Geophys. J. R. astr. Soc. (1982) **68**, 273–294

Some aspects of the late Tertiary geomagnetic field in Iceland

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Received 1981 April 6

Summary. In 1972–78, the late N. D. Watkins and others carried out a joint field programme of geological mapping in the Mio-Pliocene flood basalts of Iceland, including sampling for K-Ar dating and palaeomagnetic research. The major part of the palaeomagnetic sampling is represented by 2462 lavas in five long composite sections through the lava pile. This paper deals with various statistical properties of this data set.

It is concluded that geomagnetic reversals occur more frequently than is assumed in the current ocean-floor polarity time-scale. There is no evidence for significant asymmetries between normal and reverse polarity states of the field, neither as regards chron lengths, secular variation, or virtual dipole moment magnitude. Intensities of remanence in these lavas are shown to be well approximated in terms of a hyperbolic distribution. The latitude distribution of virtual magnetic poles can be fitted with a Bingham function having $k' \approx 4.5$, and low-latitude poles do not occur preferentially in any particular longitude interval.

1 Introduction

Information on properties of the palaeomagnetic field is gathered chiefly from direct measurements on igneous rocks and sediments, and less directly by the analysis of linear magnetic anomalies in the oceans. These three sources of information are in many aspects complimentary. The most important igneous rocks for palaeomagnetism are lava flows, which preserve a record of spot readings of the ancient magnetic field in stratigraphic sequence.

Unfortunately, terrestrial lava flows are far from ideal for these studies, and many fundamental questions on the nature of the palaeomagnetic field remain to be answered satisfactorily. The lava sequences in Iceland are among the best available for this type of study. Their ages (late Tertiary to Recent) can be measured with fairly good accuracy; they cover many tens of geomagnetic polarity epochs (chrons); they generally carry a stable and strong

primary magnetization; the number of accessible flows is virtually unlimited; secondary tilting is only a few degrees in most of the lavas so far sampled; and secondary alteration is minor.

Palaeomagnetic research in Iceland began in the early 1950s. The most comprehensive study prior to the present work was carried out by a joint UK–Icelandic expedition in 1964–65, collecting from about 1200 lavas in east and south-west Iceland. Although the main research effort on those samples concerned rock magnetism and ore mineralogy, several papers dealing with properties of the ancient field were based on the results from this expedition (e.g. Dagley & Wilson 1971; Wilson, Dagley & McCormack 1972; Watkins & Walker 1977).

In 1972, N. D. Watkins of the Graduate School of Oceanography, University of Rhode Island (URI) who had taken part in the 1964–65 expedition, initiated a new and ambitious phase of palaeomagnetic sampling in Iceland, combined with a detailed geological mapping and dating effort. With us and K. Saemundsson as chief collaborators, N. D. Watkins collected samples from over 2000 lava flows in 1972–76 for measurement at URI. This programme suffered a major setback in 1977 with his illness and with his death on 1977 November 2, but sampling was continued by us in 1977–78. Since mid-1978 magnetic measurements and the processing of geological and magnetic data has been carried out mainly in Iceland.

Sampling was done in a conventional way, using portable drills and mostly geographical sightings. Three core samples were generally taken per flow (average = 3.1), in contrast to two in the 1964–65 work, and one specimen was measured per sample. All specimens were AF demagnetized at 0.01 and 0.02 tesla (100 and 200 Oe) peak fields; in a few cases, other fields were employed additionally. Generally the results were combined for maximum internal consistency of directions (see Watkins, McDougall & Kristjansson 1977), but a slightly different approach (Kristjansson, Fridleifsson & Watkins 1980) was used for about 300 flows measured in Germany and Iceland, including some lavas that were resampled in 1978–79 due to instability.

The research effort of Watkins and collaborators was mostly directed at five long composite sections, pieced together by detailed stratigraphic mapping from several profiles partly overlapping in time. We have chosen to discuss in this paper only these five sections, as described in Table 1.

Table 1(a) includes flows that overlap in time with other flows sampled, both in adjacent profiles in each area (over 15 per cent of the total number of flows) and between the sections. Geological evidence and scrutiny of the magnetic data set itself indicates, however, that this generally does not imply that the very same flows have been sampled twice. With a large enough data set, the presence of such overlap should not cause any serious bias in the overall results.

It is hoped that the publication of the detailed data from Iceland, as well as this statistical analysis, will aid other research in palaeomagnetism in several ways. It should yield a better empirical approximation to the overall behaviour of the field than has previously been obtained from any igneous rock sequence, and so point the way to an improved model of the long-term field configuration. Smaller palaeomagnetic surveys in Iceland and nearby regions could then be tested against such a model to find out if they are sufficiently representative of the long-term field to be useful for example in tectonic reconstructions. Reliable data on the main characteristics of the field are also needed for research into its physical causes. In that context, it is particularly important that detailed palaeomagnetic work on lava sequences comparable in size and age to those in Iceland be carried out in a low-latitude region, as pointed out by Wilson *et al.* (1972).

In the following, we shall assume *a priori* that our individual lava collections belong to a

Table 1. Main basalt lava collections of N. D. Watkins and coworkers in Iceland.

(a) Including overlap between adjacent profiles

Area	Reference	Number of flows All	$\alpha_{95}<60°$	$\alpha_{95}<23.5°$	Comment
Borgarfjördur, west Iceland	McDougall *et al.* (1977); Watkins *et al.* (1977)	393	378	342	(1)
Esja area, south-west Iceland	Kristjansson *et al.* (1980)	353	339	306	(2)
Central northern Iceland	Saemundsson *et al.* (1980)	455	432	398	
North-west peninsula	In preparation	1261	1216	1117	(3)
		2462	2365	2163	

(1) Includes minor additional sampling in 1978. (2) Twelve units (hyaloclastites, intrusions and lightning-struck flows) not included in last column. (3) Includes two composite sections, plus about 200 lavas whose stratigraphic position within the north-west peninsula lava pile has not been finally settled.

(b) Excluding overlap between adjacent profiles

Area	Profiles	Age range, Myr	Number of flows	Time/ flow	Number of revs
Borgarfjördur	NP, NT	2–7	376	12	24
Esja area	FA through SC	2–4½	276	8	12
North Iceland	PA through PG	9–12	333	8	26
North-west peninsula	SK through JF	11½–14	427	5½	18
	SR through BX	8–12	382	10	18

The last three columns indicate respectively: the number of sampled flows in stratigraphic sequence; the average time interval in thousands of years, between successive flows, corrected for the presence of non-sampled flows; number of observed geomagnetic polarity reversals in section.

homogeneous and stationary set, in that no systematic change has taken place in important parameters of the geomagnetic field during the period from 14 to 2 Myr ago. This includes changes in secular variation amplitude, rate of reversals, and mean intensity of the dipole field. Some apparent time trends of this kind have been observed in the data (Watkins *et al.* 1977; Saemundsson *et al.* 1980), but they do not occur consistently between the various areas. We shall therefore look upon them as natural statistical fluctuations within the data set, although it is possible that some such variations are due to systematic errors of measurement not yet pinpointed. Furthermore, we shall assume that serial correlation (Kristjansson *et al.* 1980) does not affect the results described below.

Most of our calculations on secular variation properties of the field are done on lavas for which the within-flow field directional error limit α_{95} is less than 23.5° (Table 1a). This value corresponds to a vector sum $R = 2.93$ in the case of N = three samples per flow, and to $R = 3.82$ in the case of four samples per flow. The choice of such a parameter and of its 'cutoff' value will always be subjective, but the field-α_{95} appears a reasonable parameter to use in this type of work, because it is easy to visualize and because the commonest errors noted in palaeomagnetic research occur at the level of field direction measurement (rather than in derived quantities such as pole positions). The estimated circular standard deviation (csd or θ_{63}) is approximately $0.65 \cdot \alpha_{95}$ when $N = 3$.

The mean α_{95} value in those of our lavas which pass the above criterion is 7.5°, but if all lavas having $\alpha_{95} < 60°$ were included (see Table 1a) this mean value would rise to 9.5°. The rms value of α_{95} in the former is 8.8°.

However, it is important to realize (Saemundsson *et al.* 1980) that lava flows yielding low-latitude palaeopoles carry on average a much weaker (see Section 3.4) primary magnetization than those yielding high-latitude poles. Because of the common presence of secondary magnetization components, the field directions corresponding to low-latitude poles are more difficult to measure accurately than others, and hence also more likely to fail our consistency test. These circumstances will introduce a small bias into some statistical properties of the data set, but its sense is generally known and some limits on its magnitude can be estimated. In future work, this problem may be reduced by improved techniques in demagnetization.

2 Lengths of geomagnetic chrons

2.1 AVERAGE CHRON LENGTH

Unfortunately, no method is available for estimating the length of time intervals between any two successive lava flows in Iceland. We can only estimate the mean length of time between sampled flows in each survey from the total time interval it covers (Table 1b), as derived from K-Ar dating and correlation with the ocean floor magnetic anomaly time-scale. The time per flow values have been corrected for the presence of non-exposed and other non-sampled flows (5–10 per cent) in the profiles; these values average about $8 \pm 2 \times 10^3$ yr.

In order to find the average number of lava flows per polarity zone in Iceland, we must first make some subjective distinction between polarity zones and minor geomagnetic excursions occurring in the data set. This has been discussed by McDougall *et al.* (1977, pp. 12–13). We must then make allowance for those zones (mostly short) which may go undetected in non-sampled and unstable flows; these may increase the numbers in the last column of Table 1(b) by some 10–15 per cent.

Finally, we assume that the processes of both lava eruptions and geomagnetic reversals are random events, giving rise to two uncorrelated Poisson distributions of interval lengths. If there are on average p eruptions and m reversals per time interval, it is inevitable that a fraction of the geomagnetic polarity epochs (chrons) actually occurring will be represented by no lava flows in our sections. This fraction tends to m/p for values of p/m exceeding 10. The polarity zones above and below this time horizon will then generally merge into one, so we will be effectively losing record of a fraction $\lesssim 2\,m/p$ of the number of chrons for large p/m.

For $p/m < ½$, on the other hand, magnetic polarities of successive flows will be essentially uncorrelated, and the frequency distribution of observed polarity zone lengths will resemble that of a coin-flipping sequence. Its mean is obviously 2 lavas per zone if $p \ll m$.

In general, the relation between apparent and real lengths of geomagnetic polarity intervals may be approximated by the equation

$$p/m = \text{actual mean number of lavas per chron} = \text{observed number of lavas per polarity zone} - 2. \tag{1}$$

Numerical modelling of these processes by computer also shows that an estimate of the actual number of lavas per chron (Fig. 1) is 50 per cent likely to be in error by up to 9 per cent, when the observed rate of reversals is based on a sample of 1000 successive lava flows. This sample size is convenient to use here, as Table 1(b) contains about 1800 flows whose ages overlap considerably between the various areas.

From the above data, we obtain that a weighted average of the order of 16 ± 4 lavas have erupted per chron, and hence that the average length of a chron is $8 \times 16 \simeq 130 \pm 50 \times 10^3$ yr in the time interval 2–14 Myr ago.

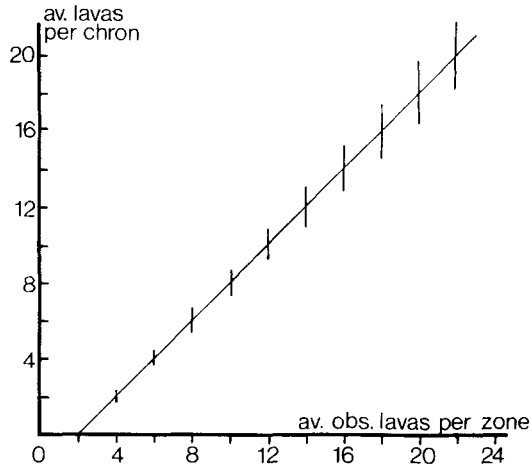

Figure 1. Relation between the observed mean number of lava flows per polarity zone in an infinitely long stratigraphic column and the mean number of lavas, p/m, erupted per geomagnetic chron (straight line). The number of reversals per unit time and the number of eruptions per unit time are both assumed to be Poisson distributed, with normal and reverse polarity states being equally probable. Vertical bars indicate 50 per cent confidence limits when there are only 1000 lavas in the pile.

A very similar result may be found from the data from eastern Iceland presented by Watkins & Walker (1977). However, it is apparent that several assumptions have been made in this analysis. The most serious ones are probably the assumptions that no major faults, or hiatuses in volcanic activity, occur in the sections covered by us.

Our estimated average chron length is considerably shorter than the 200×10^3 yr or so that Labrecque, Kent & Cande (1977) have inferred from marine magnetic anomalies for the same time interval, i.e. 2–14 Myr ago; however, they acknowledge that they may be missing several short polarity intervals. This calls for caution in establishing correlations between specific marine anomalies and lava or sedimentary sequences on shore. Our error limits include the mean value of 100×10^3 yr per chron suggested by Harrison (1969).

2.2 RELATIVE MEAN LENGTHS OF NORMAL AND REVERSE CHRONS

A computer program modelling the eruption and reversal processes as Poisson distributed (cf. Section 2.1) may also be used to investigate the significance of observed long-term asymmetries in mean normal and reverse polarity zone lengths. It is then found that in 1000 successive lavas, the excess of one polarity over the other has a 50 per cent chance of being 20 lavas or more if the rate of eruptions is very slow ($p/m < ½$). This value increases from 20 to about 100 lavas when p/m is 16 (Fig. 2).

In the actual observations, we find that our collection from NW-Iceland (Table 1a, flows with $\alpha_{95} < 23.5°$) contains 594 flows of normal polarity and 523 of reverse polarity, an excess of 71 normal flows. On the other hand, the other three surveys of Table 1(a) contain altogether 473 normal and 573 reverse flows, an excess of 100 reverse flows. Wilson *et al.* (1972) reported that their eastern Iceland collection included 576 normal and 450 reverse flows, an excess of 126 normal flows. It is obvious from these data (as well as from the fact that single-polarity zones of over 40 lavas commonly occur within Icelandic lava sequences) that one is in no position yet to reject the null hypothesis that normal and reverse geomagnetic polarity states were equally probable in the late Tertiary. It is of historical interest to note that a similar conclusion was reached by Einarsson & Sigurgeirsson (1955).

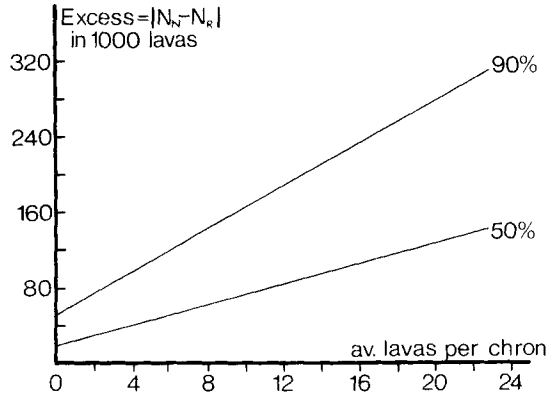

Figure 2. Approximate probability limits for the excess, in number of lavas, of one polarity over the other in a hypothetical stratigraphic pile of 1000 flows. Distributions of eruptions and of reversals both Poissonian, *cf.* Fig. 1.

3 Relative intensity and virtual dipole moment of the field

3.1 GENERAL

The measured intensity of primary magnetization in an igneous rock sample is known to depend on factors of three different categories:

(a) It is proportional to the local geomagnetic field intensity at the time of emplacement.

(b) It depends in a complex way on the amount of magnetic material in the sample, its chemical composition, grain size and shape, rate of cooling, and other circumstances of emplacement.

(c) It is also affected by the subsequent environment of the rock, particularly by elevated temperatures and alteration in hydrothermal processes, which will in general cause a decay of the original remanence with time. In this category we can also include the effects of whatever demagnetization treatment the sample may have been given to rid it of secondary magnetization.

Following Dagley & Wilson (1971) we assume that by averaging results from a large number of lava flows covering many chrons, we may smooth out the fluctuations caused by (b) and (c) above, and be left with an estimate of relative field strengths or virtual geomagnetic moments as function of, e.g. VGP latitude or longitude.

The NRM of Icelandic rocks frequently includes a considerable Brunhes age normal polarity viscous remanence. In our experience, this VRM is completely removed in most samples by 100 Oe AF treatment and in all samples by 200 Oe. We shall use the former results as our representative of the primary magnetization, because sometimes the original remanence becomes quite weak and difficult to measure accurately after 200 Oe treatment.

In order to carry out a statistical analysis of our observed remanence intensity (J_{100}) values, we must choose a method appropriate to the frequency distribution that these values (Fig. 3) actually follow. Irving, Molyneux & Runcorn (1966) and Tarling (1966) have demonstrated that the lognormal distribution is a suitable one for statistical analysis and comparison of remanence and susceptibility data from rocks.

However, when our lava-mean remanence intensity values are plotted as a frequency distribution of the logarithm of intensity, the resulting curve is much steeper at the right side.

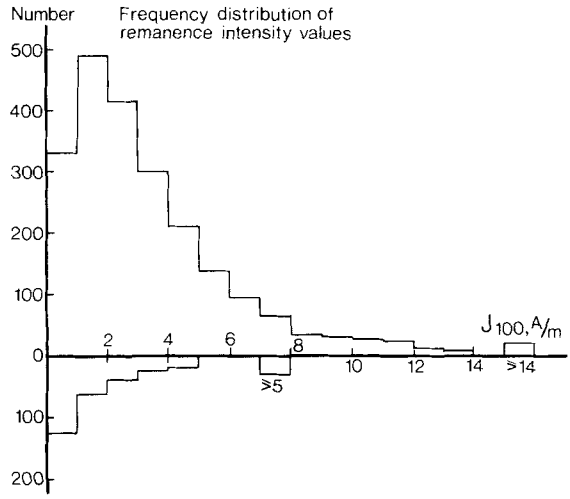

Figure 3. Observed frequency distribution of remanence intensity after 100 Oe demagnetization (J_{100}) in 2163 lavas with $\alpha_{95} < 23.5°$ (upper histogram) and in the other flows of Table 1(a) (lower histogram). Linear scales on both axes.

One may speculate on the reasons for this: possibly the remanence intensities of fresh lava flows are lognormally distributed, but a skewness in the distribution will develop with time (during processes (c) above). This is consistent with the commonly observed positive correlation between intensity and stability of primary remanence in lavas.

Pending the discovery of a simple two- or three-parameter statistical distribution that might describe these observed intensity data, we wish to point out that Barndorff-Nielsen (1977, see also Bagnold & Barndorff-Nielsen, 1980) has recently developed a versatile statistical approach to the treatment of various natural and economic frequency or size distributions. This approach seems to be very suitable in the present case, albeit only on an empirical basis. Barndorff-Nielsen (1977) points out that in a log-log graph the ordinary two-parameter lognormal distribution is a parabola, which can be looked upon as a special case of a hyperbola with a vertical axis. In turn, such a hyperbolic distribution can be generalized in terms of a hyperbola with an inclined axis.

This yields a four-parameter distribution

$$f(x) = \exp\{-\tfrac{1}{2}(\phi+\gamma)\sqrt{\delta^2+(x-\mu)^2} + \tfrac{1}{2}(\phi-\gamma)(x-\mu) + k\} \tag{2}$$

to be fitted to an observed frequency distribution of the logarithm, x, of intensity. Following Barndorff-Nielsen's notation, these parameters are:

μ, the abscissa of the intersection of the asymptotes of the hyperbola in the log-log graph;

γ, the negative of the slope of the right asymptote;

ϕ, the slope of the left asymptote;

δ, a positive parameter indicating whether the distribution resembles a parabola (high δ) or a pair of intersecting straight lines (low δ).

k is a normalizing constant involving a Bessel function.

The mode of a hyperbolic distribution (Bagnold & Barndorff-Nielsen 1980) is at $\mu^* = \mu + \delta(\phi-\gamma)/2\sqrt{\phi\gamma}$.

3.2 EQUIVALENCE OF NORMAL AND REVERSE INTENSITY DISTRIBUTIONS

We have applied the method of hyperbolic distributions (2) empirically to our collection of intensity values after 100 Oe AF demagnetization (J_{100}), in order to distinguish any differences that may be present between normally and reversely magnetized lavas. Fig. 4(a) illustrates separately the probability density of J_{100} in 1067 normal flows and 1096 reverse flows (Table 1a, $\alpha_{95} < 23.5°$). These densities have been computed from histograms where

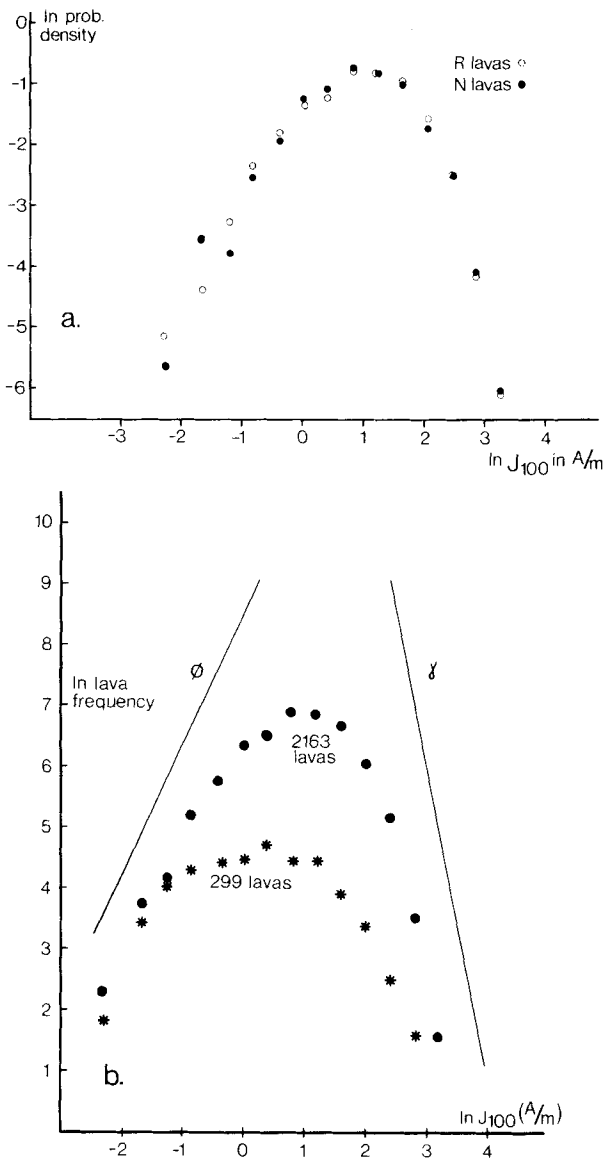

Figure 4. (a) Frequency distribution of remanence intensities J_{100} in normal (filled circles) and reverse (open circles) lava flows with $\alpha_{95} < 23.5°$. Bilogarithmic scale, each group separately normalized to total probability of unity. (b) Filled circles: unnormalized frequency distribution of remanence intensities in normal and reverse lavas combined. Same data as in (a) and upper histogram of Fig. 3. Asymptotes of best-fitting hyperbola are shown (see text for explanation of symbols). Stars: frequency of remanence intensity values in 299 lavas with $\alpha_{95} > 23.5°$ (lower histogram of Fig. 3).

the ratio between successive class boundaries in J_{100} increases by a factor of approximately 1.5 (Table 2a).

It is at once apparent from Fig. 4(a) that there is in fact no significant difference between the two populations. The statistical parameters that have been derived from this data are listed in Table 2(b) and also show a close correspondence; in particular, $\exp(\mu^*)$ which may be visualized as the peak or centre of the distribution, is only 6 per cent higher in reverse flows, a minor difference. The statistical parameters and their standard errors were computed by an iterative method using a least-squares approach. The uncertainty in the size of each histogram column was taken to be equal to the square root of that size.

Fig. 4(b) shows the combined results of our total of 2163 flows, with its computed hyperbolic asymptotes. The stars are the frequency distribution of J_{100} for 299 flows having $\alpha_{95} > 23.5°$. The very broad shape of this curve may be interpreted as its being a sum of two superimposed hyperbolic distributions: first, a distribution shaped like the upper one and containing flows wherein the high value of α_{95} is unrelated to intensity (e.g. caused by various orientation errors or by out-of-place exposures); secondly, a population of weakly and unstably magnetized flows, i.e. with a low value of $\exp(\mu^*)$.

3.3 THE STRENGTH OF INCLINED GEOMAGNETIC MOMENTS

The principles of Section 3.1 may also be applied to the quantitative consideration of relative virtual geomagnetic moment as function of VGP latitude. This was first done by Dagley & Wilson (1971), using data from Iceland.

Table 2. Distribution of remanence intensities (J_{100}) in 2163 lavas, approximated by hyperbolic functions.

(a) Observed distribution

Range of J_{100} values, $A\ m^{-1}$	Number of lava flows	
	Normal	Reverse
< 0.15	3	5
0.15–0.25	16	7
0.25–0.35	8	14
0.35–0.55	37	47
0.55–0.85	65	78
0.85–1.25	118	109
1.25–1.85	142	127
1.85–2.75	199	199
2.75–4.15	195	201
4.15–6.25	163	171
6.25–9.35	77	93
9.35–14.05	36	37
14.05–21.05	7	7
> 21.05	1	1
	1067	1096

(b) Parameters of best-fitting hyperbolic curves

	ϕ	γ	μ	δ	μ^*
Normal lavas	2.31	4.64	1.60	1.63	1.02
Reverse lavas	1.93	4.60	1.72	1.42	1.08
Standard errors	0.22	0.19	0.40	0.07	0.33

We have split the set of palaeomagnetic data (Table 1a) into 18 groups, each group containing all the lavas ($\alpha_{95} < 23.5°$) which yield a VGP in a 10° latitude interval on the globe. We consider the limit of resolution in our data to be 5–10° in pole latitude. A similar analysis could be done using as a symmetry axis the mean pole position derived from the collection itself, but this will only make a very small difference to the results. We have then transformed each intensity (J_{100}) measurement to its appropriate virtual pole (*cf.* Tarling 1966).

Averaging these values arithmetically within each latitude group, we find the relationship of Fig. 5. Again, there is no discernible difference between primary intensities in normally and reversely magnetized lava flows. In fact, when all 2163 transformed J_{100}-values are averaged, the results from normally and reversely magnetized flows are 3.82 and 3.87 Am^{-1} respectively, a difference of less than 2 per cent. Two types of systematic error are known to affect these results, but these are minor and partially cancel each other: first, residual amounts of normal polarity VRM may in some samples survive 100 Oe treatment, causing normal J_{100} values to increase and reverse ones to decrease; secondly, our youngest lavas (i.e. those in which the primary remanence has had the least time to decay) include quite thick sequences of flows of Matuyama age in the Borgarfjördur and Esja areas.

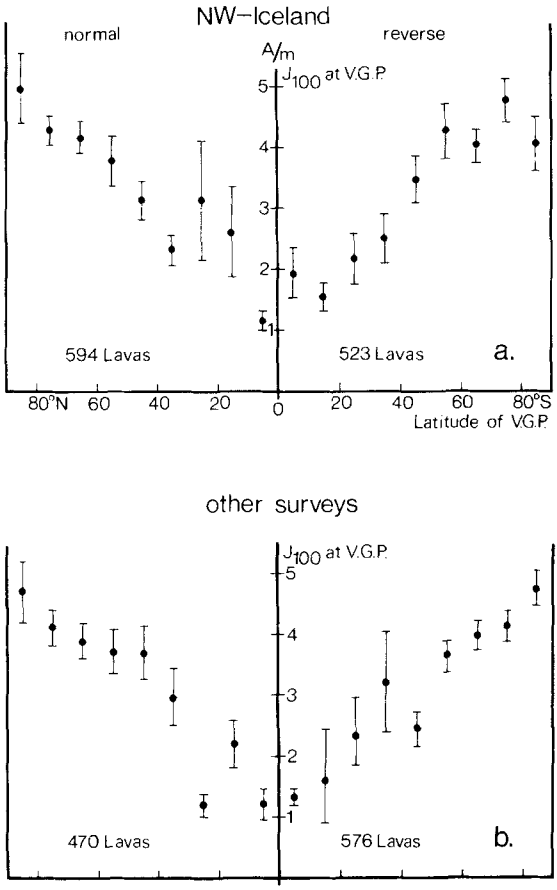

Figure 5. (a) Arithmetic means of remanence intensities after transformation to virtual geomagnetic pole (poleJ_{100}), grouped by 10° increments in VGP latitude. Normal and reverse lavas from north-west Iceland, plotted separately. Bars are standard errors. (b) Same as (a); lavas from other surveys of Table 1(a).

3.4 DIPOLE MOMENT AS FUNCTION OF VGP LATITUDE IN NORMAL AND REVERSE FLOWS COMBINED

By pooling normal and reverse data from the surveys of Table 1(a), separately for north-west Iceland and for the (mostly younger) remainder of the collection, we obtain the results of Fig. 6(a). These confirm our impression from Fig. 5, namely that the results from these two parts of the data set are almost coincident. In turn this coincidence demonstrates that we are dealing with a universal property of the geomagnetic field in Iceland. It should be noted that the overall average value of pole-J_{100} from north-west Iceland is about 3 per cent higher than that from the other areas of Table 1, so redrawing Fig. 6(a) with normalized intensity values (*cf.* Wilson *et al.* 1972, p. 216) would slightly improve the apparent coincidence of open and closed circles.

In Fig. 6(a), it may also be noted that the data point for the 20–30° VGP latitude interval in north-west Iceland stands above the general trend of the relation between transformed intensity and VGP latitude. This is a good example of the scatter that may be introduced when limited data from a distribution like that of Fig. 3 are averaged arithmetically. In fact, the excursion of this data point is mostly due to the presence of one very strongly magnetized flow (BN 18) in that latitude interval. Such excursions must therefore not be interpreted as having global significance. A similar effect may partly cause the 'strong' equatorial dipole moments observed in the data of Dagley & Wilson (1971). No evidence is seen for the relatively weak dipole moments in high VGP latitudes that were postulated by Lilley (1970).

Average results for our complete data set are shown in Fig. 6(b). The upper data points are arithmetic averages as in Figs 5 and 6(a). Standard-error bars are included, although their significance is debatable in view of the non-Gaussian shape of Fig. 3. In order to illustrate more fully the effect of scatter on the data, we have also plotted geometrical averages (the lower dots) and standard errors of the pole-J_{100} values within each 10° latitude interval. Whereas the arithmetic averages are sensitive to the occasional occurrence of very high individual intensity values, the geometric ones are sensitive to the occurrence of near-zero values.

The geometric standard deviation of pole-J_{100} values in each latitude interval is a factor generally between 2.0 and 2.5. Most of this variation is probably due to the variables (b) and (c) of Section 3.1, because considerable variations in intensity occur even within single lava flows. The variation in dipole strength with time for most VGP latitudes is therefore likely to be described by a geometrical standard deviation of less than a factor of 1.5, *cf.* fig. 1 of Wilson *et al.* (1972).

From either linear relation, we find that the ratio between the mean virtual dipole moment magnitudes for a VGP at the geographical pole and one at the equator is close to 4.0. In this derivation, all points of Fig. 6(b) are given equal weight, although the low-latitude points are based on much fewer lavas than the others. Inclusion of low-reliability lavas, i.e. those having α_{95} between 23.5° and 60°, causes this ratio to increase to between 4.5 and 5.0.

However, there is of course no known reason why the VGP moment *vs.* latitude relation should be a linear one. For instance, the average of Fig. 6(b) can also be approximated by relations of the type

$$\text{average } J_{100} \text{ at VGP} = A - B \cdot \cos(2 \cdot \text{VGP latitude}). \tag{3}$$

In the case of the geometric means of Fig. 6(b), equation (3) will give a better fit to the data than the linear relation which we have drawn. With this cosine relation, the derived ratio between the virtual pole moments at 90° and 0° latitude is only about 3.0. Dagley & Wilson (1971, fig. 2) obtained from their Icelandic data a relation very similar to the upper data set

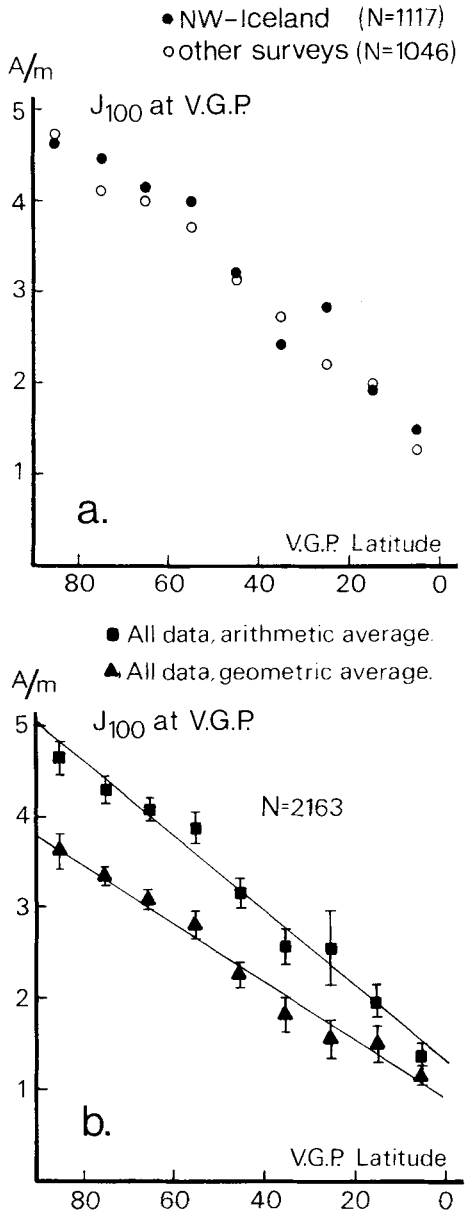

Figure 6. (a) Same data as Fig. 5, both polarities combined. (b) All data of (a) combined. Upper points: arithmetic averages of pole-J_{100} values. Lower points: geometrical averages. Standard error bars are shown. For numbers of lavas used for this graph, see Fig. 8.

of Fig. 6(b). Their results are based on more detailed demagnetization work than ours, but our data include about 3.3 times as many samples. Their rejection criteria were not stated.

Dagley & Wilson (1971) and Wilson *et al.* (1972) suggested that certain inflections occurring at mid-latitudes in their virtual moment versus latitude curve might be statistically significant. These could indicate that the configuration of the field were changing from a regular or dipole-dominated state to a transitional or non-dipole dominated state, with a corresponding sharp reduction in VGP moment as observed from Iceland. Several authors have accordingly made a distinction between regular and transitional fields at a VGP latitude of 50° N

and S. In our data, however, we do not see any persistent inflection (Figs 5 and 6) that could be significant enough to warrant this distinction. When the data of Wilson and coworkers are averaged over 10° latitude intervals with normal and reverse lavas combined, the above inflections are in fact eliminated and hence appear to be due to natural fluctuations within their data set.

A further argument against defining 50° latitude as a boundary between regular and transitional pole positions is that (both in our data and those of Wilson and coworkers) about 20 per cent of all observed pole positions would then be in the latter category. This is an unduly high percentage in view of the fact that in Icelandic lavas do we only very occasionally record complete or even partial pole paths. Most of the lavas which yield pole positions below 50° occur, either singly or as tightly grouped poles, within series of high-latitude poles in the same hemisphere. A different approach to the definition of transitional poles will be proposed in Section 4.2.

4 Frequency distribution of fields and poles

4.1 FISHER STATISTICS; THE EFFECT OF DISCARDING LOW-LATITUDE POLES

With a data set of over 2000 reliable magnetic directions, one should be able to obtain a good estimate of the directional distribution of these and their corresponding VGPs.

Mean fields and associated statistical parameters, obtained from the collections of Table 1(a) by Fisher's (1953) statistics, are listed in Table 3. The effect of within-flow scatter on the results of Table 3 is small: it is readily shown using equations on p. 417 of Sanver (1968) that correcting for this effect would lower the main θ_{63}-values in Table 3 by half a degree or less. The mean field direction from lavas of low reliability in our collection ($23.5 < \alpha_{95} < 60°$, Table 3) is quite similar to that from lavas having lower α_{95} values. However, the former exhibit much more scatter, as may be expected from the discussion in Section 1.

The following results may be seen from Table 3:

Table 3. Mean fields and poles from lavas of Table 1(a).

Fields	N	D	I	k	csd	I_d
North-west Iceland	1117	7.7	75.6	11.1	24.4	77.2
Others	1046	8.9	74.4	12.9	22.6	76.8
Normal	1067	13.1	75.4	12.3	23.2	77.0
Reverse	1096	3.9	74.6	11.5	24.1	77.0
All ($\alpha_{95} < 23.5°$)	2163	8.5	74.8	10.6	23.5	77.0
$23.5 < \alpha_{95} < 60°$	202	10.0	72.2	5.0	36.8	77.0

N is number of lava flows; D, I are declination (east) and inclination (down) of mean field; k is Fisher's (1953) precision parameter; csd is circular standard deviation (degrees); I_d is average inclination of the geocentric axial dipole field at our collection sites.

Poles	N	Long.	Lat.	k	csd	α_{95}
North-west Iceland	1117	65	87.0	5.9	33.8	1.9
Others	1046	92	85.4	6.7	31.6	1.8
Normal	1067	70	84.3	6.3	32.7	1.9
Reverse	1096	111	87.9	6.3	32.7	1.8
All ($\alpha_{95} < 23.5°$)	2163	81	86.3	6.3	32.8	1.3
All ($\alpha_{95} < 60°$)	2365	83	86.2	5.8	34.0	1.4

N, k and csd are defined above; Long., Lat. are east longitude and north latitude of each mean VGP position; α_{95} is 95 per cent confidence angle for each mean pole position, assuming that there are no systematic errors affecting our data.

Mean virtual poles from both north-west Iceland and from the remainder of the present collection are 'right-handed', i.e. they lie about 4° away from the geographical pole in a direction approximately perpendicular to the Iceland meridian. The right-handedness is in agreement with palaeomagnetic observations from other Neogene and Quaternary regions, as commented upon by Wilson & McElhinny (1974) and Watkins & Walker (1977). It characterizes the means of both high- and low-latitude poles of our collection. It is very difficult to account for this persistent tendency by any systematic errors of measurement, by the presence of right-handed VRM, or by local tectonic processes, so it may be a general property of the late Cenozoic geomagnetic field.

The greatest amounts of right-handed offset (> 5°) between mean palaeomagnetic poles and the geographical pole occur in our oldest lava flows, i.e. those from north Iceland and from the older parts (> 11 Myr) of the north-west peninsula. However, given the observed internal scatter of the data and possible errors of up to 2° due to uncertain regional tilt corrections, this variation can only tentatively be ascribed to true polar wander.

On the whole, though not in all the individual surveys of Table 1, right-handedness is more pronounced in normal than in inverted reverse magnetic directions (Table 3).

The mean poles from Table 3 are only very slightly far-sided, being on average about 1° on the far side of the geographic pole. Reverse poles are more far-sided than normal poles, and the older mean poles mentioned in the previous paragraph are less far-sided than the younger poles. The latter time variation is opposite to that found by Wilson & McElhinny (1974) in eastern Iceland. It is therefore likely that neither is significant.

The poles derived from mean field directions in our Icelandic lavas are more far-sided than the mean pole positions, because of the non-linear relationship between field inclination and VGP latitude. The difference is generally less than 3° of arc. As concluded in the case of eastern Iceland lavas by Watkins & Walker (1977), the statistical parameters of field (or pole) means are very similar for normal and reverse lavas (Table 3).

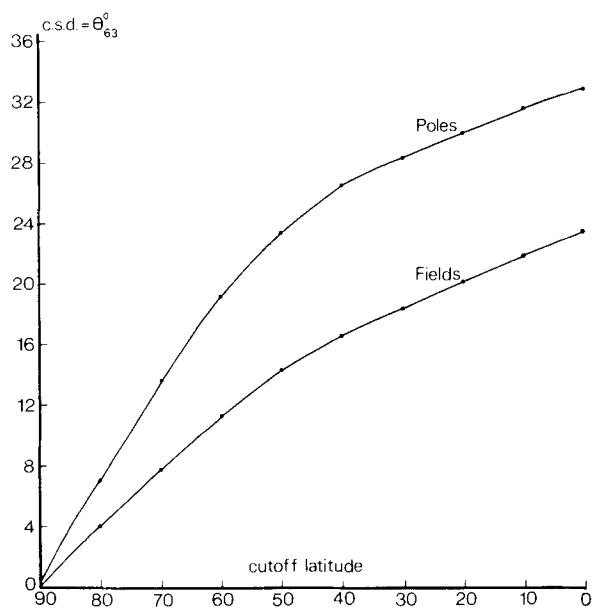

Figure 7. Variation of circular standard deviation of our observed palaeomagnetic directions (lower curve) and virtual pole positions (upper curve), when all lavas yielding VGP positions below a specified cut-off latitude are discarded. Values on extreme right are those of Table 3 (N = 2163).

With our large collection of palaeomagnetic directions, we can investigate quantitatively the effect of discarding low-latitude virtual poles or fields, as is commonly resorted to in smaller palaeomagnetic surveys. Fig. 7 shows how the circular standard deviation (θ_{63}) of the present data set ($N = 2163$) progressively decreases with increasing value of 'cut-off' VGP palaeolatitude. This graph should be useful as a standard against which to compare smaller palaeomagnetic surveys from the Iceland region: surveys yielding values of θ_{63} appreciably different from those of Fig. 7 have possibly only sampled the geomagnetic field for a short interval, and hence are not representative of the long-term behaviour of the field. As we have stated previously (Section 3.4; Saemundsson *et al.* 1980), there does not seem to be any physical justification for the exclusion of low-latitude VGPs or fields from the calculation of statistical properties in palaeomagnetic collections. Rather, many previous collections have been so small that such low-latitude directions, however real, have had the appearance of accidental outliers.

4.2 DISTRIBUTION OF VGPs IN LATITUDE

Fig. 8 shows the latitude distribution of virtual geomagnetic poles as derived from the surveys of Table 1(a). The obvious similarity between the two data sets of Fig. 8(a) when grouped as shown, is one more demonstration that we have sampled the geomagnetic field sufficiently for a long-term picture of its behaviour to be obtained. Also, the similarity between the groupings of Fig. 8(b) demonstrates that there is no significant difference between normal and reverse geomagnetic poles as regards their latitude distribution.

Fisher-distributed poles should be proportional in numbers to $\exp(k \cos\theta)$, where the colatitude θ is measured from their own mean pole, or to a good approximation, from the geographical pole. Although the distribution of Icelandic VGPs is fairly well represented by a

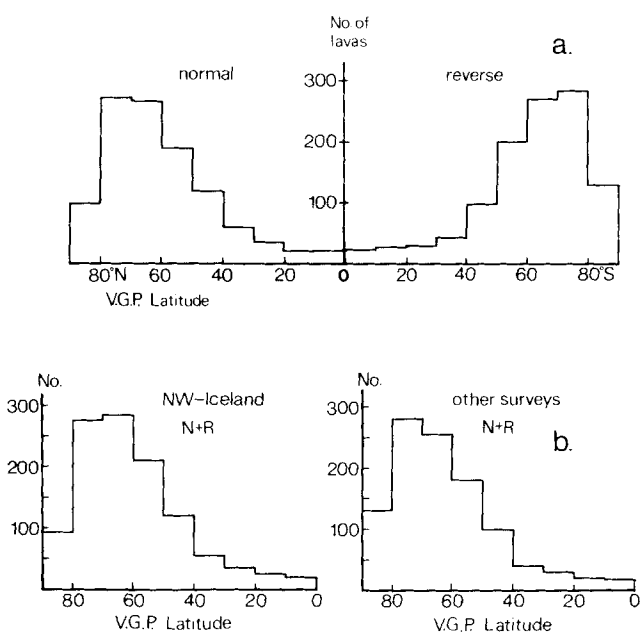

Figure 8. (a) Histogram of the distribution of VGP positions in latitude. Normal and reverse flows plotted separately, all surveys of Table 1(a) combined. (b) Same data as (a), normal and reverse lavas combined. Total number = 2163. Right diagram is same as fig. 7(a) of Saemundsson *et al.* (1980).

Fisher distribution with a precision parameter k of just over 6 (i.e. a csd of about 33°, *cf.* Table 3), it has become apparent in recent years that there are systematic differences between the two. In particular, Harrison (1980) points out that Icelandic results contain more low-latitude poles than can be accounted for by a Fisher distribution. He has therefore suggested that the observed latitude distribution of VGPs is due in part to a population of poles uniformly scattered over the globe at random.

We have fitted our data (Table 1a) to combinations of Fisherian and random pole distributions. The parameters of the best-fitting computed distribution are to some extent dependent on the method chosen for weighting deviations from it, but a much improved fit to the results of Fig. 8(b) is obtained with a 9–12 per cent proportion of random poles, the remainder approximating a Fisher distribution with $k = 7.5$–9.

However, it should be recalled that the Fisher distribution is intended to describe errors in a direction measurement rather than to model the behaviour of the geomagnetic field. Its choice for the latter purpose has been dictated largely by its computational convenience. We consider that the separation of observed poles into Fisherian and random populations (Harrison 1980) is artificial and confusing at the present stage of knowledge about the behaviour of the geomagnetic field. An alternative distribution with one variable parameter, that could be found to fit reasonably with large collections of reliably determined VGP data, would be more helpful in describing and comparing first-order characteristics of the palaeosecular variation from different surveys.

A Bingham distribution of the longitudinally symmetric type

$$f(\theta) = C \exp(k' \cos^2 \theta) \tag{4}$$

where C is a normalizing constant (Onstott 1980) is a fairly good choice for such work. However, it is inconvenient in that the parameter k' has to be evaluated by iteration. It appears that for the Icelandic poles of Fig. 8 combined, the best-fitting value of k' is about 4.5, yielding residuals only slightly larger than the model of Harrison (1980).

For comparison, both the distribution (4) and a Fisher/random distribution are shown in Fig. 9, with a histogram of our VGP latitude data. It is apparent from Fig. 9 that even more and better data will be needed before an objective judgement on the relative accuracy of their fit to Icelandic VGPs can be made.

The Bingham and the Fisher distribution functions are the exponentials of commonly used 'window functions' from spectral analysis. Other such functions may well turn out to

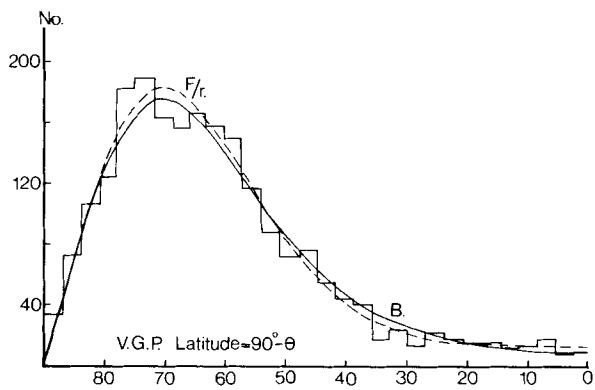

Figure 9. Histogram of 2163 observed pole latitudes, in 3° latitude intervals. For comparison, the solid curve shows a theoretical distribution proportional to $\exp(4.5 \cdot \cos^2\theta)\sin\theta$, and the broken curve shows a distribution composed of 90 per cent Fisher-distributed poles ($k = 8.5$) and 10 per cent randomly distributed poles.

be applicable to palaeomagnetic results: thus, a distribution proportional to exp (5 exp $(-\theta^2)$), where θ is colatitude, has been found to fit the Icelandic VGP data just as well as the Bingham function with $k' = 4.5$. When the observed frequency distribution of VGPs from Iceland is plotted at 3° intervals, as in Fig. 9, there is some indication of a sharp reduction in its slope near 35° latitude. Further palaeomagnetic research in Iceland, with improved sampling and measurement techniques, may perhaps allow us to distinguish such a flat 'tail end' from the main distribution of virtual poles. This tail end might then (again, perhaps) be identified with a true transitional state of the geomagnetic field, i.e. a state such that the VGP has a > 50 per cent chance of crossing the equator before it returns to the same latitude level.

4.3 SOME CONSEQUENCES OF THE OBSERVED LATITUDE DISTRIBUTION OF PALAEOMAGNETIC POLES

According to Fig. 9, our observed distribution of palaeomagnetic poles is well approximated by a continuous curve proportional to exp $(4.5 \cos^2\theta) \sin\theta$. This curve also fits satisfactorily with the distribution data of Dagley & Wilson (1971) and with the combined results of other Icelandic data available. This distribution and its integral over θ (Fig. 10) have various properties worth noting. Thus, it appears that the latitude range where the VGP is most commonly to be found, is around 70° N or S (73° in our actual data) which is unexpectedly low when compared to the present-day geomagnetic field. The chance that the VGP will be found within 10° of the geographic pole is only 11 per cent. The VGP will on average spend 50 per cent of its time below 64½° latitude, 9 per cent below 35° latitude (see Section 4.2), and about 2 per cent below 10° latitude (see Section 4.2).

An infinitely large collection of directions from this distribution would yield $k = 6.2$ or θ_{63} = csd = arc cos $(R/N) = 33°$ if analysed by Fisher statistics (*cf.* also Fig. 7). By generating in a computer finite populations of palaeopoles drawn from a Bingham distribution of $k' = 4.5$, we can calculate how various statistical properties may be expected to be distributed in typical palaeomagnetic surveys at 65° latitude.

Fig. 11 shows 90 per cent confidence limits for values of the csd in surveys of various sizes, along with average (expectation) values of α_{95} and of the angle between the mean VGP position and the geographical pole. As before, no allowance is made for effects of within-unit scatter or for possible serial correlation between successive directions in a survey. If a lava collection of given size is split into two equally large groups of directions, such as normal or reverse lava flows, or the upper and lower parts of section, the angle between the

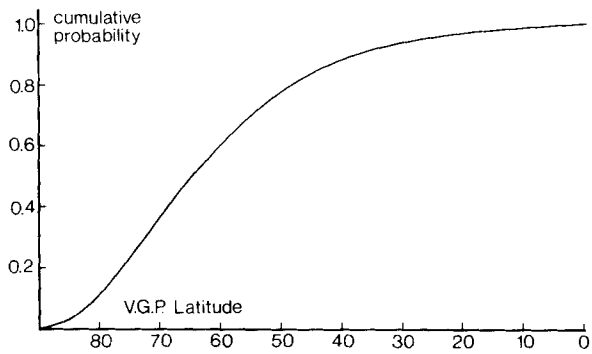

Figure 10. Cumulative Bingham distribution with $k' = 4.5$ (integral of solid curve in Fig. 9), normalized to unity.

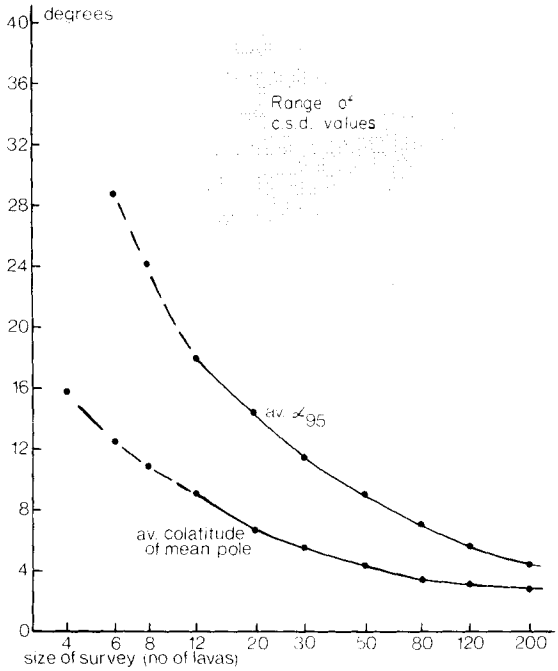

Figure 11. Expectation values of some statistical parameters in VGP distributions from small palaeomagnetic surveys at 65° latitude. These parameters were computed for randomly generated finite pole populations, drawn from a Bingham distribution with $k' = 4.5$. The abscissa shows the size of a survey in lavas. See text.

mean poles of these two sub-collections may fall within a wide range of values from zero upwards. However, average values of this angle are of similar magnitude as the mean α_{95} for such a collection (Fig. 11).

4.4 DISTRIBUTION OF LOW-LATITUDE VIRTUAL POLES IN LONGITUDE

The results of Section 3.4 indicate that the geomagnetic dipole moment changes by a factor of 4 ± 1 between VGPs at the geographical poles and at the equator. This implies that the average field intensity due to equatorial poles (latitude $< 10°$) in Iceland was about one-sixth of that from axial poles, i.e. approximately 0.07 Oe, if we use estimates of Tertiary geomagnetic dipole moment values quoted by Wilson *et al.* (1972).

Local geomagnetic anomalies, due to remanence in crustal rocks, at the time of emplacement of the lavas sampled by us, were probably somewhat smaller than the anomalies now observed within the active volcanic zone of Iceland. This is due to the quiet climatic conditions and subdued topography that apparently prevailed during the late Tertiary in Iceland. A mean anomaly value of 0.01 Oe may be assumed, and hence we conclude that the observed geomagnetic field during polarity transitions was mostly of core origin.

It has been debated for several years whether the geomagnetic pole, as seen from one particular locality, should be expected to trace a definite path across the equator in preference to others, or whether such transitional pole paths are uniformily distributed in longitude.

Fig. 12(a, b) shows the longitude distribution of observed mid- and low-latitude pole positions in the present collection of lavas ($\alpha_{95} < 23.5°$). Poles below 40° N or S and those

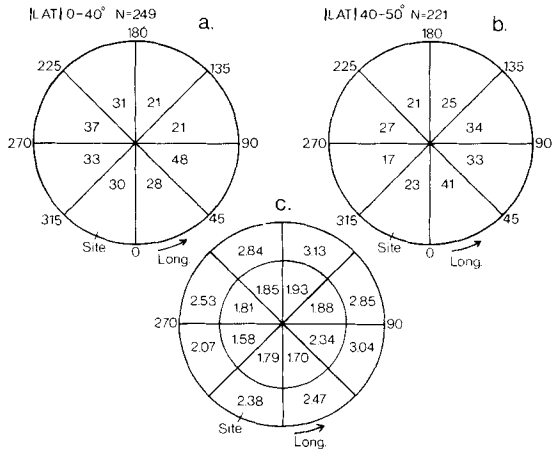

Figure 12. (a) Distribution of low-latitude VGPs in 45° segments of longitude (east of Greenwich). View from geographical north pole. Data taken from lavas of Table 1(a), $\alpha_{95} < 23.5°$. (b) As above, but using mid-latitude VGPs. (c) Mean pole-J_{100} values in all 470 lavas of Fig. 12(a, b). Outer numbers: arithmetic averages; inner numbers: geometric averages. Units are $A\ m^{-1}$.

between 40° and 50° are plotted separately. Reverse pole positions were not inverted in Fig. 12.

It is apparent from Fig. 12(a, b) that there is no strong preference for the transitional poles to be found in any one particular longitude interval. The most noticeable tendency is for the poles to be found in the two regions which are ± 90° away from Iceland in longitude.

Fig. 12(c) shows how the arithmetic and geometric means of remanence intensities (J_{100}, transformed to the respective pole in each case) vary with longitude. The standard error of each mean is about 12 per cent. Wilson *et al.* (1972) concluded from their Iceland data that there is a slight longitude dependence of mean geomagnetic moments. Fig. 12(c) is comparable to their Fig. 6(c), but there is only partial agreement between the two. Whereas our results indicate relatively strong mean moments in the whole longitude range 45°–225° E, theirs yield strong moments in parts of the 100°–320° E interval. We therefore consider that these results may be due to chance fluctuations, and hence that more detailed analysis would be beyond the practical limit of resolution in the data. A similar analysis of our VGP moments from high latitudes also yields no significant longitude effect.

5 Conclusions and discussion

The general philosophy of the present paper is conservative. Experience is teaching us that one should retain simple models and concepts of the geomagnetic field behaviour for as long as possible, and not depart from stochastic null hypotheses or first-order approximations until such departures have been reproducibly verified by different reliable sources of data and shown to be outside the range of possible errors. Most palaeomagnetic surveys only show us a very limited or filtered part of the geomagnetic variation pattern, and are subject to several types of random and systematic errors. Many details, correlations or other second-order properties which appear to be significant in one survey, turn out to be either a part of the natural short-term noise spectrum of the field, or they may be caused by inappropriate sampling or statistical procedures, rock-magnetic and geological complexities, and so forth. Unfortunately, current models of the generation of the geomagnetic field are necessarily oversimplifications and of no concrete value in the interpretation of palaeomagnetic data.

The present paper has attempted to apply data, based on an unusually large and homogeneous collection of magnetically stable and fresh lava flows, to some of the important unsolved problems of palaeomagnetic research. However, it must be remembered that our collection is by no means perfect. It is pieced together from several surveys which are partly overlapping, but they also include of the order of 10 per cent unsampled segments and possibly large hiatuses. Various error sources have also been pointed out in our previous publications on this collection (Kristjansson *et al.* 1980; Saemundsson *et al.* 1980). Further palaeomagnetic sampling of Icelandic lava flows, begun in 1980, will attempt to improve within-lava consistency of directions by increasing the number of samples collected per flow and the number of demagnetization steps. This should also reduce the rejection rate for lavas used in secular variation calculations, from our current total rate of 12 per cent (Table 1a).

The following conclusions should therefore be regarded only as tentative, to be followed up by more extensive and detailed palaeomagnetic research in Iceland and elsewhere. A complete list of magnetic directions from north-west Iceland will be published separately, along with mapping and analysis of K-Ar results and stratigraphy-related magnetic properties of that collection.

We find from the above (Section 2.2) that with our own collection of over 2000 flows as well as the collection of Wilson and collaborators of over 1000 flows, we cannot reject the null hypothesis that normal and reverse polarity states of the geomagnetic field in Iceland were equally probable during the last 14 Myr. The conclusion by Wilson *et al.* (1972) that normal polarity was significantly more probable, is erroneous. If both the number of reversals per unit time and the rate of eruptions (of lavas reaching our sampling sites) per unit time had a Poisson distribution, then the mean length of a geomagnetic chron is $130 \pm 50 \times 10^3$ yr. However, this mean may be even shorter, if substantial hiatuses in volcanic activity occurred. Long chrons ($\simeq 0.5$ Myr) of either polarity may occur, e.g. during Anomaly 5 time or the lower Matuyama.

The distribution of primary remanence intensities in a homogeneous collection of basalt lava flows is empirically well described by the hyperbolic distributions of Barndorff-Nielsen (1977). Using these distributions, we show that there is complete equivalence between normally and reversely magnetized lavas in all statistical properties of their intensity distribution.

Plotting mean virtual dipole moment magnitude versus VGP latitude shows that the mean moment, as seen from Iceland, was a factor of four (± 1) stronger during periods of axial dipole fields than during equatorial dipole fields. No significant evidence is found for either the existence of weak near-axial dipoles, strong equatorial dipoles, or a rapid decay of moment with latitude in mid-latitudes that might be used as a boundary between transitional (intermediate) and regular configurations of the field.

Moment versus latitude curves are also similar for normal and reverse polarities. From this, it is most natural to assume that both the actual mean strength of the dipole field and the rock magnetic properties of the basalts are independent of polarity. The so-called oxidation-polarity paradox (Wilson & Haggerty 1966), i.e. a supposed positive correlation between oxidation state and reverse magnetic polarity in rocks, cannot have applied in the present case (as highly oxidized lavas are generally more intensely magnetized and more stable than others), unless the reverse primary geomagnetic fields were weaker than normal fields by a factor precisely cancelling the effects of the oxidation. It is likely that much of the original sample material on which this correlation was based, simply had not received adequate demagnetization treatment to rid the less oxidized samples of Brunhes age viscous magnetization.

Mean field directions in normal and reverse lava flows are similar within a few degrees.

Normal flows are more right-handed than inverted reverse flows, but the latter give a slightly more far-sided mean pole. Right-handedness is present in means of both low-latitude and high-latitude poles, and it is somewhat more prevalent in the older than the younger parts of our collection, due to polar wandering or other effects.

The distribution of virtual poles in latitude is similar for normal and reverse lavas. It is, however, not satisfactorily described by the Fisher (1953) distribution, which has been found to drop off too rapidly at low latitudes. Accounting for most of the observed low-latitude poles by the introduction of a ~ 10 per cent random population of poles (Harrison 1980) may create difficulties for comparisons between different surveys.

It appears to be more advisable at present to replace the Fisher distribution with another empirical distribution having one adjustable parameter. In our data, it is convenient to use the exponential of a window function such as $k' \cos^2 \theta$ or $c \exp(-\theta^2)$, where the colatitude θ is in radians. A good fit to the observed Iceland data occurs for $k' \simeq 4.5$ or $c \simeq 5.0$, in which case the value of the distribution function is 90–100 times greater at the poles than at the equator. The most commonly observed latitude intervals for the VGP are around 70–75°.

The term 'transitional' (or 'intermediate') magnetic directions (or poles) has had various definitions in the past, and it has been applied loosely in the present paper. Noting, however, that our VGP distribution has a rather flat tail from 35° towards the equator, we venture to suggest that this may point the way to a meaningful distinction between regular and truly transitional geomagnetic field states.

There is a slight and possibly non-significant preference for mid- and low-latitude VGPs to occur 90° away from Iceland in longitude. There is also no significant variation of the moments of these or other VGPs with longitude. These results indicate that the observed magnetic field is not affected in any permanent or predictable way by whatever azimuthal asymmetries that may be present in the Earth's core.

We see no definite answer, in the Icelandic data alone, to the fundamental question whether dipole or multipole terms dominate the geomagnetic field during its polarity transitions. For this, comparable data from a low-latitude area must be considered.

Acknowledgments

The authors wish to pay tribute to the memory of Norman D. Watkins, whose unique qualities as a scientist were so essential for the success of our joint mapping projects in Iceland.

These projects were supported, at various stages, by NSF grants to Dr Watkins, by the University of Rhode Island, by the Science Fund of Iceland and by the Alexander von Humboldt Stiftung in Bonn.

We wish to thank those scientists, students and technicians who took part in the geological mapping of our survey areas in Iceland, and who carried out much of the measurement and computational work on the cores collected there. Particular thanks are due to Brooks B. Ellwood, now of the University of Georgia, and Kristjan Saemundsson of the National Energy Authority of Iceland. Thorkell Helgason and Sigfus Johnsen of the University of Iceland wrote special computer programs for the present paper. Bryndís Brandsdottir skilfully drafted the diagrams.

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