Some statistical properties of palaeomagnetic directions in Icelandic lava flows

L. Kristjansson *Science Institute, University of Iceland, Dunhaga 3, 107 Reykjavík, Iceland*

Summary. This paper extends the efforts of Kristjansson & McDougall to obtain a semi-quantitative description of various long-term (0.1–10 Myr) properties of the geomagnetic field in Iceland. Due to the long time intervals between eruptions of the lavas recording the field, local average and stochastic properties are emphasized, rather than detailed aspects such as pole paths. These properties can be represented by smooth functions of virtual-pole latitude. It is possible to describe both the frequency distribution of virtual poles in latitude and the estimated frequency of geomagnetic reversals, by a simple process of random walk of the pole. This is also in agreement with the observed long-term symmetry of the reversal process, and demonstrates that memory effects are unnecessary to account for the behaviour of the field. The average transition time for the field is of the order of 5–6000 yr. Right-handedness is a pervasive property of the field in Iceland, apparently increasing with age. It is demonstrated that the size of palaeomagnetic collections in lava sequences has to be much larger than 20 units in order to yield consistent values of statistical parameters for mean palaeofield directions.

1 Introduction

Most information available on the properties of the palaeomagnetic field is derived from studies on sediments and on ocean-ridge magnetic anomalies. In these it is likely that the received signal has been strongly low-pass filtered, so that we are not observing the full range of variations exhibited by the field. Palaeomagnetic studies on igneous rock units, which may approach a series of independent spot readings of the field, are unfortunately too often limited in numbers, in magnetic stability, or in the length of time covered, to allow variations in the field to be properly appreciated.

Only in Iceland and a few other areas have sufficiently extensive collections from units carrying a stable original remanence been made. A research project in Eastern Iceland, reviewed in detail by Watkins & Walker (1977) has for many years been the most comprehensive source of data from a single region on long-term (0.1–10 Myr) variations of the geomagnetic field.

The late N. D. Watkins and collaborators carried out extensive sampling in Icelandic lavas in 1972–78 for palaeomagnetic and K-Ar work. Kristjansson & McDougall (1982) combined three of these studies, totalling 1201 lava flows, for statistical comparison with a collection of 1261 lavas in NW Iceland, to extract a variety of conclusions on the long-term properties of the field.

Fig. 1 shows the approximate location of the collections studied. Their ages are in the range 1–15 Myr. All original magnetic and age data and geological maps of these areas have been published, with the principal exception of remanence intensity data from the Borgarfjördur (area 1) lavas. These data are available from the present author. After rejection of lavas with unreliable magnetic directions, the two above sets of data comprise respectively 1046 and 1117 flows. The following main conclusions on these were obtained by Kristjansson & McDougall:

The average rate of reversals of the main geomagnetic field is at least eight per Myr.

There are no significant asymmetries between normal and reverse fields.

The moment of the virtual dipole (VGP) varies with its latitude, by a factor of 4 between the geographic poles and the equator.

The secular variation of VGPs in Iceland is described by a Bingham frequency distribution $(k' \simeq 4.5)$ in latitude, rather than a Fisher distribution.

There is no preferred pole path during reversals.

Some of these results are at variance with common or conventional opinions on the nature of the field. For example, anomaly inversion in oceanic areas (see Harland *et al.* 1982) has by many been taken to indicate that only five or so magnetic reversals occurred per Myr in the last 15 Myr. However, the recent proliferation of geomagnetic reversal events suggested to have occurred in the last 150 000 yr, strongly indicates that the ocean magnetic anomaly record may not be complete as regards short-period reversals.

At the time of writing of the paper by Kristjansson & McDougall (1982), complete stratigraphic and K-Ar data on some of the areas of Fig. 1 was not yet available. With these
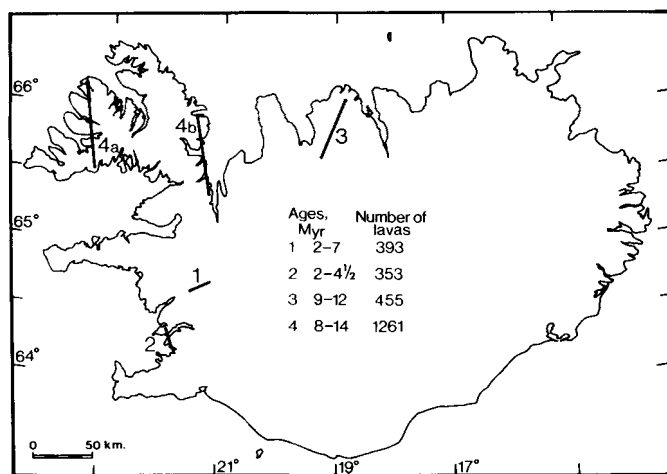
Figure 1. Map of major sampling locations by N. D. Watkins and collaborators in Iceland, 1972–78. Detailed lists of palaeomagnetic data are found in these papers: (1) Watkins *et al.* (1977). (2) Kristjansson *et al.* (1980). (3) Saemundsson *et al.* (1980). (4) McDougall *et al.* (1984).

data in hand, however, we may now try to shed light on some additional questions on the nature of the geomagnetic field, such as the following:

Was the field predominantly central and dipolar, both during and between polarity transitions? Does it average out to a centred axial dipole field?

How do you distinguish 'excursions' from proper reversals, and should you then take into account the intensity of the field as well as its direction?

How long a time does it take the field to reverse itself, and is the second half of the reversal then any different from the first half?

Are memory effects, for instance of past polarity states, important in modelling the field behaviour?

All of these questions are important, some for the continued use of the palaeomagnetic method in Icelandic geology (Kristjansson 1984), and others for possible comparisons of long-term palaeomagnetic results between strata in different latitudes and of different ages. In attempting to answer them with the data sets available at present, we must be careful at every step to select the experimental approach in such a way that our conclusions are not unduly affected by the various imperfections of the data.

2 Angular variation in observed field strength

Because of the strong influence of the Earth's rotation upon the geomagnetic dynamo, the observed long-term average field strength at any locality may be expected to decrease with increased angular deviation of the geomagnetic field from an axial-dipole configuration.

Dagley & Wilson (1971), Wilson, Dagley & McCormack (1972), and Kristjansson & McDougall (1982, figs 5, 6) presented estimates of relative virtual dipole moments as a function of VGP latitude, using lava remanence intensities after cleaning. This method assumes that short-term field strength fluctuations as well as intensity variations due to rock magnetic causes have been averaged out by virtue of the large number of units included. The success of this method is borne out by the good agreement between results from different areas in Iceland; a similar variation has also been observed in some well-documented studies of individual geomagnetic transitions elsewhere (e.g. Valet & Laj 1981).
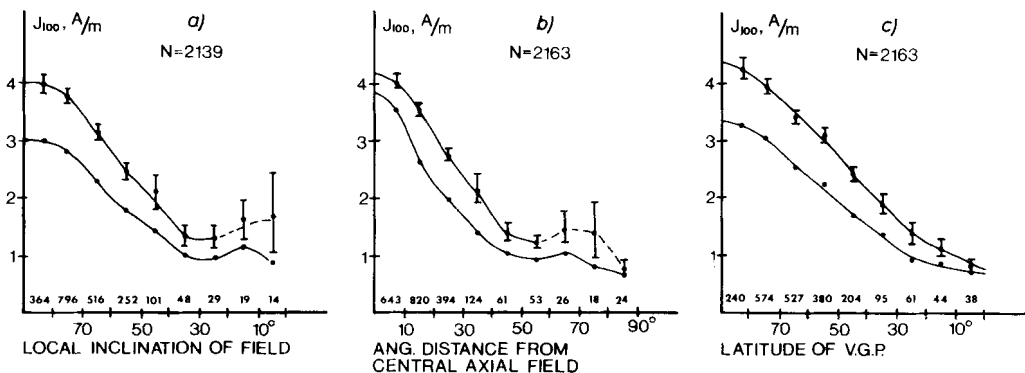
Figure 2. Variation of relative mean geomagnetic field strength in Iceland, as determined from remanence intensity (J) measurements on lavas after 0.01T cleaning. The data are plotted as a function of three different angular measures of the field. Upper curves: arithmetic averages, with standard errors. Lower curves: geometric averages. Number of lavas averaged in each 10° interval shown below.

LONG-TERM MEAN V.G.P. MOMENT
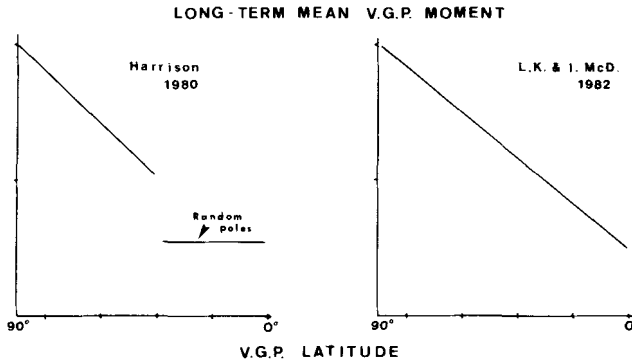
Figure 3. Schematic representation of the variation of virtual dipole moments in Iceland with VGP latitude. Left: as concluded by Harrison (1980) mostly from East Iceland lavas. Right: as concluded by Kristjansson & McDougall (1982) from lavas in the surveys of Fig. 1.

For some studies, however, it may be advantageous to present the intensity data directly, rather than in the form of virtual dipole moments. This is done in Fig. 2, where mean apparent field strength in Iceland is plotted as a function of three different angular measures of the field. The data base is the same as that in Kristjansson & McDougall (1982), and for reasons explained in that paper, both arithmetic and geometric averages are plotted in each case. Standard-error bars for the latter have been left out of Fig. 2 for clarity, but are generally $0.5-1$ times the arithmetic standard error bars in size. In order to avoid polarity ambiguities, Fig. 2(a) does not include data for which the VGP latitude has a sign opposite to that of the inclination.

The decrease of relative mean strength in Iceland with decreasing VGP latitude (Fig. 2c) is particularly smooth. The change in local field strength between axial and equatorial virtual poles amounts to a factor of $6-7$. Harrison (1980, pp. 3518–3519) has claimed that the dipole field appears to collapse at VGP latitudes below $40°$, giving way to randomly varying higher-order fields. We have examined the data set of Wilson et al. (1972) from which Harrison's (1980) fig. 8 is derived, and we are convinced that because of the small size of that data set and its statistical properties, one cannot ascribe significance to the fluctuations on which Harrison's conjecture is based. In any case, the behaviour of the field is governed by many complex and spatially distributed interactions, and our observations are influenced considerably by non-dipole fields as well as by various error sources. A smooth variation of VGP moment with VGP latitude therefore seems to be no less physically reasonable than the model of Harrison (1980). Fig. 3 illustrates the two different points of view.

At the moment, therefore, we conclude that the *average* long-term behaviour of the observed field in Iceland can be modelled by sources whose characteristics vary smoothly with VGP latitude. For simplicity and ease of comparison with data from elsewhere, a central dipole model will be used in this paper as far as possible. Dodson (1980, figs 2–5), however, points out that the relatively large secular variation in Iceland compared to that in low-latitude volcanic sites may be due to the field sources being in fact biased to polar regions of the Earth's core. This could be the case in particular during geomagnetic transitions.

3 Transition time for geomagnetic polarity

Having made the observation (Figs 2c and 3) that the mean geomagnetic intensity can in the long term be described by smoothly varying functions of VGP latitude, this cannot furnish

any natural definition of 'transitional' versus 'regular' states of the field. Rather, the spectrum of geomagnetic pole excursions to low latitudes is to be envisaged as a stochastic process, governed in each case by a number of independent contributing factors. Some of these excursions may lead to permanent reversals of the field, but it is generally not possible to document this process in detail from available palaeomagnetic data. One cannot even be certain whether a particular low-latitude VGP in a lava at the boundary of two polarity zones in the lava pile really belonged to a unique geomagnetic transition between these zones.

Nevertheless, it is for many purposes helpful to have an *ad hoc* criterion for naming some magnetic directions in a lava pile 'transitional' as distinct from others. These criteria have varied between investigators, but the present author has found the 40° VGP latitude level to be useful in this context.

With the excellent K-Ar age control available for stratigraphic sections in the Icelandic lava pile, we are now in a position to estimate statistically the average length of time elapsing while the VGP is travelling between the ±40° latitude levels.

First, we compile statistics of all such transitional lava flows which occur at polarity zone boundaries (Fig. 4). A certain standarization of the geological data is needed for this, as, e.g. multiple 'flow units' occur to a variable extent in the different areas, and the numbering of these has differed between the geologists mapping the areas. By then knowing the approximate mean length of time between successive flows, we can fit a Poisson distribution to each histogram of Fig. 4 and derive an estimated transition time from each.

An overall mean value of 7000 yr per transition is obtained from the histograms of Fig. 4, but this value may be subject to corrections due to incomplete sampling of some profiles, hiatuses in the geological record, occasional profile overlaps, and so forth.
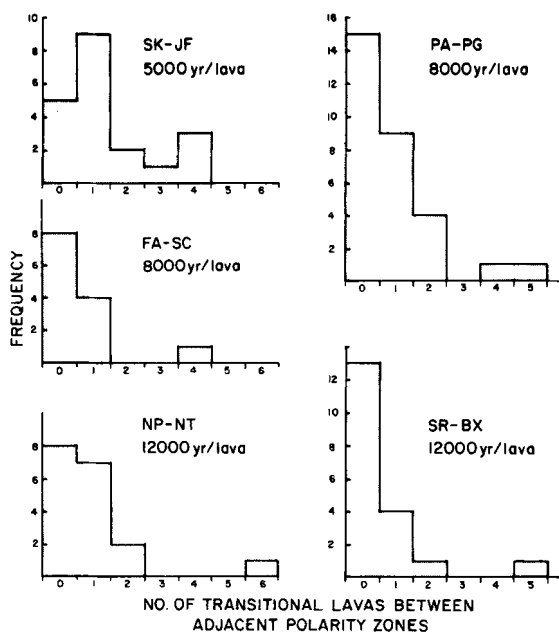
Figure 4. Histograms of the frequency distribution of low-VGP lavas at polarity zone boundaries in Iceland. NP-NT represent area 1 of Fig. 1, FA-SC area 2, and PA-PG area 3; SK-JF and SR-BX are the two major (K-Ar dated) composite sections of area 4. In some profiles, especially in NP-NT, four thin 'flow units' have been counted as one lava flow before plotting the histograms.

A more straightforward procedure of estimating the mean geomagnetic transition time is to consider all the surveys of Fig. 1 together. Using the results of Kristjansson & McDougall (1982) which already include corrections for most of the above error sources, the mean transition time will then be found as: average length of geomagnetic chron × percentage of all flows having VGP latitudes below 40°N or S × percentage of these occurring at polarity zone boundaries ≃ 130 000 × 0.11 × 0.39 ≃ 5500 yr.

The value of 0.11 is, for instance, obtained from the data of Fig. 2(c). Possible errors in this value, yet to be allowed for, include a sampling bias (as profiles are often made to begin or end near a polarity zone boundary) and a stability bias (because transitional lavas carry a relatively weak primary remanence).

The statistically estimated value of 5500 yr is in agreement with various other estimates for transition time lengths in the literature, usually obtained from single transitions only. However, it is clear that this value is very dependent on the definitions employed, particularly regarding the latitude limits used for distinguishing between excursions and transitions.

With the transition time being similar to the time interval between successive lavas as derived from K-Ar dates (see Fig. 4) it is natural to expect continuous pole paths during transitions to be very rarely observed in Icelandic lavas. However, four to six such flows do occasionally appear together. As also noted by Dagley & Lawley (1974), low-latitude poles are somewhat more common at R→N boundaries than at N→R boundaries (60 versus 35 lavas in our collections), but due to the grouping just mentioned, binomial statistics cannot be used to assess the significance of this difference.

4 Modelling VGP movements in latitude

4.1 SYMMETRY ASPECTS

One important question, already mentioned in the Introduction, concerns the point whether the process of reversal is symmetric with respect to its beginning and end. In our collections from Iceland (Fig. 1) we find for example that 126 lava flows with latitudes between 10° and 50° occur at polarity zone boundaries. Of these, 60 were apparently erupted during the first half of the reversal (i.e. before the virtual pole had crossed the equator) and 66 during the second half. The difference in arithmetic or geometric average VGP moments is only 20 per cent (the former group being stronger), and so we feel justified in concluding that the two halves of the reversal are not too different in character.

One may also ask whether there is a substantial difference between apparent dipole moment strengths during polarity transitions (to latitudes > 40°) on one hand and during major excursions (to < 40°) on the other. This has been tested by estimating the ratio of mean virtual dipole moments for low-latitude poles in the two categories. In a total of 238 lavas, the difference in arithmetric mean values of transformed primary remanence intensities is 20 per cent. In geometric averages, the difference is 2 per cent, the lavas at polarity zone boundaries giving the lower averages in both cases. However, as the standard error of each group average is 7−10 per cent, this difference is hardly significant.

Still another problem concerning the reversal process, is how the movement of the virtual pole across the equator may be described. Harrison (1980, fig. 18) has in this context observed that low-latitude (≤ 30°) virtual poles in Icelandic lavas are preferentially (37 poles out of 64) found at polarity zone boundaries rather than in apparently abortive excursions. However, the model to which Harrison (1980) connects this observation may not be sufficiently realistic, as remarked above.

We shall examine below the extreme but still physically reasonable possibility that low-latitude poles always have a tendency of < 50 per cent towards reversing the polarity of the

main field. It turns out that it is quite feasible to describe *both* the latitudinal frequency distribution of VGPs and the observed rate of reversals in this way by a single process. This is the process of random walk, using a Markov chain matrix of transition probabilities to higher or lower latitudes. In keeping with the inference from Fig. 3, the probabilities are postulated to be a smoothly varying function of latitude. This model may also furnish a standard against which to test various observed long-term statistical aspects of the field as recorded in igneous formations, including the serial correlation between palaeomagnetic directions in successive lava flows, and certain lateral magnetization changes on the ocean floor.

4.2 MARKOV CHAIN MODEL OF VGP MOVEMENTS IN LATITUDE

We seek a simple concept, with as few adjustable parameters as possible, to give a satisfactory semi-quantitative description of the stochastic latitudinal movement of the virtual pole as seen in Icelandic lavas. Due to the known westward drift of the field sources, movements of the pole in longitude may on short time-scales ($< 10\,000$ yr) be more regular than those in latitude, but we are not concerned with the former here.

Let the latitude of the VGP perform a perpetual random walk between $+90°$ and $-90°$, using the theory of regular Markov chains (Kemeny & Snell 1976). By making a choice every τ yr, the VGP will decide with probability p to go one step south, q to go one step north, and s to stay put at that latitude. It turns out that the mathematics of this exercise is much simplified, without loss of physical insight, if we first set $s = 0$ at all except the highest latitudes reached. The interval τ is fixed in the simplest version of this model, and so is the size Δ of the latitude step (north or south) taken each time, although in reality the rates of short-term latitude drift of the virtual pole may be different at low and high latitudes.

The size of the latitude step Δ of the random walk can be chosen as $1°$ or, to save computing time, some convenient divisor of $90°$ such as $2°$, $6°$ or $9°$. As may be expected, the long-term characteristics of the field turn out to be reasonably invariant if we let the interval time τ vary in proportion to the square of Δ.

The bias function p is to depend on latitude in such a manner that over a long period of time the frequency distribution of VGPs in latitude resembles a Bingham distribution with $k' = 4.5$ (Kristjansson & McDougall 1982). Symmetry about the equator $[n(i) = n(-i)]$ is ensured if $p(-i) = q(i)$, the index i taking the values $\pm1, \pm2, \pm3, \ldots \pm r$, where $r = +90/\Delta$. Of these, $q(r)$ and $p(-r)$ are necessarily zero, so that $s(r) = 1 - p(r)$.

The steady-state population of the ith latitude interval of Δ degrees will be $n(i)$, where the sum of the ns in the total of $2r$ latitude intervals between $+90$ and $-90°$ is either 1 or a convenient number of VGPs (lavas), such as 1000.

By operating upon the vector n by the probability matrix, one should obtain the same vector in the steady state. As $n(i)$ is known (being the integral of the Bingham distribution function over the respective latitude interval), we can write up a finite set of equations of the type

$$n(i) = n(i+1)\,p(i+1) + n(i-1)\,q(i-1)$$

in order to determine p. If $s(r)$ is also to be found, the number of unknowns will then be one too many. However, it turns out that if we set $p(r)$ close to 1, the other values $p(i)$ will vary smoothly with i, yielding a very satisfactory value for $p(1)$ of just below 0.5. Low values of $p(r)$ result in erratic behaviour of the function $p(i)$. So we shall, with little loss of generality, set $p(r) = 1$.

Table 1 lists, as an example, values of the bias function $p(i)$ for a chosen latitude step Δ of $6°$. We stress that this function depends here neither on time nor on previous move-

Table 1. Values of the bias function p to generate a Bingham distribution ($k' = 4.5$) for VGP positions by random walk.

i	latitude interval	n(i) when Σ n(i) = 1000	p(i)
15	+84 - +90	20.4	1.0000
14	+78 - +84	55.3	0.6315
13	+72 - +78	75.8	0.5388
12	+66 - +72	79.8	0.4883
11	+60 - +66	71.5	0.4549
10	+54 - +60	57.3	0.4319
9	+48 - +54	42.4	0.4169
8	+42 - +48	29.9	0.4089
7	+36 - +42	20.6	0.4067
6	+30 - +36	14.2	0.4106
5	+24 - +30	10.1	0.4190
4	+18 - +24	7.4	0.4323
3	+12 - +18	5.8	0.4487
2	+6 - +12	4.9	0.4683
1	0 - +6	4.5	0.4890
-1	-6 - 0	4.5	0.5110

etc. for negative latitudes.

ments of the VGP. It has a value of 0.5 at around 70° VGP latitude, i.e. at the maximum in the observed frequency distribution of poles, and it has a minimum at close to 40° latitude.

4.3 RESULTS FROM MARKOV CHAIN MODEL

In a period of 8 Myr about 1000 lava flows were erupted in typical Late Tertiary palaeomagnetic profiles in Iceland (Kristjansson & McDougall 1982, section 2.1). The same authors have estimated that if both the occurrence of reversals and of eruptions of successive lavas followed a simple exponential distribution of interval lengths (Poisson process), the observed average of 18 lavas per polarity zone in the lava pile should indicate that an average of 16 lavas were erupted per geomagnetic chron.

Choosing some convenient value for the latitude step Δ of the random walk, we can then simulate this process repeatedly by computer, record the calculated VGP latitudes of 1000 lava flows at a time, and find how the resulting mean reversal rate varies with the size of the time interval τ. Conformity of the simulated pole distribution to the Bingham function is ensured by the probability values used (Table 1).

Some results are illustrated in Fig. 5, normalized to a latitude step Δ of 6° for various values of τ. It is seen that the number of lavas per polarity zone is very nearly proportional to the time interval τ, and that τ must be around 65 yr to generate the observed number of lava flows per polarity zone in the Icelandic lava pile.

A VGP latitude drift of 6° in 65 yr is a little larger than the ~4° drift per 65 yr typical for observatory records from middle and high latitudes in the past couple of centuries. However, we should take into account indications that the present geomagnetic field is relatively strong and therefore stable compared to Late Tertiary averages (Smith 1967). The current longitude drift of the VGP may also be at other times replaced by a pre-
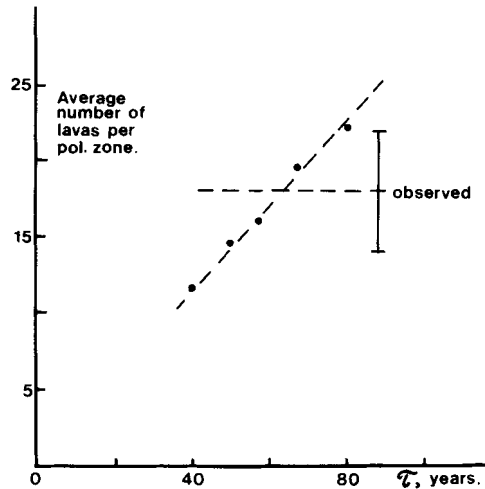
Figure 5. Average number of lava flows per zone of uniform polarity in a computer-generated lava pile, for various values of the time interval τ btween successive 6° steps of the pole to a lower or a higher latitude. Average time interval between lava flows is set at 8000 yr. Horizontal line: observed mean in the surveys of Fig. 1, with error limits as estimated by Kristjansson & McDougall (1982).

dominantly latitudinal drift, as is evident in many of the detailed transition records in the literature.

4.4 TEST OF MARKOV CHAIN MODEL

The previous results show that both the major first-order characteristics of the geomagnetic field in Iceland can be reproduced by the same simple and physically reasonable model. Details of this model can be tested against observational data in various ways, for instance in the distribution of polarity zone thicknesses. We shall use here the approach of Harrison (1980, pp. 3519–3520) to compare actual and predicted long-term behaviour of the field at polarity zone boundaries. As the data set available to us is considerably larger than that used by Harrison (1980), we feel justified in analysing the data in a more quantitative way.

The parameter which we have calculated is the relative number of virtual poles below a certain latitude, which are situated in the lava pile adjacent to or within a polarity zone boundary. The variation in this parameter with the chosen VGP latitude may tell us whether the drifting of the pole across the equator at reversals is a simple random-walk process, or whether it is underlain by a more deterministic mechanism with a time constant in the range of thousands of years.

Using the definition of McDougall, Kristjansson & Saemundsson (1984) for distinguishing between polarity zones and excursions, the graphs of Fig. 6 are obtained. As the graphs are obtained from data that accumulate from right to left, estimated errors become smaller towards the left. The upper curve is experimental results from the data set of Fig. 1; we have also analysed other published data sets from Iceland including that of Watkins & Walker (1977) and obtained comparable results. The lower curve in Fig. 6 is obtained from a continuous series of computer-simulated lava flows, erupted with an average time interval of 8000 yr. The limited results of Harrison (1980) are also shown. The difference between his results and ours may be in part due to the use of different criteria, but subjective decisions are also involved in such a compilation, for instance when a low-latitude lava flow occurs next to either an unstable flow or a hiatus in the record.

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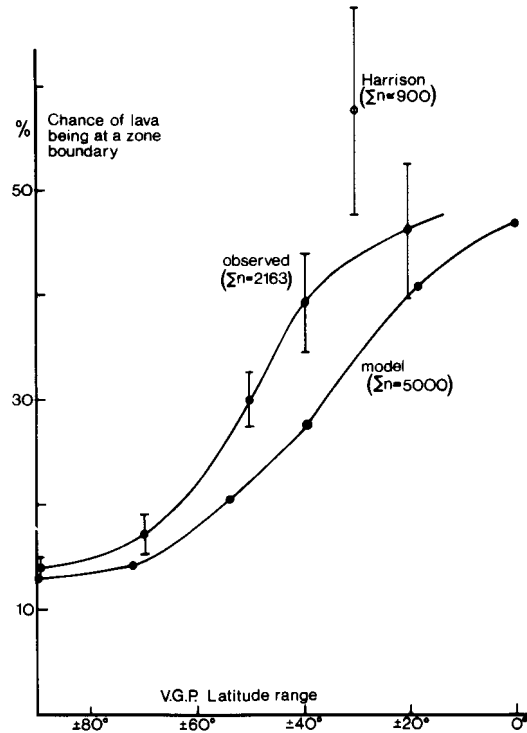
Figure 6. Upper curve: graph of that proportion of lava flows with VGPs below a certain latitude, which occur at polarity zone boundaries in the surveys of Fig. 1. Over 100 polarity zones are represented. Lower curve: same property, in a simulated lava pile of 5000 flows, assuming random walk (6° step/65 yr) of the VGP between eruptions.

It is seen from Fig. 6 that low-latitude poles have a somewhat higher tendency to occur at polarity zone boundaries than would be expected from the Markov-chain model. If taken at face value, it may indicate that reversals do take place at a slower pace than excursions, cf. the intermediate 'metastable' state suggested by Shaw (1975). Possibly, the model may be modified to account for this, by making either the latitude step Δ or the time interval τ a · function of latitude. However, it may equally well be related to the fact that extrusive volcanism in Iceland is more episodic in character than we have assumed cf. the following section. Further analyses along these lines may have to wait until larger, more precise, and more complete palaeomagnetic data sets from Iceland become available.

5 Scatter and serial correlation in palaeomagnetic data from Iceland

It is universal practice in palaeomagnetic research to apply to each particular collection of directional results the statistical parameters derived from the collection itself. Thus, two mean field directions are taken to be distinct if their 95 per cent confidence circles do not overlap.

However, it is becoming increasingly clear from work on Icelandic lavas that such a procedure is only valid if the collections are large, preferably covering at least a few geomagnetic chrons.

As a specific example, we shall examine the suggestion of Watkins, McDougall & Kristjansson (1977) that 20 is a suitable minimum number of lava directions to average in

providing a measure of axial dipole field behaviour. This minimum figure of 20 directions was at the time a considerable improvement from some earlier estimates (see Wilson & McElhinny 1974).

We have computed palaeomagnetic directional statistics from 50 groups of 20 successive lavas (Fig. 7a), taken from table 1 of the paper by McDougall *et al.* (1984). These include some of the lavas designated as overlap flows in their fig. 2.

It is readily seen from Fig. 7(a) that there is much variation in the α_{95} values for these 20-lava groups. This variation does not take place systematically through the lava pile, and it must be looked upon as an intrinsic uncertainty in the determination of the α_{95} parameter from any group of 20 stably magnetized successive Late Tertiary lava flows. The scatter in α_{95} values is very similar to that derived from other Icelandic lavas by Saemundsson *et al.* (1980, fig. 8) which is reproduced here as Fig. 7(b). Upon inspection of the original data it is apparent that the lowest α_{95} values in Fig. 7(a, b) are those obtained from serially correlated lava groups. These lavas appear from geologic evidence to have been erupted in relatively rapid succession, compared to geomagnetic secular variation time-scales. Among these are the 20 lava flows at the bottom of profile BT, those in the middle of SV, and the thin flows JF 60–80 (McDougall *et al.* 1984, fig. 2).
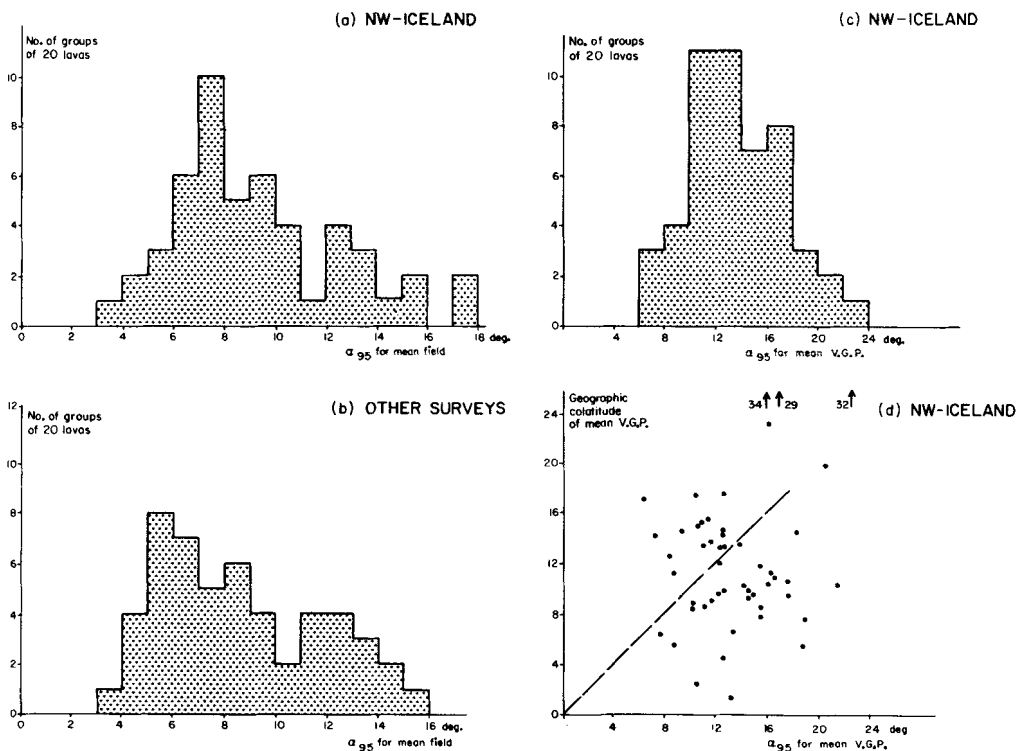
Figure 7. (a) Histogram of between-lava field α_{95} values in 50 groups of 20 successive lava flows each, NW Iceland. Data from McDougall *et al.* (1984); only lavas with internal α_{95} values $<23.5°$ have been used. (b) As for (a) but using data from previously published Late Cenozoic lava collections in Iceland. After Saemundsson *et al.* (1980); total 51 groups. (c) As for (a) but using α_{95} for VGP positions instead of field directions. (d) Mean VGP colatitude for 20-lava groups. Note that the present geographic pole lies outside the α_{95} circle for all points above broken line. The overall mean pole is slightly right-handed and far-sided (Kristjansson & McDougall 1982, table 3).

Data on the overall serial correlation between successive palaeomagnetic directions in Icelandic lavas have been presented by Kristjansson, Fridleifsson & Watkins (1980, table 3). In addition, we have now calculated this correlation for the two most complete parts of the NW Iceland collection by McDougall *et al.* (1984), comprising 730 flows with reliable directions in their profiles SK to JF and SR to BX. After inversion of reverse directions, the mean cosine of the angle between successive lavas is found to be 0.884, decreasing to 0.856 for a lag of two flows, 0.849 for a lag of three flows, and 0.843 on average for a lag of four to nine flows. These correlation indicators are similar in magnitude to those given by Kristjansson *et al.* (1980); they demonstrate that memory effects in the field, other than a memory of its polarity state, cannot extend beyond the mean time interval represented by four lavas, i.e. 30 000 yr.

Fig. 7(c) shows the scatter in α_{95} values from groups of 20 successive NW Iceland lavas when virtual geomagnetic poles are considered instead of directions. The data base is the same as in Fig. 7(a). Because tectonic tilts in the NW Peninsula are in general only a few degrees, we can also with some confidence plot each α_{95} value against the geographic colatitude of the respective mean pole. As one may expect from the stochastic model of the geomagnetic field developed by Kristjansson & McDougall (1982, section 4.3) these two variables are poorly correlated (Fig. 7d).

The scatter in our observed α_{95} values and mean pole colatitudes (Fig. 7d) is larger than would be expected from a random sampling of the geomagnetic field. We consider this to be a consequence of relatively rapid buildup in some parts of the lava pile. In this case any group of 20 successive lavas may record mostly a relatively quiet period of the secular variation and thus yield a low α_{95} value compared with the actual distance of their calculated mean pole from the geographic pole. Thus, the geographic pole lies outside our α_{95} circles in about 50 per cent of the 20-lava groups of Fig. 7(d). This is mainly because the secular variation has not been averaged out in many cases, but partly because of systematic influences such as the right-handedness to be discussed below. Alternatively, if the 20 successive lavas were erupted during a large part of a major field excursion, an unduly large α_{95} value would result.

To avoid over-confidence in and over-interpretation of directional statistics from limited palaeomagnetic data (particularly if all are of the same polarity), these data should therefore be assessed by reference to general models of the geomagnetic field behaviour, as derived from larger collections. It can, for instance, be deduced from such general models (Kristjansson & McDougall 1982, fig. 11) that the number of spot directions from magnetically reliable rock units required to reduce mean pole α_{95} values consistently to below 5°, may exceed 200. A similar point was made previously by Kristjansson (1968).

It must be stressed that in the above discussion we have not carried out selective rejection of transitional palaeomagnetic directions, which has commonly been employed in the literature to reduce the size of directional confidence circles. We consider such arbitrary rejection not to be appropriate in large data collections.

As there was a slight indication of bimodality in Fig. 7(b), Saemundsson *et al.* (1980) tentatively correlated it with previous suggestions of distinctly 'tranquil' and 'noisy' states of the geomagnetic field. Some bimodality may also be discerned in Fig. 7(a), but this feature turns out not to be statistically significant, *cf.* Fig. 7(c).

6 Right-handedness of the mean field configuration

This paper has used the present geographic pole as a convenient reference point and approximate centre of the virtual pole distribution. However, the actual distribution of virtual poles

Table 2. Centres of symmetry in subsets from the collections of palaeo-magnetic virtual poles in Fig. 1.

	Range of angular distances from center, deg.	no. of poles within range	Position of center, deg. Lat.	Lon.
Entire collection (N=2163)	0-25	1074	83	94
	15-35	1036	$85\frac{1}{2}$	101
	25-85	1092	87	89
	0-85	2148	86	82
Lavas < 9 Myr in age	0-25	550	$83\frac{1}{2}$	115
	25-85	492	88	153
	0-85	1038	87	134
Lavas > 9 Myr in age	0-25	518	$81\frac{1}{2}$	88
	25-75*	573	$84\frac{1}{2}$	57
	0-85	1109	$83\frac{1}{2}$	60

Centre of symmetry is found by first finding the average of all poles within a certain angular range of the geographic pole, then repeating for all poles within the same angular range of that average, etc. Ranges 85–90° avoided to eliminate effect of ambiguities in polarity sign.

* 75° used instead of 85° because of instability in the iteration.

is centred somewhat to the right of the north geographic pole as seen from Iceland. This is in agreement with many previous observations (Wilson & McElhinny 1974; Dodson 1980), but a convincing explanation or model of this apparently global effect is lacking.

One way of exploring this property is to search iteratively by computer for the centre of symmetry of various subsets of the collections of Fig. 1. For the total set of data from these collections ($N = 2163$), the centre of symmetry is at 82°E, 86°N, with an α_{95} of 1° and an additional small error resulting from ambiguity as to which near-equatorial poles should be inverted before averaging. In order to obtain this mean pole position from an axially symmetric field by means of systematic sampling errors or tectonic rotations in azimuth, rotation angles of at least 8° would be required.

If the right-handedness of the mean field were due to local asymmetries brought about by persistent non-dipole fields, one would according to the results of the previous section expect this effect to be greater in low-latitude VGPs than in high-latitude VGPs. However, the opposite appears to be the case; as seen from Table 2, the centre of symmetry for high-latitude VGPs is found to lie at around 7° to the right of the geographic pole, but that for low-latitude poles is only 3° offset from the geographic pole.

The right-handedness seems in the present data set to be somewhat time-dependent. If the collection is split into two subsets of data, from lavas respectively younger or older than 9 Myr, the older subset is more right-handed but somewhat less far-sided (Table 2). Hence, some of the observed right-handedness of the present data may be due to true polar wander, but as before, much more numerous and accurate data are needed to evaluate these possibilities quantitatively.

Another expression of the pervasive right-handedness in Icelandic palaeomagnetic data may be observed in Fig. 7(d). Here, poles from five 20-lava groups from NW Iceland are both seen to yield high values of α_{95} (for each group as a whole) and high mean palaeocolatitudes. These mean directions all turn to be strongly right-handed. A similar feature has been noted in lavas of similar age from central northern Iceland (Saemundsson *et al.* 1980), and the effects of right-handedness are also manifested in fig. 12 of Kristjansson & McDougall (1982).

7 Conclusions and discussion

Palaeomagnetic data from Icelandic lavas are a unique type of information source on the behaviour of the past geomagnetic field by virtue of the very long near-continuous record of reliable spot readings of the field, which they provide.

Various techniques of mathematical analysis which have been developed for other types of geomagnetic information (such as polar wandering paths, or spherical harmonics) are not readily applicable to Icelandic lavas on their own. In this and other recent publications (Kristjansson & McDougall 1982; Kristjansson 1984) the present author has therefore been developing a stochastic approach to the description of palaeomagnetic data in Icelandic lavas.

The major principle of this work has been to utilize the simplest possible descriptive models of the processes involved, such as secular variation, rate of reversals, and rate of lava emplacement.

The smooth variation of mean field or VGP moment with VGP latitude (Figs 2c and 3), rather than with other angular parameters, has shown that the central dipole field approximation can be a useful tool to describe and compare secular variation from different locations on the globe. It is also evident from this observation that other long-term properties of the observed field are likely to be smoothly varying functions of VGP latitude.

The mean time for the VGP to travel between the $\pm 40°$ levels during permanent reversals of the field has here been estimated to be about $5-6000$ yr on average. The field configuration during these reversals should not be expected to be very different in character or in strength from the field configuration during excursions.

A simple stochastic Markov chain process for the movements of the virtual pole in latitude is described. It is based on a random walk where successive movements of the pole by a fixed amount (say $6°$) at fixed time intervals (say of $50-80$ yr) are only correlated through a time-independent bias function (Table 1) of the VGP latitude itself. According to the model, the probability of a low- or mid-latitude VGP moving towards the equator is always less than 0.5. This model predicts no periodicities in the field, but some such periodicities may appear in the real field configuration by the process of steady longitude drift which has been left out of the present treatment.

Serial correlation is generally likely to be present in palaeomagnetic directions from sequences of successive lava flows (as well as dyke swarms and other igneous rocks) due to episodicity in the volcanism. This will cause statistical indicators of directional accuracy, such as α_{95}, in small sets of such units to be very unreliable. Any conclusions on tectonic processes or peculiar observed features of the palaeomagnetic field should be stringently tested against models of the long-term behaviour of the field to avoid attaching spurious importance to them.

However, serial correlation in palaeomagnetic directions in Iceland (apart from a correlation in polarity) does not seem to extend beyond 30000 yr. This is to be considered a conservative (i.e. too high) estimate of the minimum time to elapse between successive spot readings of the field direction so that they may be considered independent for the purpose of secular variation calculations.

A persistent right-handedness of palaeomagnetic directions in Iceland is noted. It occurs both in our low- and high-latitude VGPs and is, somewhat surprisingly, more pronounced in the former. Right-handedness at any one locality may be explained by polar wandering or tectonics: its suggested global occurrence (Wilson & McElhinny 1974) is a very enigmatic problem in palaeomagnetism.

The right-handedness of the field appears to increase with age of the lavas investigated, and may therefore be partly due to polar wander in the past $6-12$ Myr. It is sufficiently

small (4° of arc) for the conclusions and graphs of Kristjansson & McDougall (1982) and the present paper to apply equally well, whether the symmetry axis of the pole distribution, or the geographic pole, is chosen as a reference direction. Thus, the k' value of the best-fitting Bingham function for the combined collections of Fig. 1 will change by less than 0.1 from the previously stated value as a result of this change of reference coordinates.

To sum up, we can only reiterate the concluding words of the very first paper describing laboratory palaeomagnetic measurements on Icelandic lava flows: 'De nouveaux échantillons seront nécessaires avant toute généralisation' (Chevallier 1930).

Acknowledgments

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