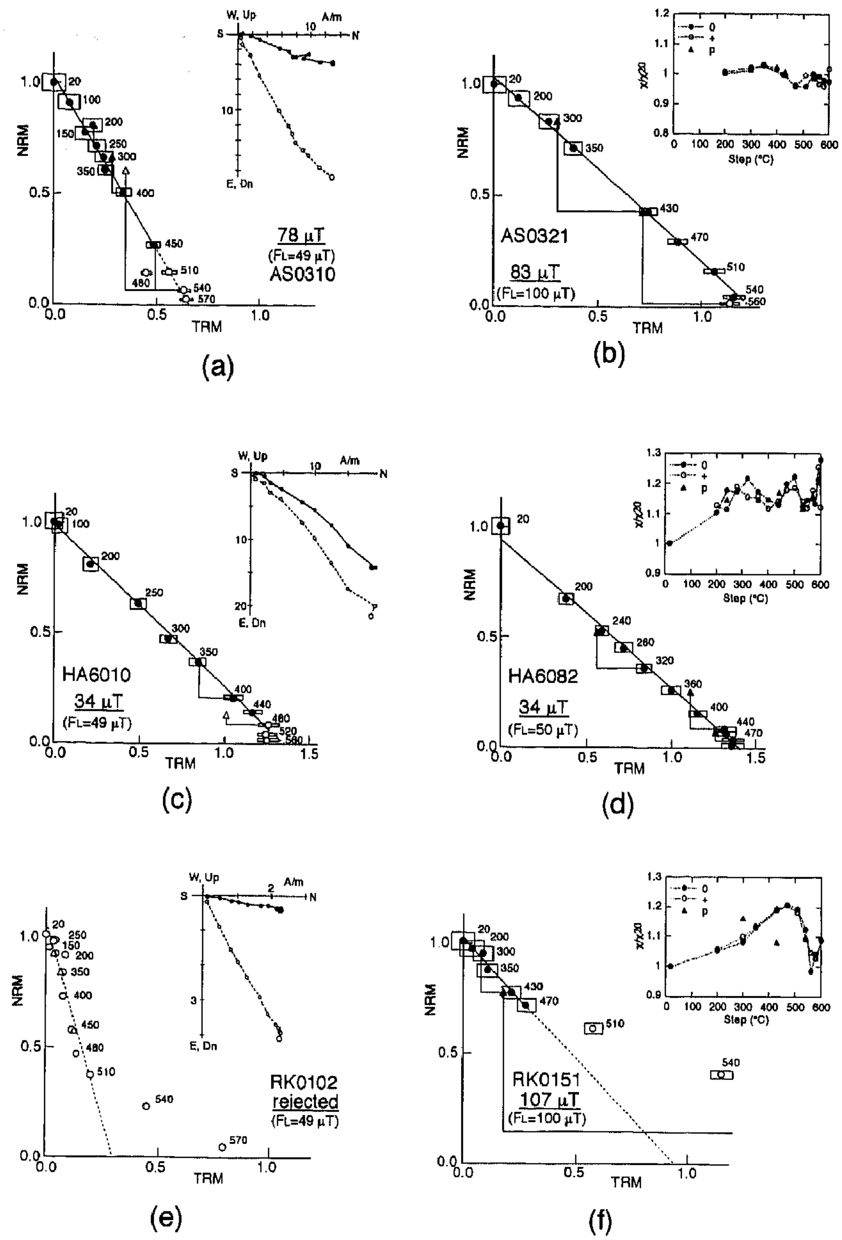
Table 2. Paleodirections and paleointensities from section RK (64.4°N, 21.5°W) in southwestern Iceland.

Lava	Altitude (m)	Inc	Dec	α_{95}	n	Plat (°N)	Plon (°E)	J (A/m)	F (μT)	N	VDM ($\times 10^{22}$ Am^2)
RK01	35	62.3	16.8	1.7	5	67.1	125.9	4.0 ± 1.1	99.2 ± 18.6	3	16.9 ± 3.2
RK02	38	−8.4	71.8	4.8	5	3.9	86.8	0.3 ± 0.1			
RK03	41	−9.8	73.0	5.1	3	2.8	86.0	0.6 ± 0.4			
RK04	60	−24.0	76.0	4.6	5	−5.4	86.5	0.6 ± 0.1	16.6 ± 6.9	5	4.1 ± 1.7
RK05	150	−64.8	167.0	2.1	3	−71.0	6.7	5.7 ± 2.9			
RK06	155	−59.2	153.9	4.0	3	−61.3	23.0	3.7 ± 1.9			
RK07	160	−67.5	144.0	4.2	4	−66.6	49.0	2.4 ± 1.2			
RK08	175	−79.3	162.7	2.7	4	−81.7	112.0	5.7 ± 1.6			
RK09	180	−71.7	206.7	1.6	4	−74.8	267.2	6.7 ± 1.7	16.2	1	2.4
RK10	190	−75.2	191.3	2.8	4	−84.5	267.3	4.7 ± 1.2			
RK11	195	−77.6	187.4	5.4	4	−86.4	214.1	5.4 ± 2.5			
RK12	200	−73.9	192.6	2.9	4	−82.7	279.6	5.6 ± 1.8			
RK13	205	−69.5	177.0	4.0	4	−78.7	347.7	7.2 ± 1.8			
RK14	215	−79.9	173.5	2.9	5	−83.5	138.8	8.0 ± 1.2	22.3 ± 6.6	4	3.1 ± 0.9
RK15	230	−80.1	152.4	3.1	4	−77.9	111.9	7.1 ± 2.6			
RK16	235	−76.6	176.3	3.0	5	−88.4	74.6	7.2 ± 0.4	12.9 ± 3.1	3	1.9 ± 0.4
RK17	250	−82.6	141.9	2.8	4	−73.4	125.6	5.9 ± 2.7	19.4 ± 5.4	2	2.6 ± 0.7
RK18	280	−74.4	136.3	2.1	4	−70.0	78.5	6.9 ± 2.8	26.6 ± 0.5	2	4.0 ± 0.1
RK19	290	−73.2	233.1	5.8	4	−65.0	236.2	6.8 ± 3.6			
RK20	295	−72.0	179.6	6.3	5	−82.6	340.2	7.0 ± 4.7			
RK21	310	−75.3	187.0	5.1	4	−86.2	278.9	1.7 ± 0.3			
RK22	315	−81.4	186.8	4.5	4	−80.9	171.0	1.0 ± 0.1	42.2 ± 10.5	2	5.8 ± 1.4
RK23	330	−84.3	202.0	4.8	5	−74.3	174.3	3.4 ± 5.9	38.1 ± 7.4	5	5.1 ± 1.0
RK24	340	−81.0	139.3	4.5	5	−73.5	114.7	5.2 ± 9.7	32.1 ± 3.8	4	4.5 ± 0.5
RK25	355	−79.3	184.7	1.6	4	−84.8	177.0	1.8 ± 0.5			
RK26	370	−75.9	172.6	5.8	4	−86.6	53.6	0.9 ± 0.3			
RK27	380	−81.6	185.9	4.8	3	−80.6	168.8	1.1 ± 0.2			
RK28	390	−80.0	201.2	5.5	4	−79.9	201.8	0.7 ± 0.1			
RK29	410	−80.7	191.6	1.8	4	−81.4	183.3	1.7 ± 0.7			

Note: Inc, Dec, inclination and declination; α_{95}, 95% confidence circle; n, number of samples used for calculation of lava mean directions; Plat, Plon, latitude and longitude of VGP position; J, mean NRM intensity; F, paleointensity; N, number of specimens used for mean paleointensity; VDM, Virtual Dipole Moment.

however, we sampled lavas above 180 m altitude, up to 240 m level. Difference angles of the lava mean directions between the two studies are less than about 5° (minimum 0.4°, maximum 5.1°), indicating that three samples per flow is sufficient in this section. 95% confidence circles (α_{95}) in the lava mean directions are similar between the two studies although those in this study are often a little smaller.

Detailed comparison of the paleodirections from section RK with the results of Wilson *et al.* (1972) was impractical because the latter does not include a table of data. However, general agreement of the paleodirections between the two studies is ascertained. As shown in Table 2, section RK includes a normal direction in the lowest lava and three transitional directions in the next three lavas. The lowermost normal direction was discovered in this study, and the transitional directions are in agreement with those directions grouped as anomalous by Wilson *et al.* (1972). Variation of inclination versus altitude is shown in Fig. 4 with the results of paleointensity.



(a)
78 μT
(FL=49 μT)
AS0310
(b)
AS0321
83 μT
(FL=100 μT)
(c)
HA6010
34 μT
(FL=49 μT)
(d)
HA6082
34 μT
(FL=50 μT)
(e)
RK0102
rejected
(FL=49 μT)
(f)
RK0151
107 μT
(FL=100 μT)
NRM
TRM
W, Up
E, Dn
A/m
Step (°C)

Fig. 3.

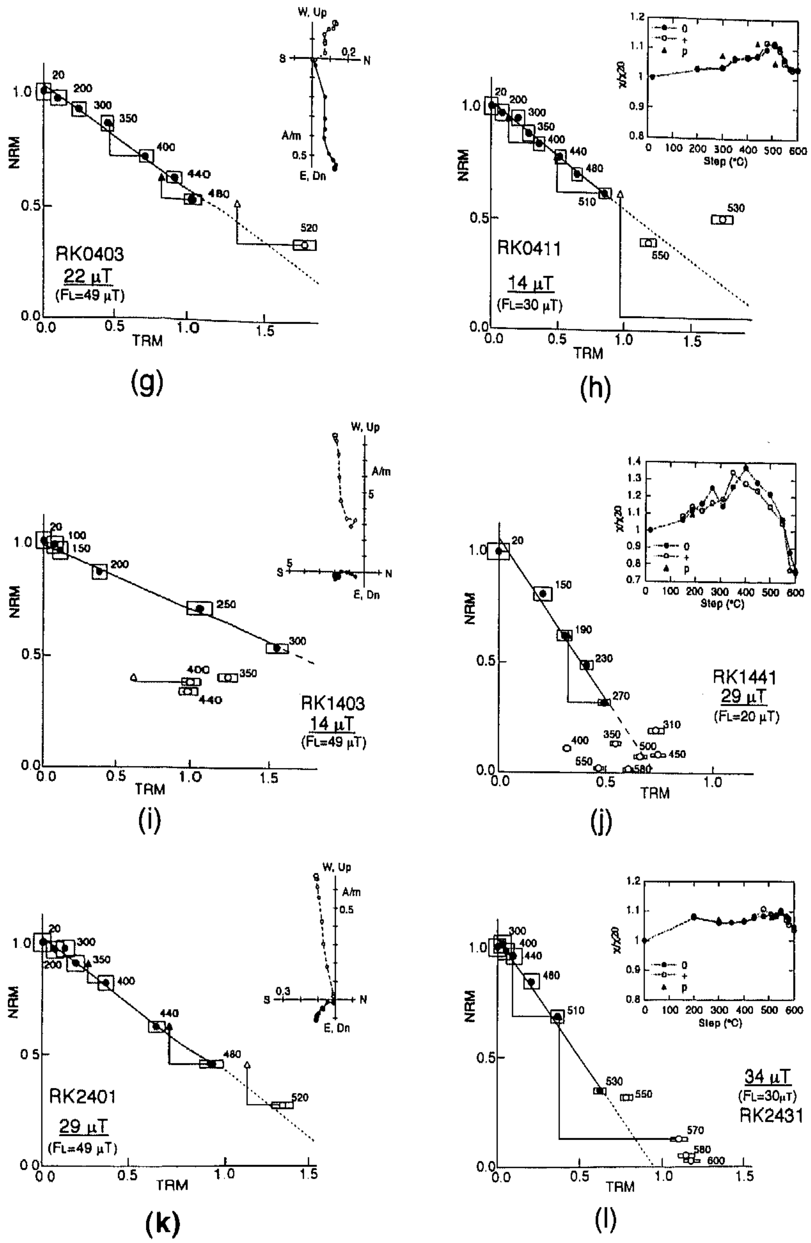


Fig. 3. Some representative NRM-TRM plots of the Thelliers' experiment on lavas from section RK, which includes the Gauss to Matuyama transition at its base. The figures on the left-hand side (a, c, e, ...) and right-hand side (b, d, f, ...) are from experiment A made at University of Southern California and experiment B at Tokyo Institute of Technology, respectively. Results from some standard samples are also included in (a)–(d). Data points which were included (rejected) in the least squares fitting are shown by solid circles (open circles). A rectangle attached to each data point shows an error estimate based on Kono and Tanaka (1984). Triangles are the results of pTRM tests following the notation of Coe *et al.* (1978), in which solid and open symbols denote positive and negative results, respectively. Inset attached to each diagram shows either the orthogonal plot for the zero field steps or the change in magnetic susceptibility against step. In the latter plot, closed and open circles, and triangles represent the measurements after heating to the steps of zero field, TRM inducing, and pTRM test, respectively.

3.2 Paleointensities

Two series of paleointensity experiments using the Thelliers' method were performed at University of Southern California (USC) and Tokyo Institute of Technology (TIT). As this was a good opportunity to check the inter-laboratory consistency of the experimental method, experiments were also made on the standard samples such as present-day lavas. The experimental procedure described by Coe (1967) in which samples are heated twice to each temperature (first in zero-field and second in a laboratory field) was adopted throughout both series of experiments. The first experiment at USC was made in air with a Schonstedt thermal demagnetizer using a laboratory field of 49 μT. In the second experiment at TIT, the laboratory field was selected to match the expected paleointensity, because it is considered that this yields minimum overall error (Tanaka and Kono, 1984; Aitken *et al.*, 1989). Remanences were measured using spinner magnetometers; a Minispin of Molspin Ltd. at USC and a Schonstedt SSM-1A at TIT.

Results were analyzed on the NRM-TRM diagram or Arai diagram (Arai, 1963; Nagata *et al.*, 1963) using the scheme of Kono and Tanaka (1984) which employs the least squares method of Williamson (1968). Some representative results are shown in Figs. 3(a) to 3(l). In the NRM-TRM diagrams, data points which were included (rejected) in the least squares fitting are shown by solid circles (open circles). A rectangle attached to each data point shows an error estimate based on Kono and Tanaka (1984). Triangles are the results of pTRM tests following the notation of Coe *et al.* (1978), in which solid and open symbols denote positive and negative results, respectively. Either the orthogonal plot of the NRM component (zero field steps) or the change in magnetic susceptibility against temperature step is shown as an inset to each diagram. Criteria for adopting

Table 3. Specimen paleointensity results.

Specimen	J (A/m)	T_1 (°C)	T_2 (°C)	n	r	$-b$	s_b	Lab	F_L (μT)	$F \pm \Delta F$ (μT)
2000 ybp Kotaki Pyroclastic Flow, Asama Volcano (Mean F: 81.0 ± 9.2 μT, $n = 4$*)*										
AS0310	2.4	20	450	9	0.995	1.586	0.259	A	49	77.7 ± 12.7
AS0312	1.9	100	560	10	0.985	1.893	0.150	A	49	92.8 ± 7.4
AS0321	6.1	20	540	8	0.999	0.827	0.041	B	100	82.7 ± 4.1
AS03183	1.9	20	560	9	0.991	0.709	0.040	B	100	70.9 ± 4.0
1935 AD Hawaii Volcano Lava (Mean F: 35.0 ± 1.1 μT, $n = 5$*)*										
HA6002	26.2	150	450	7	0.991	0.708	0.050	A	49	34.7 ± 2.4
HA6003	22.8	200	520	8	0.995	0.734	0.038	A	49	36.0 ± 1.9
HA6005	25.6	100	400	6	0.992	0.743	0.054	A	49	36.4 ± 2.6
HA6010	31.7	20	440	8	0.999	0.699	0.046	A	49	34.3 ± 2.2
HA6082	29.3	20	570	12	0.996	0.689	0.040	B	50	34.4 ± 2.0
1951 AD Oshima Volcano Lava (Mean F: 52.2 ± 4.5 μT, $n = 4$*)*										
OS1101	37.2	20	440	9	0.996	1.179	0.066	A	49	57.8 ± 3.2
OS1107	40.9	200	520	9	0.983	0.936	0.059	A	49	45.9 ± 2.9
OS1109	33.1	200	400	5	0.996	1.110	0.116	A	49	54.4 ± 5.7
OS1110	36.2	150	450	7	0.984	1.016	0.067	A	49	49.8 ± 3.3
OS2531	29.0	20	400	7	0.996	1.060	0.078	B	50	53.0 ± 3.9
1986 AD Oshima Volcano Lava (Mean F: 51.3 ± 4.7 μT, $n = 3$*)*										
OS1204	16.0	20	250	5	0.997	0.980	0.034	A	49	48.0 ± 1.7
OS1207	25.8	200	400	5	0.995	1.007	0.076	A	49	49.3 ± 3.7
OS1213	67.7	150	450	7	0.993	1.158	0.065	A	49	56.7 ± 3.2

Table 3. (continued).

Specimen	J (A/m)	T_1 (°C)	T_2 (°C)	n	r	−b	s_b	Lab	F_L (μT)	$F \pm \Delta F$ (μT)
					Section RK					
RK0131	4.5	20	470	6	0.994	1.127	0.243	B	100	112.7 ± 24.3
RK0141	4.0	20	470	6	0.982	0.778	0.155	B	100	77.8 ± 15.5
RK0151	4.7	20	470	6	0.989	1.069	0.235	B	100	106.9 ± 23.5
RK0403	0.6	20	480	7	0.992	0.450	0.020	A	49	22.1 ± 1.0
RK0404	0.6	20	520	8	0.985	0.516	0.016	A	49	25.3 ± 0.8
RK0411	0.6	20	510	8	0.994	0.458	0.046	B	30	13.8 ± 1.4
RK0431	0.5	20	510	8	0.991	0.434	0.037	B	30	13.0 ± 1.1
RK0443	0.6	20	550	10	0.996	0.289	0.014	B	30	8.7 ± 0.4
RK0902	5.1	150	300	4	0.986	0.331	0.040	A	49	16.2 ± 2.0
RK1403	8.8	20	300	6	0.997	0.290	0.013	A	49	14.2 ± 0.6
RK1404	10.7	20	250	5	0.995	0.404	0.005	A	49	19.8 ± 0.3
RK1441	8.9	20	270	5	0.989	1.463	0.170	B	20	29.3 ± 3.4
RK1451	8.2	20	270	5	0.980	1.286	0.127	B	20	25.7 ± 2.5
RK1602	9.8	150	300	4	0.989	0.321	0.025	A	49	15.7 ± 1.2
RK1603	8.3	20	300	6	0.997	0.273	0.010	A	49	13.4 ± 0.5
RK1604	4.8	150	350	5	0.991	0.194	0.001	A	49	9.5 ± 0.1
RK1703	9.3	20	300	5	0.987	0.474	0.041	A	49	23.2 ± 2.0
RK1705	3.8	20	300	5	0.987	0.317	0.009	A	49	15.5 ± 0.5
RK1803	8.9	20	440	6	0.992	0.548	0.066	A	49	26.9 ± 3.2
RK1804	9.2	20	440	6	0.983	0.535	0.036	A	49	26.2 ± 1.8
RK2202	1.3	20	450	9	0.991	1.013	0.044	A	49	49.6 ± 2.2
RK2204	1.2	20	400	7	0.993	0.709	0.028	A	49	34.7 ± 1.4
RK2303	0.9	20	440	6	0.993	0.945	0.037	A	49	46.3 ± 1.8
RK2305	0.6	200	440	5	0.993	0.886	0.084	A	49	43.4 ± 4.1
RK2321	14.1	400	530	5	0.991	0.649	0.087	B	50	32.4 ± 4.4
RK2341	1.8	320	470	5	0.983	0.787	0.045	B	50	39.3 ± 2.2
RK2351	0.4	20	470	9	0.995	0.575	0.040	B	50	28.8 ± 2.0
RK2401	0.7	20	480	7	0.996	0.600	0.024	A	49	29.4 ± 1.2
RK2402	0.6	250	450	5	0.998	0.585	0.021	A	49	28.6 ± 1.0
RK2404	0.6	200	480	6	0.994	0.753	0.047	A	49	36.9 ± 2.3
RK2431	22.7	20	530	9	0.995	1.118	0.054	B	30	33.5 ± 1.6

Note: J, NRM intensity of the specimen; T1, T2, n, lower and higher temperature steps and number of data points of the linear plot; r, correlation coefficient; b, sb, slope of the linear plot and its error; Lab, A and B indicates the experiment made at University of Southern California and Tokyo Institute of Technology, respectively; F_L, Laboratory field; F, ΔF, specimen paleointensity and its error.

a result as successful are, 1) linearity of NRM-TRM plot in which at least four points are included and the correlation coefficient exceeds 0.980, 2) a positive pTRM test over the temperature range of the linear NRM-TRM plot, 3) the absence of viscous components and no indication of thermo-chemical remanence in the remanence directions over the same temperature range, 4) less than 20% change in the initial magnetic susceptibility within the temperature range for the linear part of the NRM-TRM plot.

Some examples of the inter-laboratory comparison of the method using the standard samples are shown in Figs. 3(a)–(d). Two results from the Kotaki Pyroclastic Flow from Asama Volcano, Japan are shown in Figs. 3(a) and (b). This flow is dated at 2200 years bp (before present) by the ^{14}C method (Kono, 1978) and has been frequently studied by both Thellier and Shaw methods (Kono, 1978; Tsunakawa and Shaw, 1994). A grand mean paleointensity is 86 ± 8 μT which was obtained by averaging 14 previous results. Figure 3(a) shows a result obtained in the first experiment at USC in which the laboratory field was 49 μT while Fig. 3(b) shows one from the second experiment at TIT where the laboratory field was 100 μT. The paleointensity of 78 μT resulting from the steep slope, of 1.58, of the linear part of the NRM-TRM plot in the former is in good agreement with the results in the latter experiment in which a laboratory field twice as large gave a slope of 0.83 resulting in a paleointensity of 83 μT.

Figures 3(c) and (d) are examples from the Hawaii 1935 lava. Results from the two series of experiment are in complete agreement giving about 35 μT. These values are reasonable according to DGRF45 which gives the total force of 37 μT at the site (Langel, 1992). Specimen level data are summarized in Table 3, in which some other results using 1951 and 1986 lavas at Oshima Volcano, Japan are also included. Consistency of the results between the two institutes is also good for the Oshima 1951 lava (the 1986 lava was studied only at USC). However, the lava mean paleointensities of 51–52 μT are larger than the expected total force of 46 μT at the site by about 10%. As most previous results on this lava are also about 10% larger (Kono, 1978), we think the results obtained at both institutes are acceptable. The reason of the difference is unknown, but probably it is attributed to a local geomagnetic anomaly. Although possible rock magnetic problems have been suggested for similar inconsistencies of paleointensity results from the Hawaii 1960 lava (Tanaka and Kono, 1991; Mankinen and Champion, 1993; Tsunakawa and Shaw, 1994), this is not likely in the case of Oshima lavas.

Paleointensity experiments on the samples from section RK were also made at both institutes. In the first experiment made at USC, no stability check of the remanence was made in advance to select suitable samples. Obviously this is the reason for the low success rate of the first experiment; only 19 out of 56 specimens (34%) gave successful results. In the second experiment made at TIT later, only those samples which gave successful results at USC were studied, giving 12 successful results out of 16 specimens. Several representative examples of the NRM-TRM plots from four lavas are shown in Figs. 3(e)–(l), and the specimen level data is included in Table 3. Two NRM-TRM diagrams from the lowermost, normally magnetized lava, are shown in Figs. 3(e) and (f). The result obtained from the first experiment, shown in Fig. 3(e), was unsuccessful due to the low correlation coefficient, 0.938, of the linear portion of the data. However, three unsuccessful results obtained from the first experiment still suggested that the paleointensity might have been very high. So in the second experiment three further specimens were examined in a laboratory field of 100 μT. All three specimens gave successful results as shown in Fig. 3(f). This pre-transitional normal lava gave a high paleointensity of 99 ± 19 μT.

The three overlying lavas had transitional directions and the NRM intensities were weak, as indicated in Table 2. Only one of these lavas gave successful results. An example from the first experiment with a laboratory field of 49 μT is shown in Fig. 3(g), in which a low paleointensity of 22 μT was obtained. The second experiment on this lava was made with a smaller laboratory field of 30 μT, and low paleointensities were also obtained. An example from the second experiment, giving a paleointensity of 14 μT, is shown in Fig. 3(h). Unfortunately the consistency of the results between the two experiments was not perfect. The first experiment gave 22 μT and 25 μT, while values between 9 and 14 μT were obtained from the second experiment. As the paleointensity is rather small, we think this amount of difference is allowable.

Figures 3(i) and (j) show two examples of the NRM-TRM diagram from a lava which is about 150 m above the transitional lava. Two low paleointensities, of 14 μT and 20 μT, were obtained in the first experiment, and the second experiment using a laboratory field of 20 μT, also gave low paleointensities, of 26 μT and 29 μT. Again the consistency between the experiments carried out at USC and TIT is not very good, as in the former examples.

A lava at an elevation of 340 m still gave a low paleointensity, as shown in the examples of NRM-TRM diagrams in Figs. 3(k) and (l). Results from the two series of experiment were in good agreement. Figure 3(k) shows an example from the first experiment giving 29 μT, and Fig. 3(l) shows one from the second experiment in which the laboratory field was 30 μT and a paleointensity of 34 μT was obtained. It is noted that the mean paleointensity of 32 ± 4 μT is quite low for Iceland, because a dipole field of 57 μT is expected at the high latitude of the site (64.4°N) if an axial dipole moment of 8×10^{22} Am^2 is supposed.

4. Discussion

Kristjánsson *et al.* (1988) suggested that the lavas of their section IG had accumulated over a short period of time, on the basis of the similarity in the mean paleodirections. This is confirmed by this study. The angular standard deviation (ASD) of VGPs from section RG, around the mean pole is 10.3° ($N = 22$), after correcting for the contribution of the within site dispersions (Doell, 1970). The upper and lower 95% confidence limits (Cox, 1969) are 13.0° and 8.5°, respectively. This is a very low value when the high latitude of the site is taken into consideration, compared to the general trend for the last 5 my (McElhinny and Merrill, 1975; McFadden *et al.*, 1991). A serial correlation test by Watson and Beran (1967) also supports the rapid accumulation of the lava flows. In this method, the sum of the cosines of the difference angles between the field directions of adjacent lavas (L) is the statistical parameter. This sum was 20.922 for 22 RG directions (L_0). Randomization of the directions for 2500 permutations resulted in a distribution of L which is similar to a Gaussian distribution with no observation that exceeds L_0, suggesting that the RG directions are serially correlated. The mean time interval between lava eruptions in Iceland has often been discussed in the previous studies, and estimates range from 5000 to 40000 years depending on the region and the age of the lava sections (e.g., Watkins and Walker, 1977; McDougall *et al.*, 1984; Kristjánsson, 1985a). It should be noted, however, that there are also lavas which are inferred to have accumulated more rapidly (e.g., Kristjánsson *et al.*, 1988).

It seems that the time span covered by the RK lavas is rather short, too. Although we collected only three transitional lavas at this section, Wilson *et al.* (1972) reported seven more lavas of "anomalous" direction which we missed. The facts that the paleodirections of these extra lavas are all similar and the presence of the large number of lavas which recorded the transitional directions suggest that these lavas erupted rapidly. The ASD of 25 VGPs from section RK, calculated after omitting the three transitional and one pre-transitional normal directions, was 13.0° with upper and lower 95% confidence limits of 10.9° and 16.2°, respectively. This is again too small for the high latitude of Iceland. A serial correlation test on the 25 reversed field directions gave L_0 of 23.704, and only ten observations out of 2500 permutations of the data exceed L_0. As these represent only 0.4% of the total observations of L, the possibility of the RK field directions being random is rejected at the 5% significance level.

The variation of the geomagnetic field is commonly pictured as a combination of usual, ordinary paleosecular variation and occasional abnormal behavior such as a transition or an excursion. However, this separation of usual and anomalous behaviour is not statistically necessary according to the analysis of the large number of Icelandic data (Kristjánsson and McDougall, 1982; Kristjánsson, 1985a). The distribution of VGP latitudes of 2163 observations from Icelandic lavas was best fitted by a single Bingham distribution. This rather continuous picture of the geomagnetic field, also posed by Harrison (1995, this issue), will be one of the major issues to be solved in the near future. Paleodirections obtained from the section RK in this study seem to support the conventional idea, although the time span covered by the section is too short to conclude it as a general feature of the geomagnetic field.

The variations of inclination and paleointensity versus altitude at section RK are shown in Fig. 4. The dotted lines in Figs. 4(a) and (b) indicate the expected values of inclination and total force at the site for an axial geomagnetic dipole moment of 8×10^{22} Am^2. A general paleointensity low is noted in the paleointensity variation curve. The low paleointensity observed in the transitional lava is typical for transitional fields. Actually, a low paleointensity of 11 μT was previously reported from one of the transitional lavas in this section in the study of Smith (1967). However, it is noted that the low paleointensity values extended up to some 300 m altitude although the field direction returns to the reversed dipole direction at about 150 m level. We interpret this as an indication of slower recovery of paleointensity after a transition. This is in contrast to the Steens Mountain polarity transition in which both direction and intensity changed almost simultaneously (Prevót *et al.*, 1985). In the case of section RK, it is difficult to estimate the exact time span the lava sequence covers. Besides, rapid accumulation of the lavas is probable as discussed before. Still, the time span for recovery of paleointensity seems to be two or three times longer than that for paleodirection. We speculate that this phenomenon might be an indication of the idea of "dead time" in the statistical model of geomagnetic field reversals by McFadden and Merrill (1993). It is surprising that the pre-transitional normally magnetized lava gave a very high paleointensity. It is impossible to tell whether this high paleointensity was general for the latest part of the Gauss chron or was a temporary phenomenon associated with the transition. Considering the rapid lava accumulation at this section, the latter interpretation is more plausible.

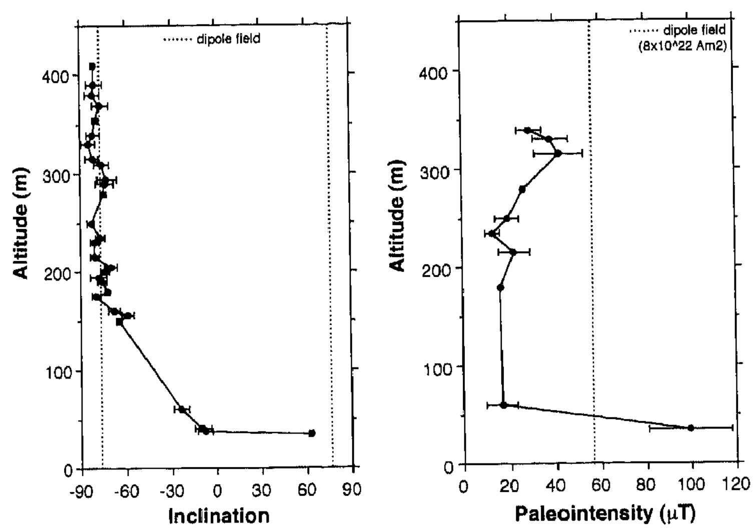


Fig. 4. Variation of paleodirection (inclination) and paleointensity at RK section in western Iceland. It is noted that low paleointensity persisted some time after the field direction returned to complete dipole direction.

5. Conclusions

We revisited section K of Wilson *et al.* (1972) and sectoin IG of Kristjánsson *et al.* (1988) in Southwestern Iceland which are Pliocene–Pleistocene age. The angular standard deviation of VGPs is 10.3° and 13.0° for the former and the latter sections, respectively. Both lava sequences seem to have erupted in a short time judging from these small angular standard deviations. A serial correlation test applied to the paleodirections of adjacent lavas also indicates possible correlation at both sections. Paleointensity experiments using the Thelliers' method were applied to 72 specimens from the latter section, which includes the Gauss to Matuyama transition at its base, giving 31 successful results. A high paleointensity, twice the present-day value, preceded the transition. It seems that low paleointensity prevailed not only during transition but also for some time after its completion.

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