Geophys. J. R. astr. Soc. (1977) **49**, 609–632

Upper Miocene and Pliocene geomagnetic secular variation in the Borgarfjördur area of Western Iceland

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Received 1976 October 18; in original form 1975 August 21

Summary. A total of 362 successive lava flows, which were extruded at a regular rate between $t = 6.7$ and 1.6 Myr in the Borgarfjördur area of Western Iceland, have been subjected to palaeomagnetic study.

In contrast to the result of a study by Wilson & McElhinny of palaeomagnetic data from a long sequence of lava flows in Eastern Iceland, there does not exist any long-term increase of geomagnetic inclination in Western Iceland between $t = 7$ and 3 Myr which, as they show, would produce a change in the distance to the associated virtual geomagnetic poles (VGP's) from greater than the geographic co-latitude to less than the co-latitude (or, with respect to the site, from 'far side' of the geographic pole to 'near-side' of the geographic pole). Instead the geomagnetic inclination is less than that required for an axial dipole field, providing 'far-side' VGP positions for all data groups.

The mean VGP positions are almost identical for four successive polarity epochs (two of reversed polarity, and two of normal polarity), consistent with reversal of the main dipole being accompanied by reversal of the non-dipole field.

S_F, the angular standard deviation of groups of VGP positions, is used as an expression of palaeosecular variation of the magnetic field. It is shown to be almost constant throughout the 5-Myr period, suggesting that standing and drifting non-dipole fields have not combined to produce strong secular variation which is in principle possible in high latitudes. This conclusion is weakened by the suspicion that the conventional exclusion of data from lavas with low-latitude VGP positions has discriminated against the discovery of high palaeosecular variation rates.

1 Introduction

The established geomagnetic polarity timescale for the past 4.5 Myr (summary by Watkins

1972a) resulted almost entirely from combined K : Ar and palaeomagnetic studies of igneous rocks. This is a direct method of analysis, whereas the substantial extrapolations of the scale which have been made using marine magnetic anomalies (Heirtzler *et al.* 1968) and palaeomagnetic properties of deep-sea sedimentary cores (Opdyke 1972) are indirect. The method of compilation of the original polarity timescale was to combine age and polarity data from igneous bodies which were from diverse locations. While this practice assisted in demonstrating the global nature of polarity changes, it required very rigorous K : Ar techniques, since no simple between-unit stratigraphic checks of the results could be made. Cox & Dalrymple (1967) showed that limits in K : Ar experimental precision would prevent extension of the polarity timescale back to beyond about 6 Myr, unless very long stratigraphic sequences were employed. Such young and long sequences of basalts are available only in Iceland. McDougall *et al.* (1977) recently presented the results of an attempt to extend the polarity timescale beyond 4.5 Myr by applying the direct K : Ar and palaeomagnetic method to a 3500-m thick sequence of basalts in the Borgarfjördur region of Western Iceland. A total of 362 successive lava flows were sampled, and the age-polarity results are reproduced in Fig. 1.

It is the purpose of this paper to present an analysis of these data in terms of the associated ancient geomagnetic field behaviour, particularly palaeosecular variation. Hitherto, similar analyses have suffered from uncertainty about the time range involved, since the meaning of any between-unit comparison of palaeomagnetic directions clearly will depend on the time range covered, and thick lava sequences can accumulate in anywhere from a few thousand years (e.g. Watkins 1969) to a few million years (Tarling & Gale 1968). Aziz-Ur-Rahman & McDougall (1973), in particular, have stressed this difficulty in the palaeomagnetic testing of geomagnetic field models. The data obtained for the Borgarfjördur region (Fig. 1) provide the first opportunity to analyse geomagnetic field variations over a several million year period, without ambiguity insofar as lava extrusion rates are concerned.

2 Geomagnetic field models

2.1 PALAEOSECULAR VARIATION

Past secular variation of the geomagnetic field has been most commonly studied using the methods of Doell & Cox (1972). Here, the total angular standard deviation (S_T) of virtual geomagnetic poles (VGP) each of which is derived from a single igneous body (or point in time) is corrected for within-body variation and other possible signal distortion in an attempt to measure the corresponding true geomagnetic field variation (S_F). Methods of computation of S_F have been published several times. A summary appears in Ellwood *et al.* (1973).

As shown by Doell & Cox (1972) and others, the geomagnetic model involving simple wobble of the main dipole will produce no latitudinal variation of S_F. When non-dipole components are added to the main dipole, the result is an increase of S_F with latitude, the rate of increase depending on the ratio of non-dipole to dipole field and the dipole wobble. McElhinny & Merrill (1975) have recently summarized studies of the present and ancient geomagnetic field secular variation, and have expanded the models employed to include one which divides the non-dipole field into standing and drifting components. They show that these can in principle combine to occasionally produce very high latitudinal gradients of S_F. Their analysis of all available palaeomagnetic data for lava flows less than 5 Myr old shows that it is probably impossible to measure palaeomagnetic secular variation at any single locality, and it was therefore suggested that such analyses can only be made using

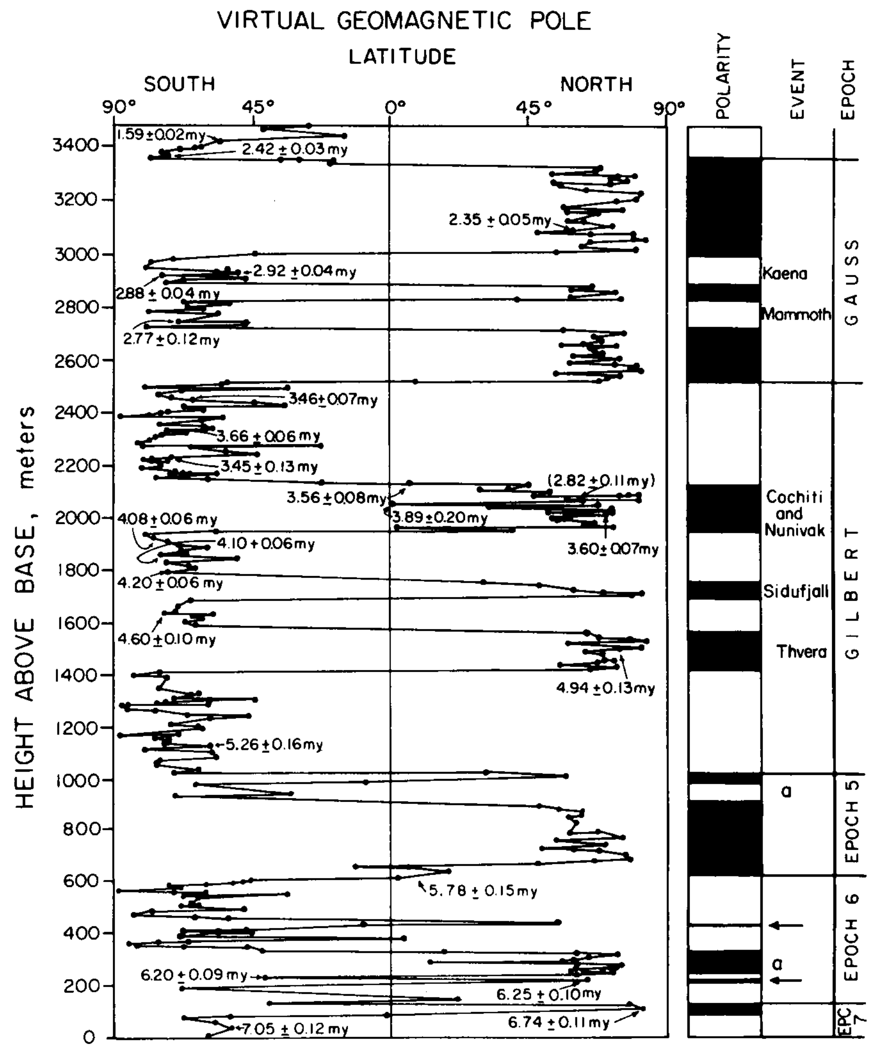

Figure 1. Latitude of virtual geomagnetic pole (VGP) versus height above the base of the section for lavas in the Borgarfjördur area of Western Iceland. See Table 1 for details of number of samples per lava, exact VGP latitudes, and precision parameters. K : Ar results added, for specific lavas. See McDougall *et al.* (1977) for exact stratigraphic details and K : Ar analyses. Polarity log at right is black = normal, clear = reversed. For discussion of the polarity epochs and events identified, see McDougall *et al.* (1977).

global coverage. One of the reasons for this difficulty appears to be the fact that lava flow sequences in single localities are usually not erupted regularly over a long period. As stressed above, and as shown in Fig. 1, this is not a problem with the data from Borgarfjördur.

2.2 THE OFFSET DIPOLE MODEL

According to most Upper Cenozoic palaeomagnetic data, the long-term geomagnetic field behaviour may have been distorted by possessing an inclination which is slightly shallower than that required by a centred dipole field. This results in computed VGP colatitudes which are greater than the geographic colatitudes, so that the VGP lies beyond the geographic pole from the site. This 'far side' property has been explained by Wilson (1970, 1971) as possibly reflecting an offset to the north of the axial dipole. He showed that an offset of 285 ± 74 km would best fit all Upper Cenozoic palaeomagnetic data. Watkins (1972b) later analysed all Brunhes epoch palaeomagnetic data in terms of the offset dipole model, and demonstrated a hemispheric asymmetry: while northern hemisphere data were consistent with Wilson's offset dipole model, many southern hemisphere data were not, so that an unequal co-axial dipole pair was invoked to provide dominantly axial dipole inclinations in the southern hemisphere, and dominantly shallower inclinations in the northern hemisphere. Watkins & Richardson (1975) have recently presented further refinement of this model, incorporating both offset and minor axial dipoles, to explain fine details of Brunhes epoch geomagnetic inclination variation on a global scale. This was accomplished by matching the latitudinal variation of dI (the difference between the mean palaeomagnetic inclination at a site, and the value which would be produced by a centred axial dipole) for the published data, with the theoretical result of combinations of offset major and minor axial dipoles (having magnitudes up to 4 per cent of the main dipole) located at the core–mantle boundary. Cox (1975) has also employed inclination anomaly analysis in an examination of the symmetry of the non-dipole field. He has shown that the apparent northward displacement of the axial dipole could as well reflect long-term non-dipole effects which do not average out over the long period, and that such effects may not be randomly distributed with respect to latitude. Wilson & McElhinny (1974) have refined the offset dipole model by examining the variation of the apparent offset with time during the last 25 Myr. They show that the data fit a northward dipole offset which decreases from 555 km between 25 and 7 Myr ago, to 316 km between 7 and 3 Myr ago, to only 143 km between 2 Myr age and the present. Merrill & McElhinny (1977) have recently extended their initial analysis of the geomagnetic field for the past 5 Myr (McElhinny & Merrill 1975). They have demonstrated that the offset dipole can be considered as a simple equivalent of a geocentric axial dipole upon which is superimposed quadrupole and perhaps higher even harmonics. Together with hemispherically asymmetrical odd harmonics, an apparent northward offset of the geocentric dipole will result at at any given site. This effect is cancelled when data for longitudinal strips are averaged. The term 'offset dipole' must therefore not be understood to express literally the nature of the geomagnetic field source, but to be a useful means to both recognize and express the equivalent net result of an axial dipole with superimposed quadrupole and higher even harmonics. While 'offset dipole equivalent' may thus be a more appropriate term, the simple term 'offset dipole' is used with the above qualifications in mind throughout this paper.

A second aspect of Wilson & McElhinny's (1974) analysis was detailed examination of palaeomagnetic data from a long sequence of lava flows in Iceland. The polarity variation in this sequence was first published by Dagley *et al.* (1967), but no firm correlation with the polarity timescale was possible, because of inadequate K : Ar results. The sequence consists of 21 separate sections (labelled A to V). Wilson & McElhinny show that while the oldest 15 sections (A to P) produce mean palaeomagnetic inclinations which are all shallower than that required for an axial dipole field (and thus produce 'far sided' VGP's), the youngest six sections (Q to V) in great contrast produce near sided VGP's (or mean palaeomagnetic inclinations which are steeper than that required for an axial dipole field). There does not appear to be any period of transition represented between these two conditions. Wilson & McElhinny's (1974) preferred explanation for these data employs their suggested decrease of apparent offset of the axial dipole for younger materials, and invokes a gap in volcanic activity between $t = 7$ and 3 Myr, during which time the apparent axial dipole position changed drastically from one with northern offset, to one with slight southern offset. This interpretation is supported by the demonstration of a higher mean intensity of magnetization (J) in five of the six younger sections (which is interpreted to indicate different magma sources being represented), and the arguments of Saemundsson (1974) who favours a hiatus in regional volcanic activity between $t = 8$ and 4 Myr, in order to explain tectonic complexities in Eastern and Northern Iceland.

The palaeomagnetic results from the Borgarfjördur region of Western Iceland (Fig. 1), in addition to providing a series of data with unique time control, are therefore relevant to Wilson & McElhinny's (1974) interpretation of the Eastern Iceland results, since the K : Ar results (Fig. 1) clearly show that the sequence spans the period during which a major change in mean geomagnetic inclination is suspected to have occurred in Iceland.

3 Methods

The field mapping was carried out by Drs Haukur Johannesson and Kristjan Saemundsson of the National Energy Authority in Iceland. All details of methods, and finely detailed stratigraphic sketches are presented in McDougall *et al.* (1977). This mapping included definition of the zeolite zones, providing evidence of the degree of low-temperature metamorphism undergone by the lavas. From each hand sample, a thin section was made for petrographic examination, in order to facilitate selection of materials for K : Ar analyses. A full description of the techniques employed to arrive at the K : Ar results in Fig. 1 are presented in McDougall, Watkins & Kristjansson (1976).

A specimen of 2.2 cm length was sliced from each core, and subjected to palaeomagnetic analysis. The direction and intensity of natural remanent magnetism (NRM) of each specimen was measured on a 5-Hz spinner magnetometer, and unstable components were minimized by application of alternating magnetic fields of 100 and 200 Oe to each specimen with remeasurement of the direction and intensity of magnetization being made following each demagnetizing treatment. The final mean direction of remanent magnetism for each unit was computed by combining results so that a minimum scatter of directions was obtained (Watkins & Richardson 1968).

4 Results

The K : Ar results, stratigraphic position of each body, and latitude of the VGP for each body are given in Fig. 1. In Table 1 the mean palaeomagnetic declination (D) and inclination (I), as well as resultant vector R (employing unit vector per specimen), and VGP position are given for each sampled body. Copies of all results, for all demagnetization treatments, as well as the natural remanent magnetism, can be obtained from the senior author on request. The identification number of each body corresponds to that in the detailed stratigraphic sketches of McDougall *et al.* (1977). Of the 362 separate bodies which have been sampled, 21 yielded R values too low to be statistically accepted as non-random at the 95 per cent confidence level (Vincenz & Bruckshaw 1960), and are thus not employed in Fig. 1, or in further analyses.

5 Discussion

5.1 MAGNETIC PROPERTIES

Although not presented in Table 1, the stability (as indicated by the fraction of J removed by the alternating magnetic field demagnetization treatment) is highly variable, both within and between bodies. Together with the generally low scatter of the final directions within each body, as indicated by R values in Table 1, this is some evidence that the original

Table 1. Palaeomagnetic data for all units in the Borgarfjördur sequence of Western Iceland.

NO	N	D	I	R	θ'	φ'
NT 112	3	254.0	-39.3	2.9933	-26.8	252.8
NT 111	3	207.8	-36.1	2.9961	-41.6	302.4
NT 108	3	292.0	-44.3	2.8569	-14.7	217.9
NT 107	3	288.2	31.3	1.4351*	23.0	239.2
NT 106	3	165.3	-51.2	2.9631	-55.9	0.9
NT 103	3	179.3	-56.4	2.9875	-62.2	339.5
NT 101	3	140.2	-66.3	2.9990	-63.7	50.3
NT 100	3	141.3	-70.4	2.9929	-68.4	58.7
NT 99A	3	174.1	-67.0	2.9983	-74.6	352.8
NT 99	4	178.3	-65.4	3.8780	-72.7	342.3
NT 98	4	186.0	-69.7	3.8247	-78.3	320.6
NT 97	3	246.6	-38.9	2.9923	-29.7	260.0
NT 96	3	243.6	-46.1	2.9723	-35.8	259.8
NT 95	3	265.7	-34.3	2.9853	-18.8	243.9
NT 94	3	262.0	-33.4	2.9352	-19.8	247.5
NT 93	3	215.9	-16.8	2.5267*	-28.4	297.1
NT 92	3	32.0	68.4	2.9858	69.0	91.8
NT 91	4	37.4	69.0	3.9898	67.5	83.3
NT 90	3	53.0	61.4	2.9908	53.2	79.2
NT 89	3	0.7	70.8	2.9969	80.3	156.1
NT 88	3	29.8	73.1	2.9917	74.9	77.9
NT 87	4	10.9	66.0	3.9966	72.6	133.5
NT 86	3	2.9	69.3	2.9992	78.1	150.0
NT 85	3	14.3	66.6	2.9963	72.6	125.6
NT 84	3	359.1	47.4	2.9978	53.7	159.7
NT 83	3	6.9	50.0	2.9979	55.8	147.8
NT 82	3	290.4	80.3	2.9976	64.7	293.3
NT 80	3	1.7	72.3	2.9984	82.6	151.1
NT 75	3	7.6	71.7	2.9990	81.0	130.6
NT 68	3	14.0	68.3	2.9990	74.8	123.2
NT 67	4	355.9	51.1	3.9950	57.0	164.7
NT 66	3	2.1	68.2	2.9047	76.5	152.8
NT 65	3	315.9	62.6	2.9903	58.0	229.5
NT 64	3	22.8	65.3	2.9997	68.7	112.0
NT 63	3	191.9	86.9	2.9934	58.7	335.9
NT 62	3	357.3	57.7	2.9685	63.5	163.1
NT 60	3	358.0	65.7	2.9913	73.1	162.9
NT 58	3	60.0	71.3	2.9961	60.3	56.8
NT 57	3	28.7	46.2	2.9907	48.6	118.3
NT 56	3	55.3	75.2	2.9953	65.9	48.9
NT 55	3	358.0	82.2	2.9247	80.0	335.4
NT 52	3	10.1	82.0	2.9937	79.9	354.1
NT 51	3	13.6	76.1	2.9969	84.0	73.0
NT 50	3	359.3	59.6	2.9926	65.6	159.7
NT 49	4	328.4	62.4	3.9646	62.6	213.6
NT 48	3	340.0	75.4	2.9920	80.8	243.0
NT 46	4	45.1	59.9	3.5788	55.0	89.3
NT 38	3	150.8	-40.5	2.9943	-44.2	17.1
NT 31	3	131.7	-80.3	2.9970	-71.4	109.2
NT 28	3	198.9	-72.5	2.9863	-78.6	277.3
NT 26A	3	203.9	-79.3	2.9834	-79.7	211.5
NT 26	3	309.8	-82.3	2.7557	-53.3	178.0
NT 25	3	16.2	-82.0	2.9889	-49.4	151.7
NT 24	3	217.5	-77.9	2.9950	-74.7	224.1
NT 23	3	203.2	-54.2	2.8330	-56.9	302.0
NT 22	3	336.5	-80.4	2.9905	-47.0	169.2
NT 21	3	151.5	-65.5	2.9986	-67.1	34.0
NT 20	3	200.7	-68.4	2.9989	-73.1	289.4
NT 19	3	30.8	65.6	2.9975	66.4	99.3
NT 18	3	63.5	72.1	2.7374	59.7	52.4
NT 16	3	324.9	74.9	2.9868	74.1	253.2
NT 15	3	23.8	70.4	2.7490	74.4	97.8
NT 13	3	35.6	60.7	2.9875	59.4	99.8
NT 12	3	27.0	73.4	2.9963	76.3	79.5
NT 11	3	104.3	70.0	2.7351	42.0	28.5
NT 10	3	184.7	-61.4	2.8253	-67.6	329.2
NT 9	3	131.7	-58.3	2.9996	-52.2	49.3
NT 8	4	221.0	-69.4	3.9969	-66.4	258.4
NT 7	3	170.8	-56.1	2.9974	-61.4	353.8
NT 6	3	169.1	-70.6	2.9776	-78.7	12.2
NT 5	3	269.6	-78.0	2.9892	-56.5	203.4
NT 4	3	266.3	-76.5	2.9990	-55.8	208.7
NT 3	3	231.5	-77.3	2.9933	-69.0	222.3
NT 1	3	342.7	83.2	2.9955	77.0	320.7
NP 320	4	293.0	-75.7	3.9955	-46.9	196.1
NP 319	3	203.3	-80.0	2.9944	-79.5	204.2
NP 318	4	33.2	57.1	3.9894	56.7	106.4
NP 317	3	359.6	84.0	2.7031	76.6	338.0
NP 316	4	354.2	60.9	3.9970	66.9	169.5

Table 1 – *continued*

NO	N	D	I	R	θ'	φ'
NP 315	3	352.5	63.5	2.9872	69.8	174.0
NP 314	3	348.0	58.4	2.9990	63.4	179.6
NP 313	3	207.7	85.4	2.9997	56.4	330.7
NP 311	3	21.3	69.4	2.9966	74.1	105.7
NP 310A	3	4.6	70.6	2.9992	79.9	143.1
NP 310	4	7.2	59.6	3.9926	65.3	145.2
NP 309E	3	26.5	64.1	2.9995	66.2	108.2
NP 308	4	32.3	69.2	3.9930	69.8	89.2
NP 306	3	320.0	62.8	2.9964	59.9	225.1
NP 305E	3	32.2	74.9	2.9957	75.3	66.0
NP 304	3	358.7	53.1	2.9986	58.9	160.5
NP 303	3	336.7	69.4	2.9923	73.3	214.6
NP 302	4	19.1	74.8	3.9989	80.8	80.9
NP 301	4	19.1	72.5	3.9910	78.5	97.2
NP 300	4	348.2	73.8	3.9955	82.7	212.0
NP 299	3	15.5	49.4	2.9969	54.1	135.3
NP 298	3	8.0	68.5	2.9985	76.4	137.0
NP 297	3	5.3	64.2	2.9976	71.0	147.1
NP 296A	2	118.7	-29.3	1.9999	-26.2	48.6
NP 296	3	1.3	61.7	2.9992	68.0	155.9
NP 295A	3	192.0	-56.9	2.9857	-61.8	318.0
NP 295	2	302.9	-11.2	1.9956	8.1	216.0
NP 294A	3	310.5	-75.6	2.9924	-42.6	186.7
NP 294	3	197.0	-48.3	2.9918	-52.9	313.4
NP 293A	3	202.1	-80.5	2.9704	-79.5	199.2
NP 293	3	296.3	-81.7	2.9978	-54.7	184.0
NP 292A	3	182.3	-67.9	2.9995	-76.1	332.4
NP 292	3	158.4	-75.1	2.9837	-80.0	62.3
NP 291A	3	184.7	-66.2	2.9985	-73.6	327.5
NP 291	3	181.5	-67.9	2.9947	-76.2	334.4
NP 290A	3	272.3	-57.6	2.9632	-33.1	228.0
NP 290	3	152.8	-65.9	2.9914	-67.9	32.7
NP 289	3	165.3	-84.2	2.9996	-75.6	146.6
NP 288	3	213.4	-76.2	2.9484	-75.7	236.7
NP 287	3	170.1	-65.0	2.9984	-71.4	0.0
NP 286	3	147.0	-64.7	2.9758	-64.5	38.8
NP 285	3	138.4	-45.9	2.9997	-44.2	33.9
NP 284	3	131.3	-35.1	2.9987	-34.4	37.6
NP 283	3	183.7	-60.9	2.5990	-67.1	331.3
NP 282	3	120.2	-71.8	2.9934	-60.8	80.9
NP 281	3	177.8	-64.8	2.9994	-71.9	343.4
NP 280	3	153.9	-71.7	2.9993	-75.0	47.7
NP 279	4	171.7	-70.0	3.9994	-78.4	3.6
NP 278	4	184.5	-76.5	3.9922	-88.0	259.9
NP 277	3	140.6	-57.3	2.9997	-54.7	38.3
NP 276	3	196.1	-57.6	2.9784	-61.8	310.9
NP 274	3	201.8	-70.5	2.9500	-75.2	281.2
NP 273	3	164.2	-56.7	2.9994	-61.0	4.9
NP 272	3	139.7	-60.9	2.9973	-57.9	43.0
NP 271	4	175.5	-65.3	3.9580	-72.5	348.5
NP 270	4	169.3	-63.7	3.9958	-69.7	0.6
NP 269	3	131.6	-72.3	2.9944	-66.2	73.6
NP 268	3	179.9	-66.8	2.9975	-74.6	338.7
NP 267	3	202.4	-72.1	2.9942	-76.8	273.5
NP 266	3	193.1	-70.6	2.9493	-78.1	299.0
NP 265	3	186.9	-72.7	2.9980	-82.5	309.4
NP 264	3	187.4	-71.7	2.9930	-80.9	311.6
NP 263	3	22.8	-64.3	2.9979	-22.3	141.6
NP 262	3	132.7	-70.3	2.9992	-64.7	67.0
NP 261	3	164.3	-60.9	2.9993	-65.4	7.4
NP 260	3	188.2	-48.0	2.9995	-53.9	326.2
NP 259	3	141.3	-42.8	2.9710	-43.0	29.2
NP 258	3	197.2	-66.2	2.9959	-71.4	300.6
NP 257	3	209.5	-77.1	2.9965	-77.7	232.6
NP 256	3	160.0	-80.5	2.9975	-80.0	119.5
NP 255	3	167.4	-81.6	2.9961	-80.3	136.9
NP 254	3	163.7	-82.5	2.9992	-78.3	137.8
NP 253	3	144.0	-83.7	2.9954	-73.2	132.6
NP 252	3	147.2	-76.8	2.9995	-76.2	83.5
NP 250	3	145.0	-78.0	2.9919	-75.7	92.7
NP 248	3	147.5	-74.5	2.9968	-74.9	68.9
NP 247	3	159.3	-79.0	2.9970	-81.0	103.3
NP 246	3	190.4	-63.9	2.9919	-70.0	316.7
NP 245	3	201.8	-64.6	2.9850	-68.1	294.9
NP 244	3	186.2	-64.6	2.9674	-71.5	325.0
NP 242	3	210.7	-65.1	2.9986	-65.8	280.4
NP 241	3	148.5	-56.4	2.9844	-56.6	27.7
NP 240	3	163.8	-70.1	2.9987	-76.6	23.2

Table 1 – *continued*

NO	N	D	I	R	θ'	φ'
NP 239	3	226.2	-65.3	2.9926	-60.0	261.1
NP 234	3	217.4	-5.2	2.6979	-22.3	297.4
NP 233	3	216.6	45.7	2.9934	6.2	306.2
NP 232	3	219.3	7.6	2.3203*	-15.6	297.4
NP 231	3	353.5	55.8	2.5991*	61.2	169.4
NP 230	3	340.3	39.8	2.7187	45.9	185.0
NP 229	3	280.4	75.4	2.3941•	56.9	282.0
NP 223	3	313.4	41.7	2.9946	39.4	217.7
NP 221	3	299.8	35.1	2.9142	30.0	229.3
NP 220	3	314.2	58.1	2.6586	52.9	226.5
NP 217	3	277.3	67.9	2.9761	47.4	270.9
NP 214B	3	15.5	74.3	2.9929	81.8	91.3
NP 214A	3	19.2	72.2	2.9992	78.1	98.4
NP 213	3	15.1	68.9	2.9984	75.3	119.6
NP 212	3	2.6	71.7	2.9951	81.7	148.4
NP 211	3	32.2	58.6	2.9744	58.5	106.4
NP 210	3	26.3	60.3	2.9988	62.1	113.0
NP 209	3	338.8	60.3	2.9923	63.5	196.0
NP 208	3	261.1	10.2	2.9794	0.9	258.5
NP 207	3	359.1	62.0	2.9981	68.5	160.2
NP 206	3	27.5	20.2	2.8160	32.4	125.8
NP 204	3	1.9	65.6	2.9703	72.9	154.1
NP 203	3	313.7	80.3	2.9954	72.0	289.1
NP 202	3	250.0	83.4	2.9989	58.1	314.8
NP 201	3	15.8	46.4	2.9968	51.6	135.5
NP 199	3	315.6	84.7	2.9977	70.9	315.1
NP 198	3	0.8	53.5	2.9969	59.3	157.0
NP 197	3	330.5	51.9	2.9900	53.1	202.1
NP 195	3	335.2	54.8	2.9970	57.1	197.3
NP 194	3	333.7	53.8	2.9974	55.7	198.8
NP 191	3	305.4	76.6	2.9992	67.3	272.8
NP 190	3	65.2	77.0	2.9952	63.7	37.3
NP 189	3	32.0	76.3	2.9983	76.3	56.8
NP 188	3	246.9	24.3	2.9007	2.1	274.4
NP 187	3	289.4	55.0	2.9827	39.9	248.6
NP 186	3	168.6	-52.2	2.9989	-57.3	356.2
NP 185	3	203.9	-77.5	2.9976	-80.0	230.2
NP 184	3	204.5	-73.2	2.9941	-77.1	264.1
NP 183	3	222.1	-77.7	2.9750	-72.8	224.0
NP 182	3	133.9	-74.7	2.9999	-69.3	80.3
NP 181	3	219.6	-62.7	2.9976	-60.0	272.3
NP 179	3	191.0	-62.6	2.9997	-68.3	316.5
NP 178	3	165.2	-62.2	2.8915	-67.1	6.9
NP 177A	3	152.1	-75.6	2.9939	-77.6	72.0
NP 177	3	198.9	-69.2	2.9886	-74.7	290.4
NP 176	3	156.0	-46.5	2.9767	-50.0	12.3
NP 175	3	221.9	-78.7	2.6582	-73.3	218.1
NP 174	3	126.6	-74.1	2.9710	-65.7	82.8
NP 173	3	210.7	-63.6	2.9879	-64.2	282.6
NP 172	3	186.8	-65.2	2.9854	-72.2	323.2
NP 171A	3	73.2	77.2	2.9774	60.9	33.2
NP 171	4	66.0	40.1	3.9865	30.7	79.9
NP 170A	3	15.1	66.9	2.9778	72.8	123.5
NP 170	4	299.7	60.2	3.9849	49.0	243.4
NP 169A	3	295.5	56.1	2.9796	43.4	243.8
NP 169	3	339.6	57.1	2.9976	60.4	192.3
NP 168A	3	332.0	61.5	2.9991	62.8	207.5
NP 168	4	345.7	64.5	3.9959	70.0	188.2
NP 167	4	7.8	72.9	3.9920	82.6	124.7
NP 166A	3	25.9	67.1	2.9997	69.7	103.7
NP 166	4	348.0	71.6	3.9833	79.8	189.8
NP 165A	3	236.6	-72.4	2.9991	-62.9	236.4
NP 165	4	228.7	-71.6	3.9671	-65.3	245.1
NP 164A	3	290.3	-65.9	2.9776	-35.1	208.2
NP 164	4	126.6	-79.7	3.9955	-69.6	106.8
NP 163	4	230.2	-83.6	3.9752	-70.4	188.4
NP 162	3	197.7	-68.1	2.9920	-73.6	295.8
NP 161	4	223.1	-62.3	3.9964	-58.2	268.6
NP 160	4	227.7	-70.7	3.9992	-64.9	248.5
NP 159	4	192.5	-56.8	3.9975	-61.7	317.0
NP 158	4	188.8	-61.6	3.9949	-67.5	321.3
NP 157	4	240.7	-75.4	3.8680	-64.0	224.8
NP 156	4	346.2	60.3	3.9535	65.2	183.7
NP 155	3	316.3	73.2	2.9916	69.0	252.9
NP 154	3	11.9	70.9	2.9910	78.9	120.9
NP 153	3	359.0	73.5	2.9991	84.6	163.6
NP 152	3	302.2	68.9	2.9924	58.7	253.1

Table 1 – *continued*

NO	N	D	I	R	θ'	φ'
NP 151	3	346.2	74.1	2.9918	82.2	219.2
NP 150	3	337.4	71.2	2.9993	75.7	219.8
NP 149	3	336.4	61.7	2.9989	64.4	201.0
NP 148	3	2.0	63.5	2.9976	70.3	154.1
NP 147	3	45.8	76.5	2.9771	70.8	48.5
NP 146	3	18.3	68.4	2.9983	73.9	113.9
NP 145	3	325.0	69.1	2.9884	68.5	230.6
NP 144A	3	332.0	72.9	2.7934	75.4	235.7
NP 144	3	351.5	50.0	2.7544	55.6	171.2
NP 143	3	8.0	67.7	2.9939	75.3	138.0
NP 142	3	316.3	69.7	2.9821	65.6	242.0
NP 141	3	199.7	-69.9	2.9986	-75.3	286.7
NP 140	3	194.5	-78.0	2.9979	-83.7	221.3
NP 139	3	191.8	-66.2	2.9886	-72.7	311.3
NP 138	3	144.6	-78.4	2.9989	-75.6	95.8
NP 137	3	192.6	-57.7	2.9905	-62.5	316.5
NP 136	3	154.5	-62.8	2.7308	-65.0	25.3
NP 135	3	147.5	-70.3	2.9881	-70.9	51.2
NP 134	3	92.8	-66.4	2.7927	-44.0	92.3
NP 133	3	213.1	-60.0	2.9620	-59.5	283.7
NP 132	4	192.3	-66.7	3.9991	-73.2	309.5
NP 131	4	188.5	-68.5	3.9963	-76.3	315.5
NP 130	3	83.5	-82.6	2.9164	-59.7	128.7
NP 129	4	171.5	-77.9	3.8645	-86.0	101.4
NP 128	4	176.5	-75.4	3.9242	-87.2	14.0
NP 127	3	179.0	-74.4	2.9993	-86.0	345.3
NP 126	4	162.5	-70.7	3.9921	-76.9	28.0
NP 125	4	216.9	-67.8	3.9791	-66.4	266.9
NP 124	3	232.7	-53.2	2.9785	-45.9	266.6
NP 123	3	178.4	-53.5	2.9730	-59.3	340.9
NP 122	3	208.8	-70.3	2.8851	-72.3	270.7
NP 121	3	157.8	-60.3	2.9975	-63.3	17.5
NP 120	3	252.2	-77.2	2.9873	-61.4	213.4
NP 119	3	178.3	-75.7	2.9548	-88.1	3.0
NP 118	3	206.1	-66.6	2.9898	-69.1	284.3
NP 117	3	204.2	-82.3	2.9616	-77.0	186.6
NP 116	3	194.2	-66.4	2.9973	-72.4	305.9
NP 115	3	190.9	-66.8	2.9986	-73.5	312.5
NP 113	3	156.8	-56.8	2.9897	-59.4	16.2
NP 112	3	190.0	-71.5	2.9945	-80.2	303.8
NP 111	4	208.0	-57.7	3.9707	-58.9	292.7
NP 110	3	167.6	-52.2	2.9750	-57.1	357.7
NP 109	3	177.6	-67.5	2.9752	-75.6	344.5
NP 108B	3	177.5	-68.0	2.9998	-76.3	345.0
NP 107	3	132.0	-69.0	2.9483	-63.0	64.5
NP 106	3	194.8	-65.3	2.9954	-70.9	306.5
NP 105	3	312.5	29.5	2.9185	31.6	214.6
NP 104	3	75.4	74.4	2.9720	57.4	39.2
NP 103A	3	207.9	27.2	2.9708	-8.0	311.0
NP 103	4	186.3	-41.6	3.6143	-49.0	329.6
NP 102	3	204.8	-62.5	2.7007	-64.9	292.8
NP 101	4	55.8	-72.2	3.8975	-39.2	123.1
NP 100	3	126.4	-41.7	2.4910*	-36.8	45.0
NP 99	4	92.6	-55.4	3.9488	-33.1	83.4
NP 98	4	162.7	-66.5	3.9901	-71.7	16.8
NP 97	4	61.2	59.7	3.9848	48.1	73.0
NP 96	4	359.3	48.1	3.9992	54.4	159.4
NP 95	4	358.9	56.2	3.9744	62.0	160.2
NP 94	4	13.5	56.7	3.9931	61.3	135.6
NP 93	4	29.0	56.3	3.9951	57.2	112.6
NP 92	4	358.5	54.2	3.9933	60.0	160.8
NP 91	4	28.8	57.0	3.9990	58.0	112.3
NP 90	4	6.6	60.8	3.9550	66.8	145.9
NP 89	4	5.3	84.5	3.8333	75.6	342.3
NP 88	4	306.6	61.5	3.9688	53.1	237.9
NP 87	3	318.9	72.1	2.9991	69.1	246.3
NP 86	4	41.8	51.5	3.9732	48.6	99.8
NP 85B	4	26.0	57.4	3.6248	59.2	116.0
NP 85A	4	32.5	67.3	3.9639	67.6	93.6
NP 84C	3	19.9	70.9	2.9997	76.4	102.8
NP 84B	3	100.0	60.2	2.1611*	32.7	40.1
NP 84A	3	335.6	81.4	2.9995	78.0	303.4
NP 83	3	61.6	88.5	2.9297	66.1	344.9
NP 81	3	289.2	63.2	2.9965	47.4	255.8
NP 80	3	213.2	17.0	2.9896	-12.5	304.7
NP 79	3	251.7	26.8	2.9988	5.2	270.8
NP 78	3	279.1	36.9	2.2040*	22.4	249.3

Table 1 – *continued*

NO	N	D	I	R	θ'	φ'
NP 77	3	239.4	52.4	2.8571	18.1	288.9
NP 76	3	196.2	-9.1	2.2149*	-28.7	319.8
NP 75	3	238.2	35.5	2.2931*	5.3	284.8
NP 74	3	199.6	44.1	2.6773	1.9	320.8
NP 73	3	182.7	-38.1	2.9503	-46.6	334.7
NP 72	3	189.0	-42.1	2.9798	-49.1	325.7
NP 71	3	214.9	-53.2	2.9956	-52.5	287.0
NP 70	3	240.4	-73.0	2.9997	-61.8	232.3
NP 69	3	173.5	-66.0	2.9996	-73.2	353.3
NP 68	3	168.8	-63.3	2.9979	-69.2	1.2
NP 67	3	181.8	-77.2	2.9970	-88.9	198.1
NP 66	3	176.9	-64.3	2.9910	-71.3	345.0
NP 65	3	198.2	-57.5	2.9979	-61.3	307.5
NP 64	3	157.2	-65.4	2.9922	-68.8	24.7
NP 63	3	70.2	-65.2	2.9830	-34.5	107.6
NP 62	3	189.3	-58.6	2.9989	-64.0	321.7
NP 59	3	188.9	-60.7	2.9714	-66.4	321.5
NP 58	3	207.2	-61.9	2.9997	-63.5	290.0
NP 57	3	201.2	-65.5	2.9993	-69.4	294.5
NP 55A	3	179.1	-47.8	2.9679	-54.1	339.7
NP 55	3	191.7	-42.2	2.9616	-48.9	322.0
NP 54B	3	192.6	-52.2	2.9916	-57.1	318.6
NP 54A	3	172.2	-60.5	2.9886	-66.3	353.0
NP 54	4	202.4	-74.2	3.9086	-78.9	260.8
NP 53	2	192.4	-73.3	2.0000	-81.9	287.0
NP 52	3	179.8	-73.8	2.9968	-85.1	339.6
NP 51	3	168.9	-59.9	2.8856	-65.2	358.6
NP 50	3	122.9	-63.4	2.9893	-53.4	63.8
NP 49	3	205.2	-66.3	2.9968	-69.1	286.5
NP 48	3	219.1	-48.1	2.9992	-46.8	284.7
NP 47	3	69.7	69.0	2.9966	53.8	53.9
NP 46	3	109.4	-4.1	2.8981	-10.0	51.5
NP 45	3	12.5	-52.6	2.0304*	-8.5	147.8
NP 44A	3	177.6	-44.3	2.9961	-51.2	341.8
NP 44	3	166.9	-41.6	2.9688	-48.3	356.5
NP 43	3	154.2	-55.8	2.9883	-57.7	19.3
NP 42	3	207.7	-87.2	2.8693	-69.6	165.9
NP 41	3	292.5	-12.6	2.9971	3.5	225.2
NP 40	3	240.9	-80.2	2.9949	-67.3	205.9
NP 39	3	189.6	-77.1	2.8443	-85.9	235.3
NP 38	3	191.8	-69.4	2.9948	-76.9	305.6
NP 37	3	175.1	-73.5	2.9980	-84.1	3.6
NP 36	3	231.7	-76.9	2.9352	-68.6	224.0
NP 35	3	235.1	-56.4	2.8240	-47.6	261.9
NP 34	3	124.8	-51.0	2.9931	-43.0	51.2
NP 33	3	346.2	-15.0	2.9921	16.9	172.6
NP 32	3	27.2	58.9	2.9638	60.4	113.0
NP 31	3	327.3	74.6	2.9956	74.9	249.9
NP 30	3	285.8	81.9	2.9702	64.4	300.7
NP 29	3	313.1	65.2	2.9988	59.5	236.2
NP 28	3	100.1	79.5	2.9806	55.3	15.3
NP 27	3	175.4	56.5	2.9046	11.9	342.1
NP 26	3	45.8	65.9	2.9978	60.7	80.5
NP 25	3	31.2	74.0	2.9958	75.0	71.8
NP 24	3	345.7	67.4	2.9968	73.6	192.4
NP 23	3	346.0	65.6	2.9979	71.5	189.1
NP 22	3	18.7	56.1	2.9993	59.8	127.5
NP 20	3	345.7	54.2	2.9872	58.7	181.3
NP 18	3	329.9	67.9	2.9423	69.2	221.2
NP 17	3	358.3	57.0	2.9194	62.8	161.3
NP 16	3	332.0	70.5	2.9118	72.9	225.6
NP 15	3	307.9	68.2	2.9640	60.4	246.6
NP 13	3	90.4	-65.2	2.8900	-41.8	92.8
NP 12	4	70.9	79.5	3.9104	63.7	26.4
NP 11	4	152.5	-87.4	3.8462	-69.2	151.5
NP 10	3	125.1	57.1	2.6603	21.1	22.2
NP 9	4	80.7	-67.6	3.9363	-40.9	102.2
NP 8	4	21.7	72.4	3.9535	77.4	93.0
NP 7	4	18.1	79.1	3.9980	81.8	30.1
NP 6	3	59.4	-28.6	2.9255	-1.7	102.2
NP 5	3	104.9	-71.0	2.8918	-53.8	90.0
NP 4	4	194.4	-63.4	3.9811	-68.6	309.5
NP 3	4	213.9	-59.0	3.9639	-58.3	283.6
NP 2	4	200.9	-48.9	3.9930	-52.7	307.6
NP 1	4	158.5	-57.2	3.9954	-60.2	14.0

ambient geomagnetic field is the dominant source of the direction of remanent magnetism, since no feasible means exist to produce systematic magnetic overprints or spurious results on a series of lavas with variable high-temperature oxidation states, which can be inferred from the stability variation (Watkins & Haggerty 1967).

5.2 EXTRUSION RATE

McDougall *et al.* (1977) have demonstrated that the section accumulated at an unusually regular rate for the 5-Myr period involved (Fig. 1). The following linear regression equation was obtained relating age (T) in Myr to lava number (N) above the section base

$$T = 6.496 - (0.013269)N. \tag{1}$$

The equation is linear at the 99 per cent confidence level.

5.3 PROBLEMS IN ANALYSIS OF PALAEOSECULAR VARIATION

As discussed by McElhinny & Merrill (1975), a long-standing difficulty in the application of conventional statistical techniques to palaeosecular variation studies involves the problem of whether or not the data are serially correlated. The data employed should ideally be drawn from a random population. Watson & Beran (1967) have produced a method for the detection of serially correlated results: a comparison is made of the sum of the cosines of the angles between directions from successive lavas with sums resulting from random combinations of the same data. The amount by which the former exceeds the latter sum is a measure of the amount of serial correlation. McElhinny & Merrill (1975) have argued that the data from a sequence of lava flows may appear to be serially correlated because a long-period change in secular variation exists, from which they conclude that application of the Watson & Beran (1967) technique may be counter-productive in terms of searching for palaeomagnetic information on secular variation. In this paper we therefore do not consider the serial correlation problem.

A second difficulty in secular variation analysis of palaeomagnetic data concerns the rejection of results which may represent anomalous geomagnetic field behaviour, such as

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Footnotes to Table 1:

NO = Stratigraphic number. These are in stratigraphic order (youngest lava at top; oldest at base), and correspond exactly to the numbers in the detailed stratigraphic sketches of the two groups of sections (NP and NT) given in McDougall *et al.* (1977).
N = Number of separate specimens.
D = Mean declination of remanent magnetism, in degrees of east of north.
I = Mean inclination of remanent magnetism in degrees with respect to the horizontal (+ = down; − = up).
R = Resultant vector, applying unit vector per specimen.
θ' and ϕ' = Latitude and longitude of virtual geomagnetic pole, in degrees north (+) or south (−), and in degrees east of Greenwich, respectively.
• = Statistically random at the 95 per cent confidence level (Vincenz & Bruckshaw 1960).

Notes:

(i) These are the entire data set for the Borgarfjördur collection.
(ii) Because there was overlap between some of the 18 separate sections involved, 25 of the data represent repeated sampling of the same lava, and these are excluded in the compilation of Fig. 1 and the computations shown in Tables 2–4, and Figs 2–5. See McDougall *et al.* (1977) for the finely detailed stratigraphic sketches and between-section correlations.
(iii) All data result from demagnetization at 100 and 200 Oe, and application of the minimum-scatter computational method (Watkins & Richardson 1968).

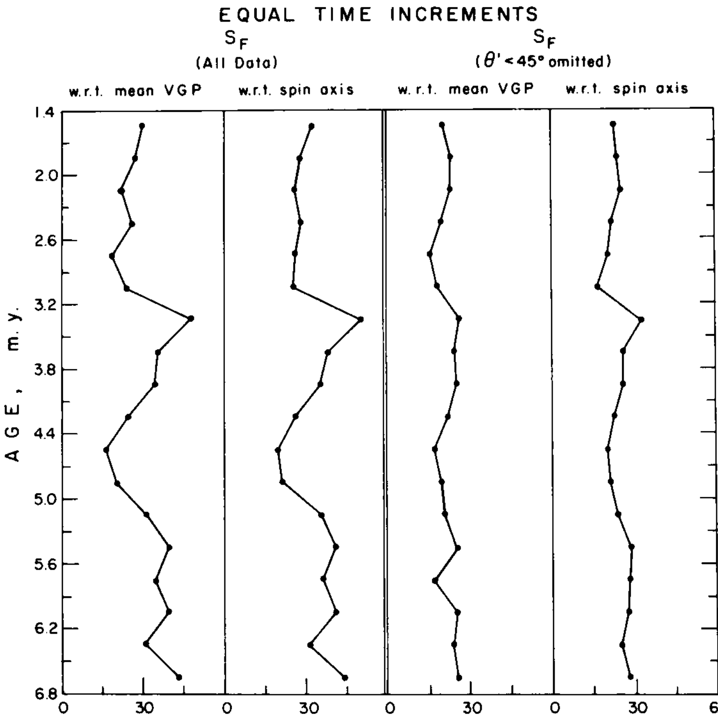

Figure 2. Variation of S_F (corrected angular standard deviation of the VGP (virtual geomagnetic poles)) for lava increments of 0.3 Myr duration, as a function of age in the Borgarfjördur region. S_F is shown in degrees for all data (left two columns), and for groups excluding data from lavas with VGP latitudes less than 45° (right two columns). Each column pair shows S_F computed with respect to the mean VGP (left) and with respect to the present geographic pole (right). Selection of the number of lavas within the 0.3-Myr age range is made using the linear regression equation between age (T) in Myr and height (H) above the base of the section in metres: the equation is $T = 6.7309 - (0.001405)H$.

transitions between opposite polarities, or excursions of the geomagnetic field. As summarized by McElhinny & Merrill (1975), various authors have employed data cutoffs based on VGP latitudes ranging from 40 to 45°, below which the results are assumed to represent anomalous behaviour. In certain cases, especially when data volumes are limited, the cutoff choice can drastically affect computed S_F values. In this paper we shall present results for analyses without any such data rejection, and also for data rejection when VGP latitudes are less than 45°. Our presentation of the complete set of results (Fig. 1) allows other cutoffs to be applied.

A third decision which is necessary in computation of S_F is selection of the reference pole used to compute the total angular standard deviation (S_T) of the measured VGP's. This may be the mean VGP for the data set. Alternatively, since little evidence exists to suggest that the Earth's geographic pole position has changed significantly since the Upper Miocene, the reference pole for the data can as well be the present geographic pole. In Fig. 2 we show a comparison of the results using the different computational procedures, for groups of equal time increments compiled using equation (1). While it is clear that, as may be expected, rejection of data for lavas with VGP latitudes less than 45° alters both the magnitude and variation of S_F, the selection of the reference pole has very little effect in this particular set of results. Throughout our analyses we have chosen to use the mean VGP as the reference pole for each data set, in computation of S_F.

5.4 PALAEOSECULAR VARIATION

The palaeomagnetic data for the Borgarfjördur area (Fig. 1) are unique, in that the lava extrusion rate is known for the period $t = 6.7$ to 1.6 Myr. The data can therefore be analysed in successive groups representing (a) equal laval numbers, (b) equal lava thickness increments and (c) equal time increments. In this way, it should be possible to distinguish between actual average geomagnetic field behaviour for selected time intervals, and results which because of a rapid rate of lava extrusion represent only a very short period. Although the results (Fig. 1) certainly show a linear extrusion rate over the period involved, the possibility of rapid extrusion rates over much shorter periods cannot be totally excluded.

5.4.1 *Equal lava numbers*

An increment of 20 lavas was selected for each group, because this is the number which Wilson & McElhinny (1974) propose as being the minimum necessary to provide a measure of the axial dipole field behaviour. Starting at the top of the section, 17 successive groups of 20 sampled lavas are available. The lowest group provides the remaining 11 lavas. The results of statistical analyses of the 18 successive groups are given in Table 2. Unlike the Wilson & McElhinny analytical method, we have rejected data from an average of between 1 and 2 lavas per group, because of an unacceptably high scatter of directions within the lavas. The results are illustrated in Fig. 3.

Inspection of Fig. 3 and Table 2 provides several conclusions. When no data are excluded the mean declination tends to swing about geographic north ($D = 360°$) with westerly declinations being stratigraphically grouped between NP12 and 58, and NP211 and 270. Some periodicity may therefore be present. When the results from lavas with VGP latitudes less than 45° are excluded (lower half of Table 2) there is a strong tendency for less variable declinations to result (compare solid line with dotted line in declination data of Fig. 3), suggesting that non-dipole components (which can be expected to dominate when lower latitude VGP's exist) may be the source of much of the measured declination variation.

The mean inclination (I) is in *all* cases shallower than that required for the axial dipole field configuration. An apparently systematic increase of I towards axial dipole values occurs between 260 and 300 lavas above the base, but the axial dipole value is nevertheless not exceeded. Values of I are therefore consistent with offset to the north of the axial dipole throughout the whole period. Wilson & McElhinny's (1974) interpretation of Eastern Iceland data therefore requires modification: it would on first inspection appear that any period during which the mean I increased to yield 'near-side' rather than 'far-side' VGP's must lie outside the period $t = 7$ to 2 Myr. But since McDougall *et al.* (1976) have now shown that the hiatus in volcanic activity in Eastern Iceland between $t = 7$ and 4 Myr employed for different reasons by both Wilson & McElhinny (1974) and Saemundsson (1974) does not exist, and that section Q of Dagley *et al.* (1967) in fact ranges in time from about $t = 6.5$ to 4.0 Myr, an enigma is evident, particularly since McDougall *et al.* (1976) have confirmed the 'near-sided' nature of the mean VGP for the younger sections of the Eastern Iceland sequence. As those Eastern Iceland sections which constitute the younger (steeper I) group of Wilson & McElhinny (1974) certainly lie within the period represented in Fig. 3, a further substantial modification of their interpretations may therefore be required. A subjective varying of the grouping of the data can yield higher I values, but the subjectivity employed is not acceptable, and in any case the higher I values cannot be maintained between groups. To explain the conflicting result of mean I being $> 76°$ in Eastern Iceland but $< 76°$ in Western Iceland would require tectonic arguments of impressive scale:

Table 2. Statistical analysis of palaeomagnetic data for the Borgarfjördur sequence, Western Iceland, for equal increments of 20 successive lavas.

EQUAL LAVA NUMBER INCREMENTS (n=20)

(i) All Units

Group	Range	No.	D°	I°	R	K	ϕ'	θ'	S_F	K_w	S_u	S_i
1	NT112-NT87	20	39.7	63.5	18.07169	9.9	91.3	60.7	33.8	35.5	43.0	27.9
2	NT86-NT52	20	6.4	69.0	19.32765	28.3	140.6	77.3	22.1	60.4	28.1	18.2
3	NT51-NT15	20	10.0	74.3	18.89514	17.2	106.0	83.9	27.3	17.7	34.7	22.5
4	NT13-NP313	20	16.1	74.9	19.18968	23.4	84.3	82.1	26.0	22.8	33.1	21.4
5	NP311-NP291	20	1.5	66.5	18.55472	13.1	154.8	74.2	25.7	207.0	32.8	21.2
6	NP290-NP270	20	341.1	66.2	19.36929	30.1	199.4	70.9	19.0	33.9	24.2	15.7
7	NP269-NP248	20	346.4	74.4	19.28023	26.4	222.5	82.7	24.2	121.3	30.8	20.0
8	NP247-NP211	20	350.3	67.1	17.79131	8.6	182.0	74.2	35.4	26.6	45.1	29.2
9	NP210-NP186	20	336.4	66.6	17.33974	7.1	208.2	69.9	38.5	89.6	49.0	31.7
10	NP185-NP165	20	5.6	70.3	19.16953	22.9	140.7	79.3	23.8	29.3	30.2	19.6
11	NP164-NP145	20	1.8	72.2	19.53346	40.7	151.2	82.5	20.3	60.5	25.8	16.7
12	NP144-NP125	20	355.8	71.8	19.49655	37.7	174.5	81.6	18.3	17.2	23.3	15.1
13	NP124-NP104	20	3.4	67.7	19.09659	21.0	149.7	75.8	23.7	36.9	30.2	19.6
14	NP103A-NP84A	20	9.8	63.3	18.02455	9.6	138.5	69.3	29.9	25.4	38.1	24.6
15	NP83-NP58	20	350.7	70.2	16.50751	5.4	186.7	78.5	45.6	45.4	58.1	37.6
16	NP57-NP35	20	355.7	66.9	17.24660	6.9	169.0	74.5	35.0	20.7	44.5	28.8
17	NP34-NP12	20	344.9	71.2	17.88519	9.0	204.7	78.3	35.1	25.9	44.7	29.0
18	NP11-NP1	11	346.5	79.3	9.63674	7.3	294.8	83.1	43.6	17.5	60.7	34.1
All	NP1-NT112		2.0	69.5	306.02930	13.2	151.9	78.4				

(ii) Excluding Units with θ' <45°

Group	Range	No.	N_{RJ}	D°	I°	R	K	ϕ'	θ'	S_F	K_w	S_u	S_i
1	NT112-NT87	13	7	4.5	68.0	12.71850	42.6	146.7	76.1	18.1	32.1	24.5	14.4
2	NT86-NT52	20		6.4	69.0	19.32765	28.3	140.6	77.3	22.1	60.4	28.1	17.3
3	NT51-NT15	18	2	7.4	76.6	17.44698	30.7	69.9	86.8	22.6	16.1	29.2	18.4
4	NT13-NP313	19	1	12.2	74.2	18.28450	25.2	100.9	82.9	25.4	32.6	32.5	20.8
5	NP311-NP291	19	1	8.4	68.0	18.55672	40.6	136.7	75.7	18.9	204.3	24.3	15.6
6	NP290-NP270	18	2	347.0	68.4	17.66803	51.2	191.5	75.2	16.0	30.9	20.7	13.1
7	NP269-NP248	18	2	353.1	73.9	17.68260	53.6	195.8	84.3	16.7	118.2	21.7	13.7
8	NP247-NP211	16	4	359.0	68.4	15.42475	26.1	161.3	76.8	22.2	24.2	29.2	17.9
9	NP210-NP186	16	4	351.8	67.5	15.32316	22.2	179.0	74.9	25.8	181.1	34.0	20.9
10	NP185-NP165	19	1	359.3	70.7	18.44817	32.6	160.7	80.1	20.6	27.7	26.3	16.9
11	NP164-NP145	20		1.8	72.2	19.53346	40.7	151.2	82.5	20.3	60.5	25.8	16.7
12	NP144-NP125	19	1	359.5	71.0	18.61693	47.0	160.1	80.6	15.9	19.7	20.4	13.1
13	NP124-NP104	19	1	9.1	68.7	18.44765	32.6	134.0	76.4	20.5	36.0	26.3	16.9
14	NP103A-NP84A	18	2	12.0	65.0	17.36024	26.6	132.4	71.1	22.2	23.9	28.7	18.1
15	NP83-NP58	15	5	5.4	64.6	14.36371	22.0	146.7	71.5	24.4	69.7	32.4	19.6
16	NP57-NP35	18	2	12.4	68.8	17.16460	20.3	125.6	75.9	23.9	19.1	30.9	19.5
17	NP34-NP12	16	4	355.5	71.8	15.44499	27.0	175.4	81.6	24.3	28.4	32.0	19.7
18	NP11-NP1	8	3	6.0	70.4	7.67127	21.3	139.5	79.3	26.3	24.9	38.8	19.9
All	NP1-NT112			2.8	70.1	281.94043	32.0	148.8	79.4				

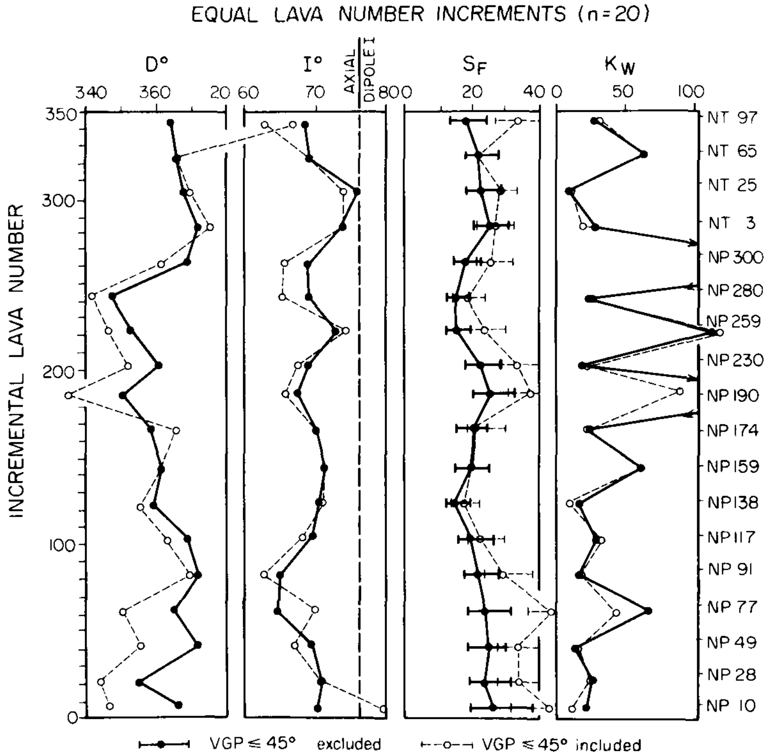

Figure 3. Palaeomagnetic results for the Borgarfjördur region of Western Iceland for successive groups of 20 lavas. The increments were chosen at 20 lavas for comparison with other published results (see text). D and I = mean declination and inclination of remanent magnetism in degrees east of north and below the horizontal, respectively; S_F = angular standard deviation of virtual geomagnetic poles (VGP's) computed with respect to the mean virtual geomagnetic pole for each group; 95 per cent confidence intervals (Cox 1969) added; K_W = within-lava precision parameter. For plot of each parameter, solid line = data for units with VGP latitudes $\leqslant 45°$ excluded; dashed line = all data included. See Table 1 for original data, and Table 2 for computations used to construct this diagram, and for details of data rejected.

Footnotes to Table 2:

Group = Number of data group under specific increment.

Range = Stratigraphic range of increment.

No. = Number of separate lavas in the increment.

N_{RJ} = Number of lavas rejected: refers to lavas with virtual geomagnetic pole latitudes lower than 45°. Lavas with poorly defined directions (see Table 1) are excluded from all computations.

D, I, R, ϕ' and θ' = See caption to Table 1.

K = No. − 1/No. − R.

S_F = Corrected angular standard deviation of VGP, applying unit pole per lava. See Ellwood *et al.* (1973) for details of computational method.

K_W = Within-lava precision parameter.

S_u and S_l = Upper and lower 95 per cent confidence parameters for S_F (Cox 1969).

All data for lavas with southern hemisphere VGP latitudes are transposed to northern hemisphere.

while these cannot be totally excluded, they appear highly unlikely, and we therefore propose that the answer must lie elsewhere. We are presently investigating the possibility that both J and I may be affected by mild burial metamorphism, which Watkins & Walker (1977) show is both present and variable in the Eastern Iceland sequence. They show that there is certainly a relationship between mean J and degree of zeolitization (corresponding to degree of burial metamorphism), so that it becomes unnecessary to postulate a significant change in magma source to explain the change in J in the Eastern Iceland sections which is Wilson & McElhinny's (1974) preferred interpretation. It is not yet clear if a corresponding distortion of I would occur, but it would seem unlikely, since no evidence exists to show that mild burial metamorphism selectively diminishes the vertical component of remanent magnetism, to yield lower values of I.

Although a slight possible 2.5-Myr periodic variation of S_F appears apparent in Fig. 3 (S_F; solid line), when the 95 per cent confidence limits are considered, the apparent variation cannot be considered definite.

A comparison of the two curves of S_F in Fig. 3 (representing zero exclusion and exclusion of data from lavas with VGP latitudes less than 45°, respectively) gives the strong impression that periods of systematically higher S_F have occurred: the increasing discrepancy between the two computations (as indicated by the gap between the curves) is systematic, and exceeds the respective 95 per cent confidence values of S_F. If real, this could mean the existence of a previously undetected fundamental geomagnetic field behaviour, in which the field moved with greater vigour during certain periods. Although demonstrated for parts

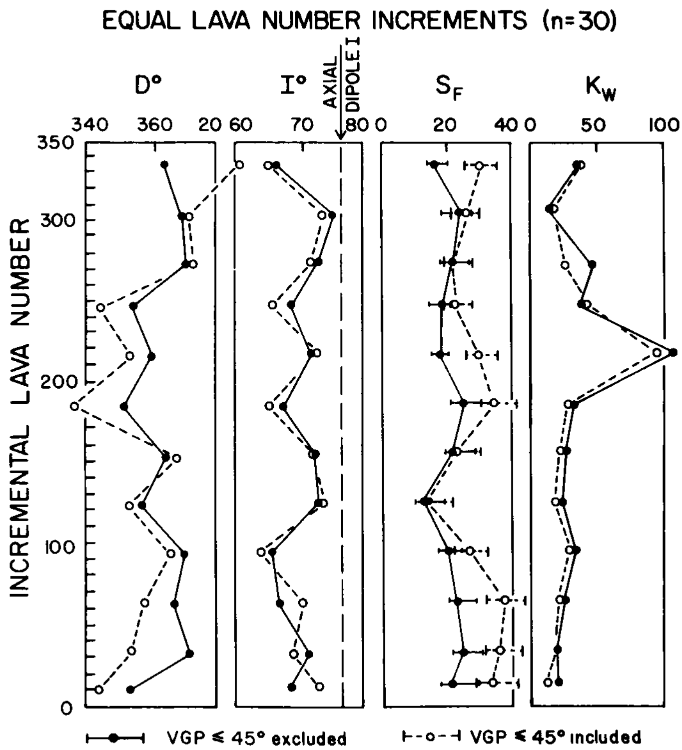

Figure 4. Palaeomagnetic results for the Borgarfjördur region of Western Iceland for successive groups of 30 lavas. See Fig. 2 and Table 3 for explanation of the table. The interval of 30 successive lavas was chosen in order to examine the possibility that groups of 20 successive lavas (Fig. 3) would not yield sufficient information.

Table 3. Statistical analysis of palaeomagnetic data for the Borgarfjördur sequence, Western Iceland, for equal increments of 30 successive lavas.

(i) All Units

Group	Range	No.	D	I	R	K	ϕ'	θ'	S_F	K_W	S_u	S_i
1	NT112-NT66	30	27.2	65.2	27.59317	12.0	105.4	67.2	30.8	43.5	36.9	26.4
2	NT65-NT15	30	11.0	73.8	28.49655	19.3	108.0	82.9	26.2	22.2	31.4	22.5
3	NT13-NP301	30	12.4	72.8	28.96036	27.9	110.5	81.3	23.9	33.4	28.7	20.5
4	NP300-NP270	30	345.6	65.5	28.11497	15.4	189.8	71.2	24.0	45.6	28.7	20.6
5	NP269-NP233	30	355.3	73.0	27.88023	13.7	180.3	83.3	30.3	96.4	36.3	26.0
6	NP230-NP186	30	336.0	65.6	26.58807	8.5	207.2	68.7	35.1	36.3	42.1	30.2
7	NP185-NP155	30	8.2	70.9	28.87918	25.9	131.4	79.8	23.1	33.8	27.7	19.9
8	NP154-NP125	30	353.9	71.8	29.34714	44.4	181.3	81.3	17.4	23.1	20.8	14.9
9	NP124-NP92	30	5.5	64.2	27.49782	11.6	146.6	71.0	27.9	38.8	33.4	23.9
10	NP91-NP58	30	358.3	70.3	26.08379	7.4	163.8	79.5	39.5	28.1	47.4	33.9
11	NP57-NP25	30	354.0	69.2	25.45131	6.4	175.5	77.6	38.2	25.4	45.7	32.8
12	NP24-NP1	21	343.7	74.0	19.21027	11.2	224.7	81.3	35.5	17.7	44.9	29.3

(ii) Excluding Units with Θ' <45°

Group	Range	No.	N_{RJ}	D	I	R	K	ϕ'	θ'	S_F	K_W	S_u	S_i
1	NT112-NT66	23	7	3.3	66.8	22.48495	42.7	150.4	74.6	17.2	42.9	21.5	14.3
2	NT65-NT15	28	2	9.6	75.2	27.03505	28.0	95.5	85.0	23.3	20.9	28.1	19.9
3	NT13-NP301	29	1	10.1	72.2	28.06963	30.1	120.5	81.1	23.2	47.5	27.9	19.8
4	NP300-NP270	27	3	354.1	68.3	26.35588	40.4	174.2	76.3	18.5	42.1	23.3	15.7
5	NP269-NP233	26	4	358.2	72.3	25.47391	47.5	165.9	82.6	18.0	105.6	21.8	15.3
6	NP230-NP186	24	6	351.4	67.7	22.93376	21.6	180.1	75.2	25.1	36.5	31.2	21.0
7	NP185-NP155	29	1	4.1	71.3	28.14517	32.8	144.0	80.8	21.2	32.7	25.5	18.2
8	NP154-NP125	29	1	356.4	71.3	28.46127	52.0	171.5	80.9	15.9	26.6	19.1	13.6
9	NP124-NP92	27	3	10.5	65.9	26.18074	31.7	134.6	72.5	20.4	37.0	24.7	17.4
10	NP91-NP58	25	5	7.4	66.6	23.95987	23.1	140.7	73.9	23.7	29.5	28.9	20.1
11	NP57-NP25	25	5	12.0	71.1	23.86409	21.1	120.0	79.1	25.1	23.2	30.5	21.3
12	NP24-NP1	17	4	356.4	68.9	16.41502	27.4	168.7	77.5	22.7	23.0	29.6	18.4

See Table 2 for explanation of the above.

Table 4. Statistical analysis of palaeomagnetic data for the Borgarfjördur sequence, Western Iceland, for increments of equal height or thickness.

EQUAL HEIGHT INCREMENTS (h=200 meters)

(i) All Units

Group	N	Height (m)	Range	D°	I°	R	K	ϕ'	Θ'	S_F	K_W	S_U	S_i
1	7	3600-3400	NT112-NT100	25.8	63.8	6.00923	6.1	109.8	66.0	45.3	45.9	69.0	33.8
2	21	3400-3200	NT99A-NT68	31.1	65.8	19.67937	15.1	98.6	66.5	26.8	47.4	33.9	22.2
3	18	3200-3000	NT67-NT46	9.9	70.2	17.12267	19.4	128.7	78.4	25.7	48.7	33.2	20.9
4	20	3000-2800	NT38-NT8	13.2	75.1	19.03096	19.6	88.2	83.5	26.6	13.2	33.9	22.0
5	20	2800-2600	NT7-NP305E	12.7	73.9	19.34023	28.8	101.6	82.5	24.0	42.0	30.6	19.8
6	24	2600-2400	NP304-NP281	347.0	65.7	22.19968	12.8	187.2	71.7	26.0	42.6	32.3	21.7
7	29	2400-2200	NP280-NP250	347.7	71.6	28.04887	29.4	199.7	79.7	22.8	103.8	27.4	19.5
8	32	2200-2000	NP248-NP198	350.1	66.8	28.18135	8.1	182.0	73.8	35.6	34.9	42.4	30.7
9	21	2000-1800	NP197-NP173	344.0	70.8	19.47304	13.1	205.3	77.5	30.9	29.2	39.1	25.5
10	15	1800-1600	NP172-NP158	12.2	69.9	14.33799	21.1	123.3	77.5	26.1	104.2	34.6	20.9
11	17	1600-1400	NP157-NP141	351.7	70.7	16.65375	46.2	185.2	79.4	17.4	32.7	22.7	14.1
12	20	1400-1200	NP140-NP121	1.4	71.3	19.38658	31.0	153.4	81.1	20.7	17.8	26.3	17.0
13	16	1200-1000	NP120-NP104	359.9	68.9	15.28560	21.0	158.7	77.5	23.8	44.0	31.3	19.2
14	10	1000- 800	NP103A-NP92	8.9	56.2	8.52624	6.1	143.5	61.5	34.6	42.1	49.0	26.8
15	17	800- 600	NP91-NP73	347.9	73.7	13.72488	4.9	211.5	82.4	46.9	18.5	61.1	38.1
16	24	600- 400	NP72-NP44	1.8	64.6	22.10765	12.2	154.5	71.7	30.0	65.7	37.2	25.1
17	29	400- 200	NP43-NP12	347.4	71.6	25.51059	8.0	200.1	79.5	34.8	19.8	41.8	29.8
18	11	200- 1	NP11-NP1	346.5	79.3	9.63674	7.3	294.8	83.1	43.6	17.5	60.7	34.1

(ii) Excluding Units with Θ' <45°

Group	N	Height (m)	Range	D°	I°	R	K	ϕ'	Θ'	S_F	K_W	S_U	S_i
1	4	3600-3400	NT112-NT100	339.9	62.1	3.92870	42.1	195.9	65.8	16.7	86.0	29.3	11.7
2	17	3400-3200	NT99A-NT68	10.8	68.2	16.69446	52.4	130.7	75.4	15.4	43.4	20.1	12.5
3	17	3200-3000	NT67-NT46	2.7	71.0	16.43919	28.5	149.0	80.5	22.4	46.9	29.2	18.2
4	18	3000-2800	NT38-NT8	15.4	75.5	17.35445	26.3	79.0	82.9	24.3	15.1	31.4	19.8
5	20	2800-2600	NT7-NP305E	12.3	73.6	19.34071	28.8	105.6	82.2	24.0	41.2	30.6	19.8
6	21	2600-2400	NP304-NP281	358.8	69.1	20.48369	38.7	161.9	77.8	18.8	38.5	23.7	15.5
7	27	2400-2200	NP280-NP250	351.5	71.1	26.46071	48.2	186.9	79.9	17.3	101.4	20.9	14.8
8	26	2200-2000	NP248-NP198	358.1	68.7	25.04942	26.3	163.7	77.2	22.8	35.5	27.7	19.4
9	19	2000-1800	NP197-NP173	356.5	69.7	18.29115	25.4	169.2	78.6	22.9	27.9	29.3	18.8
10	14	1800-1600	NP172-NP158	4.4	70.6	13.59317	32.0	144.0	79.9	22.7	101.2	30.4	18.2
11	17	1600-1400	NP157-NP141	351.7	70.7	16.65375	46.2	185.2	79.4	17.4	32.7	22.7	14.1
12	19	1400-1200	NP140-NP121	5.1	70.4	18.52216	37.7	142.1	79.4	18.3	20.6	23.4	15.0
13	15	1200-1000	NP120-NP104	7.3	70.2	14.63240	38.1	135.9	78.8	19.7	43.0	26.1	15.8
14	8	1000- 800	NP103A-NP92	12.8	59.4	7.80643	36.2	135.5	64.3	18.5	38.8	27.3	13.9
15	13	800- 600	NP91-NP73	3.8	69.8	12.28460	16.8	146.9	78.6	28.1	18.3	38.0	22.3
16	22	600- 400	NP72-NP44	10.0	63.6	21.20493	26.4	137.9	69.6	21.4	68.0	26.9	17.8
17	24	400- 200	NP43-NP12	2.3	73.0	23.16550	27.6	147.6	83.7	23.1	19.1	28.7	19.3
18	8	200- 1	NP11-NP1	6.0	70.4	7.67127	21.3	139.5	79.3	26.3	24.9	38.8	19.9

See caption to Table 2 for explanation of table. Height (*m*) refers to the interval above the base of the section (Fig. 1) selected for the computation.

of the Miocene and Pliocene periods (Heinrichs 1967), no periodicity has hitherto been identified. Closer inspection of the data and use of Fig. 1 reveals, however, that the difference between the two S_F curves in Fig. 3 is to a large (if inconsistent) extent a function of the number of lavas representing polarity transitions which are included in the computation of S_F. This stresses one of the computational problems discussed earlier. While exclusion of data from lavas which have recorded VGP latitudes less than 45° clearly eliminates prospects of analysing geomagnetic field behaviour which is anomalous, the practice at the same time minimizes the possibility of discovering long-term variations in the magnitude of geomagnetic secular variations. It could be argued that our selection of an increment of 20 lavas (less units with low precision) may have provided misleading results. In Fig. 4 and Table 3 we therefore present the results for successive groups of 30 lavas, so that a total of 11 separate points materialize. As Fig. 4 shows, our conclusions are not changed significantly. I is always less than the axial dipole value; the declination changes are less variable when data are excluded from lavas which have VGP latitudes lower than 45°; and at the 95 per cent confidence level S_F changes very little. There is clearly little variation in lava extrusion rate. In Figs 3 and 4 we also include for each data set K_W, the within-lava precision parameter, which is used to compute S_F. It is considered valuable to know whether or not the variation in S_F values has in any way resulted from poor determinations of mean directions within each lava sequence. K_W is consistent, going above 50 only once for groups of 30 lavas. Thus variation of S_F is not a function of variations in K_W. The above conclusions must now be tested and possibly refined by examination of other data groupings.

5.4.2 *Equal section thickness increments*

A 200-m increment was selected, in order to provide approximately 20 successive lavas per data set, but because of varying single lava thickness, the number involved ranged from 7 to 32. The results of statistical analyses of the 15 successive groups are given in Table 4 and are illustrated in Fig. 5.

All the conclusions made for the equal lava number groups (Section 5.4.1 above) are supported, and do not need repeating.

5.4.3 *Equal time increments*

Since the sequence features a strong linear relationship between age and lava number – equation (1) – a conclusion which is supported by the consistency of S_F computed using equal lava number increments (Fig. 3), the data can be divided into increments representing any convenient time interval. As may be expected the results do not differ from those provided by the equal lava number increment and are therefore not presented here: the variations (if any) illustrated in Figs 3 and 4 can be readily transformed into time variations.

5.5 SYMMETRY OF THE NON-DIPOLE FIELD

Cox (1975) has pointed out that the non-dipole field may lack symmetry, in the sense that core–mantle interface irregularities or other inhomogeneities render the prospects of averaging out secular variation over a finite time dependent on geographic location. Merrill & McElhinny (1977) have amplified this suggestion. Hawaii appears to be an area where asymmetry of the non-dipole field exists. Cox's model for the source of a non-dipole field which does not average out (Cox 1975, Fig. 11) shows diminished effects at the higher latitudes. A principle involved in analysing the behaviour of the non-dipole field is based on comparison of normal polarity and reversed polarity data for the area: if for a limited period

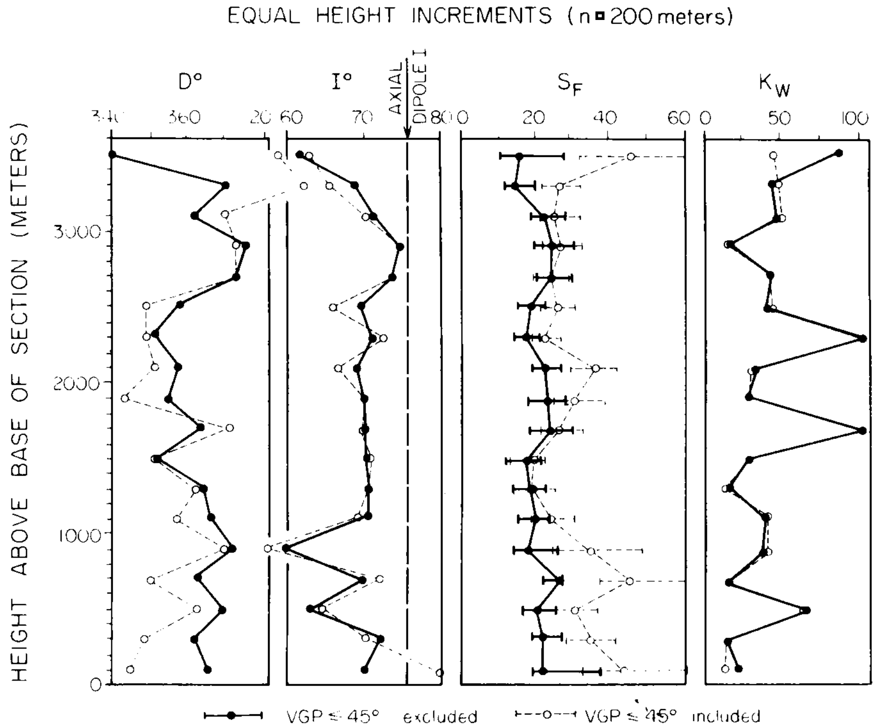

Figure 5. Palaeomagnetic results for the Borgarfjördur region of Western Iceland for successive groups of lavas representing equal thickness of lava above the base of the sequence (Fig. 1). See Fig. 3 for explanation of the diagram, and Table 4 for details of results. The thickness increment selected is 200 m.

the mean VGP for data groups differ by close to 180°, then it can be argued either that the polarity of the non-dipole field reversed with that of the main dipole, or that the non-dipole field is effectively absent.

Watkins & Walker (1977) have analysed a large volume of palaeomagnetic data from Eastern Iceland, and find that while some discrepancies in VGP positions between successive opposite polarity epochs are indicated (consistent with a lack of change in polarity in the non-dipole field as the main dipole reverses), the entire data set yields, after transposing the reversed polarity results to the northern hemisphere, virtually identical VGP positions for the two polarities. This could mean that the non-dipole field is averaged out over a 10-Myr period, whereas it is not over periods of about 1 Myr. It is also interesting to note that despite the very large data volume, the Eastern Iceland results produce a mean pole position (in the vicinity of longitude 115° E, latitude 82° N) away from the geographic pole. McElhinny & Merrill (1975) believe that similar results for many studies of igneous rocks less than 5 Myr old may reflect limited time coverage of the rock collections involved, and for this reason that data from the entire world should be averaged for a series of latitudinal strips, to arrive at a meaningful measure of palaeosecular variation. It is clear, however, that the argument of insufficient time representation cannot be applied to the Eastern Iceland results which show an unusually well-defined regular extrusion pattern, over an 11-Myr time span. Therefore the result can be interpreted to be either a true tilting spin axis by an average of about 8°, or the persistence over a long period of an inclination anomaly, caused by either an offset dipole field (Wilson 1971) or by a non-averaging non-dipole field (Cox 1975) which produces a shallowing of inclinations during both polarities.

Table 5. Mean virtual geomagnetic pole positions for four successive polarity epochs in Western and Eastern Iceland.

(a) The Borgarfjördur region of Western Iceland.

Polarity epoch	N	ϕ'	θ'	α_{95}
Gauss (normal)	35	130.6	79.0	4.8
Gilbert (reversed)	46	151.5	81.9	3.6
Epoch 5 (normal)	11	128.0	77.5	12.1
Epoch 6 (reversed)	6	133.5	75.2	7.7

(b) The Eastern Iceland region.

Polarity epoch	N	ϕ'	θ'	α_{95}
Gauss (normal)	21	323.0	87.0	8.7
Gilbert (reversed)	31	35.0	81.0	8.4
Epoch 5 (normal)	5	250.0	79.0	21.7
Epoch 6 (reversed)	12	27.0	74.0	13.5

Note:

N = Number of separate lavas (data are those remaining after rejection of lavas representing opposite polarity events in the epoch; of lavas with VGP latitudes less than 45°, and of lavas with insufficiently well defined directions (see text for definition)). ϕ' and θ' = longitude and latitude of mean VGP (assigning unit vector per pole). α_{95} = semi-vertical angle of 95 per cent confidence cone. Results for Eastern Iceland are given from Watkins & Walker (1977). For approximate age ranges of epochs see Fig. 1; for exact age ranges see McDougall *et al.* (1977).

Movement of the geographic axis seems unlikely, since if such was the case, the mean pole position would be repeated by other similar scale studies, and this has not happened. For the Cox mechanism to apply, the non-dipole field would have to reverse with the dipole field.

We now examine the relevance of the Western Iceland results to the above interpretations of the Eastern Iceland data. Table 5 shows the results of averaging the data (Table 1) by polarity epoch, after rejection of results for the polarity events within each epoch, VGP latitudes below 45°, and low precision. Added to the table are the results for identical computations of the Eastern Iceland data (Watkins & Walker 1977, Table 7).

It can be seen that the mean VGP positions for the four polarity epochs represented in the Western Iceland study (Fig. 1) are identical at the 95 per cent confidence level, and are removed from the spin axis into the geographic quadrant (longitude 90° E to 180° E) which is 'far-side' from Iceland. This would suggest that, since two normal and two reversed polarity epochs are involved, the non-dipole field reverses during the polarity change just as Cox (1975) proposed for Hawaii. But if such were the case the non-dipole source (which Cox envisages as flux leaving the core in localized regions near the equator, and entering the core at about 55° latitude), would need to be effective at high as well as low latitudes. For this reason, the mean inclinations for Western Iceland (Table 4) continue to be mostly easily explained in terms of an offset of the main axial dipole. Stated in terms which are more correct physically, the persistance of the offset dipole field equivalent and its apparent reversal with the non-dipole field could mean that higher order even-numbered multipoles reverse with the geocentric dipole, and the effect of the odd-numbered multiples cancel out.

Inspection of Table 5 shows that the Eastern Iceland collection does not provide mean VGP positions for the four separate epochs which are strongly similar to those for the Western Iceland results. For three of the four epochs, they are in fact different at the 95 per cent confidence level. This discrepancy was stated, in different terms, when the inclination of the younger sequences in Eastern Iceland were shown to be generally steeper than that of the axial dipole, whereas the western sequences had no such property. Comparison of the two sets of data in Table 5 at least serves to demonstrate that the contrasts do not vanish when averaged over 1-Myr intervals. Since the Western Iceland results produce consistent VGP positions between epochs, and the Eastern Iceland results do not, it is probable that the former are more reliable as an indicator of the palaeomagnetic field behaviour. More separate samples per lava and a slightly higher lava extrusion rate in the west may account for this.

Conclusions

Our analysis of the palaeomagnetic properties of the Borgarfjördur volcanic sequence (Fig. 1) has provided the following conclusions:

(1) No long-term change of geomagnetic inclination took place between $t = 6.7$ and 1.6 Myr in Western Iceland, to provide a change of mean VGP from far-side to near-side of the geographic pole as proposed by Wilson & McElhinny (1974) on the basis of palaeomagnetic data from Eastern Iceland. Furthermore, since McDougall *et al.* (1976) have shown that there does not exist a hiatus in volcanic activity between $t = 7$ and 3 Myr in the Eastern Iceland sections, and because such a hiatus was required by Wilson & McElhinny (1974) to occur coincident with their proposed change of mean VGP from far- to near-side, then further consideration is required in the Wilson & McElhinny (1974) interpretation of the Eastern Iceland palaeomagnetic data. Ways by which the contrasting results from Western and Eastern Iceland can be reconciled are:

(a) The axial dipole field has dominated, and all parts of Iceland except the younger Eastern Iceland sections (P to V in Dagley *et al.* 1967) migrated north by about 12° of latitude (carrying a geomagnetic inclination of 69° which is characteristic of lower latitudes). While Iceland is certainly very active tectonically, this would seem somewhat implausible, especially as some of the Western Iceland sections are only about 2 Myr old.

(b) The northward offset dipole has dominated, and the younger Eastern Iceland sections have migrated from the north into their present location (carrying an inclination characteristic of higher latitudes). This again is not plausible, not only because of the age of the sequences involved, which range from only about 3 to 6 Myr, but also because in these latitudes about 16° of latitudinal migration would be required to bring an 80° inclination into a region characterized by inclinations which are 10° or so less.

(c) The northward offset dipole has dominated and the higher values of I in sections P to V (Dagley *et al.* 1967), which have been confirmed by McDougall *et al.* (1976), result from a burial metamorphism which is anisotropic in the sense that the horizontal components of remanent magnetism are preferentially diminished, compared to the vertical components. This, again, is difficult to accept, and while such a possibility is being investigated, the substantial contrasts in mean I between sections of the same age in Western and Eastern Iceland must at present remain unexplained.

(2) The mean VGP positions for each of the four complete successive polarity epochs recorded in the Borgarfjördur are almost identical, and are in the longitudinal quadrant which is 'far-side' from Iceland. This suggests that when the geocentric axial dipole reverses its polarity, then the higher order and even numbered multipoles also change polarity, maintaining the apparent offset dipole field at the site.

(3) The mean VGP for each epoch excludes the geographic pole, and a very large amount of data from Eastern Iceland also produces VGP positions which exclude the geographic pole. Therefore explanations for non-coincidence of VGP and spin axis cannot invoke insufficient time coverage of the data.

(4) The angular standard deviation of VGP for increments of 20–30 successive lavas is about 20° throughout the section. This is the value expected for several of the conventional geomagnetic field models, based on combinations of mean dipole and non-dipole activity. At the 95 per cent confidence level there is almost no discernible variation in S_F. Such a consistency of S_F for a period of about 5 Myr is at variance with the suspicions of McElhinny & Merrill (1975), Cox (1975) and others, who propose that palaeosecular variation can be expected to be variable temporally as well as spatially. McElhinny & Merrill (1975) in particular have shown that standing and drifting non-dipole components can be expected to occasionally combine to create very high S_F values at the higher latitudes, such as those of Iceland. Our results appear to contradict this possibility, although by rejecting data from lavas with low-latitude VGP positions, discrimination takes place against the discovery of periods of high S_F. Should it become possible to justify inclusion of such data, then the palaeomagnetism of the Borgarfjördur lava could undoubtedly be used to demonstrate some long-term palaeosecular variation.

Acknowledgments

This research is supported by grants GA37170 and DES73-06517, from the National Science Foundation. Support was also provided by the Australian National University, and the National Energy Authority of Iceland. The original manuscript was greatly improved as the result of review by Dr M. W. McElhinny (Australian National University), who generously made available preprints of his joint papers with Dr R. T. Merrill (University of Washington).

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