JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B3, PAGES 5799-5816, MARCH 10, 2000

On the anisotropy of secular variation deduced from paleomagnetic volcanic data

J. J. Love

School of Earth Sciences, University of Leeds, Leeds, England, United Kingdom

Abstract. We seek to establish whether or not secular variation, the rate at which the magnetic field is changing in time, is a function of field direction: Is secular variation anisotropic? From a large number of paleomagnetic lava data, many of which record polarity transitions, we find that vectors from stratigraphically adjacent flows are most (least) correlated during nontransitional (transitional) periods. Since volcanic activity is unrelated to, and therefore uncorrelated with, magnetic secular variation, this relationship indicates that secular variation is enhanced during transitions, perhaps by a factor of ~ 2. Thus secular variation is anisotropic, being a function of the deviation of field direction from an axial dipole. Despite this spatial dependence, we find little convincing evidence that transitional fields exhibit persistent recurring quasi-stationary states which manifest themselves in terms of midlatitude virtual geomagnetic poles (VGPs), as has sometimes been hypothesized. On the other hand, we identify tentatively some relative quiescence in secular variation during midtransition when VGPs fall near the equator. Numerous subsets of the database are examined for consistency and statistical errors are estimated by bootstrap analyses. Statistical models of secular variation need to incorporate the information content in serial correlations, like those analyzed here, from stratigraphic sections if the lava data are to be fully exploited.

1. Introduction

Convective motion in the Earth's core sustains the main part of the geomagnetic field via dynamo action: advective amplification balances diffusive destruction of the field. The motion is time-dependent, and thus the observed field $\mathbf{B}$ is time-dependent as well, exhibiting variation over a wide range of timescales [*Bloxham et al.*, 1989; *Courtillot and LeMouël*, 1988; *Merrill and McFadden*, 1990]. Here we examine the secular variation of the total magnetic field of internal origin $\partial_t\mathbf{B}$ [*Courtillot and Valet*, 1995]; we make no distinction between the variation (say) of the dipolar and nondipolar fields. The data used in our analysis are paleomagnetic measurements of lavas, which individually are generally considered to be more reliable than those from sediments.

At a volcanic site the total field is recorded at discrete instants in time with the deposition and cooling of a lava flow. Although the magnetic field itself changes continuously in time, volcanic activity is sporadic, and as a result the paleomagnetic lava record is temporally discontinuous. One approach to quantifying the behavior of the Earth's magnetic field is to examine the dispersion of directions in space and the degree to which the field deviates from an axial dipole; this is usually done statistically [*Camps and Prévot*, 1996; *Constable and Parker*, 1988; *Cox*, 1970; *McElhinny and Merrill*, 1975]. Although directional dispersion is a manifestation of secular variation, by itself it does not tell us much about the rate at which the field changes. For example, just because the field spends most of its time in a nearly dipolar nontransitional (reverse or normal) state, this does not necessarily mean that when the field deviates from an axial dipole, or undergoes a transition, that the field then changes at an enhanced rate, though this may in fact be the case.

Information about both the secular variation and the local volcanic activity is contained in temporal correlations between lava data, yet we know of no attempt to incorporate such information into statistical models of the magnetic field, a shortcoming which has at least been recognized by some [*Constable*, 1990; *Hulot and LeMouël*, 1994]. Lava data are usually treated as independent quantities, or if the data appear to be correlated this is considered to be a nuisance which needs to be corrected [*Doell*, 1972a; *Mankinen et al.*, 1985; *McElhinny et al.*, 1996; *Quidelleur et al.*, 1994]. A major obstacle here is the difficulty in establishing a timescale; lavas are not easily dated radiometrically. However, partial knowledge of temporal variation can come from stratigraphy; the data are temporally ordered if they are gathered from piles of serially deposited lava flows. A

Paper number 1999JB900395.
0148-0227/00/1999JB900395$09.00

high degree of correlation between paleomagnetic data from stratigraphically adjacent flows is to be expected if the flows were deposited closely in time or if the magnetic field did not change much between successive depositions; conversely, a low degree of correlation is to be expected if the duration between successive depositions was long or if the field was changing relatively rapidly between depositions. Given just a few data, without independent knowledge of depositional dates there is no objective means of untangling these two effects. Fortunately, volcanic activity is unrelated to, and therefore uncorrelated with, variations in the magnetic field. Thus provided enough data are analyzed, it should be possible to incorporate measures of mean temporal correlation between stratigraphically ordered data into statistical models of the secular variation, since uneven temporal sampling due to rapid successive depositions of lava flows would be diluted by a preponderance of data. Without some accounting for temporal correlation the data remain underexploited.

We seek to understand how secular variation depends on field direction or, indeed, to discover whether or not there is any simple relationship at all. Does the field change more or less rapidly when it is pointing in certain directions? Partial inspiration for our investigation comes from some provocative work by ***Hoffman*** [1992], who suggested that transitional fields may, at times, assume a quasi-stationary, possibly dipolar, intermediate state. Such configurations, where the field becomes rather quiescent for a certain period of time, would be manifest as a clustering of field directions in paleomagnetic lava data, assuming, of course, that the effects of eruptive variability have been averaged out. In particular, by plotting field directions as virtual geomagnetic poles (VGPs), the magnetic pole of a dipole corresponding to paleomagnetic directions at each site, Hoffman suggested that the data indicate a clustering of midlatitude transitional VGPs. These assertions have been made on the basis of small databases and therefore might simply be the result of eruptive variability.

In this analysis we examine a large database, consisting of literally thousands of paleomagnetic measurements from consecutively deposited lava flows. Rather than repeat the dispersion analyses of our predecessors, we calculate the correlation (measured by angular difference) between vectors from stratigraphically adjacent lava flows. Insofar as mean angular differences reflect the average secular variation, we can use stratigraphically ordered paleomagnetic data to investigate the rate at which the field changes as a function of field direction. This dependence can be represented as

$$\partial_t \mathbf{B} = \partial_t \mathbf{B}[\hat{\mathbf{B}}(\theta, \phi)], \qquad (1)$$

where $\hat{\mathbf{B}}$ is the unit vector pointing in the direction of $\mathbf{B}$ at a particular paleomagnetic site and where (θ, ϕ) specifies the direction of the field (not the site location). Similarly, we can represent the direction of the field at a particular paleomagnetic site in terms of VGP latitude and longitude (λ, φ):

$$\partial_t \mathbf{B} = \partial_t \mathbf{B}[\hat{\mathbf{B}}(\lambda, \varphi)]. \qquad (2)$$

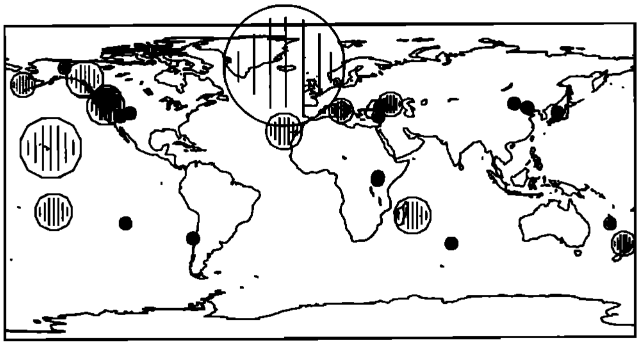
With either directional representation our study amounts to an analysis of the anisotropy of paleomagnetic secular variation. Our study here should be compared with that of *Love* [2000]; he concluded that paleosecular variation is a function of intensity, finding that secular variation is enhanced (quiet) when and where the intensity is low (high).

2. Data

The data come from studies of stratigraphically ordered, extruded lava piles deposited over the past 20 Myr, and where the data have been published in journals in tabular form. Each paleomagnetic direction in our database, inclination I and declination D, is an average of measurements from at least three magnetically cleaned samples per flow, with the precision parameter α_{95}, the semiangle of the cone of 95% confidence centered on the mean direction, $< 20°$; these selection criteria are similar to those of our predecessors [***McElhinny and McFadden***, 1997; ***Quidelleur et al.***, 1994]. The absolute intensities F in our database consist of Thellier or Shaw type measurements, made from at least two samples per flow. Generally speaking, the Thellier method is preferable [***Prévot and Perrin***, 1992]: Although laboratory comparisons have shown that the Shaw method usually yields individual results similar to the Thellier method [***Kono***, 1978; ***Senanayake et al.***, 1982], data compilations indicate that Shaw intensities are generally somewhat more scattered than Thellier intensities [***Tanaka et al.***, 1995a]. In all source papers considered here, authors report not only the mean of multiple measurements of F but also the number of measurements N and the standard deviation of the different intensity measurements σ_F. Consistent with Student's t distribution, the error on the mean is estimated as $\sigma(F) = \sigma_F/\sqrt{N}$. We accept only absolute intensities where the relative error $\sigma(F)/F$ is $< 33\%$. Among the various sites there are 137 stratigraphic sections giving a total of 4521 directions (2810 of which come from Iceland) and 323 intensities. The geographic distribution of the sample sites is shown in Figure 1, the database is summarized in Table 1, and some notes concerning specific data sets are given in Appendix A.

Some of the stratigraphic sections in our database are very short, consisting of only a few paleomagnetic measurements. It might be suggested that long stratigraphic sections are preferable, the thinking being that they (somehow) preserve a more representative record of secular variation. However, in the analysis that follows, where we are concerned with the correlation between pairs of directions, we have no motivation to discard short stratigraphic sections and keep only long ones. Two flows give one correlation which is no less in-

(a) Directional Data



(b) Intensity Data

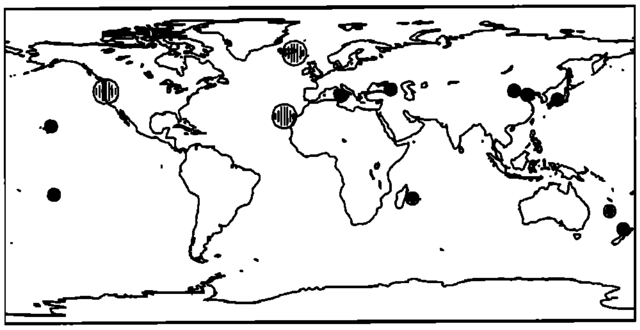


Figure 1. Geographic distribution of paleomagnetic sample sites; the size of the symbol is proportional to the number of (a) directional (I, D) and (b) absolute Thellier or Shaw intensity (F) data from each site. Note that most of the directional data come from Iceland; the intensity data, though fewer in number, are more uniformly distributed geographically.

teresting than individual correlations between pairs of flows from giant stacks of lava piles. Furthermore, we have no nonarbitrary means of distinguishing a "long" stratigraphic section from a "short" one, nor do we have any objective means of determining exactly when one stratigraphic section preserves a sufficiently complete record of secular variation and when another one does not. The only objective approach to a correlation study such as ours is to consider simply all of the available data which satisfy certain minimum criteria for quality and where those criteria are unrelated to the directions and correlations themselves.

3. Directional Dispersion

It is common to display paleodirections in terms of virtual geomagnetic poles (VGPs), the south magnetic pole of a dipole corresponding to field directions from each paleomagnetic site. With such a convention the data display a bimodal distribution, with VGPs tending to fall near one or the other geographic pole. We can also plot the data in a coordinate system fixed to the local axial dipole direction. The Cartesian components of the unit magnetic field vector are

$$(X, Y, Z) = (\cos I \cos D, \cos I \sin D, \sin I). \qquad (3)$$

For a site at latitude Λ, the off-dipole angle θ is given by

$$\cos\theta = X \cos I_{AD} + Z \sin I_{AD}, \qquad (4)$$

where the inclination for an axial dipole is given by

$$\tan I_{AD} = 2 \tan \Lambda. \qquad (5)$$

The azimuthal angle ϕ around the local axial dipole direction is given by

$$\tan\phi = \frac{Y}{X \sin I_{AD} + Z \cos I_{AD}}. \qquad (6)$$

As with VGPs, the data are scattered around the axial dipole with a bimodal distribution. Such inhomogeneous distributions should not be confused with anisotropy!

4. Measuring Correlation

For the vast majority of the data, we have only paleodirections (I, D) without corresponding intensities (F). The directions, of course, can be represented as unit vectors, and following *Watson and Beran* [1967] we define the correlation between a pair of stratigraphically adjacent unit vectors $(\hat{\mathbf{B}}_j, \hat{\mathbf{B}}_{j+1})$ as

$$r_{j,j+1} = \hat{\mathbf{B}}_j \cdot \hat{\mathbf{B}}_{j+1} = X_j X_{j+1} + Y_j Y_{j+1} + Z_j Z_{j+1}. \quad (7)$$

The angular difference between consecutive paleodirections $\xi_{j,j+1}$ is given by

$$\cos\xi_{j,j+1} = r_{j,j+1}. \qquad (8)$$

Given N pairs of stratigraphically adjacent unit vectors, the mean correlation is just

$$\langle r \rangle = \frac{1}{N} \sum_j r_{j,j+1}, \qquad (9)$$

and the mean angular difference $\langle \xi \rangle$ is given by

$$\cos\langle \xi \rangle = \langle r \rangle. \qquad (10)$$

We could consider the distribution of $\langle r \rangle$ and $\langle \xi \rangle$ as functions of both off-dipole angle θ and azimuth ϕ or as functions of both VGP latitude λ and longitude φ, but we have noted substantial scatter in the data and therefore have opted for simplicity and robustness by considering only off-dipole angular and VGP latitudinal dependence (integrating over azimuth/longitude). With more data a study of azimuthally and longitudinally dependent correlations should be possible in the future, but for now we measure just the mean correlations as functions of θ and λ. We use semipolar plots for displaying the anisotropy of the secular variation; the convention is explained in Figure 2.

We divide the range of off-dipole angle θ and VGP latitude λ into intervals, each denoted k, and since

Table 1. Summary of Database (Stratigraphic Sections)

Locality	Name	Lat °N	Long °E	Age Myr	N_F	N_{ID}	Demag Method	Demag Steps	Source
Alaska	Wait;Castles;AirII	62.3	217.0	3.4		34	AF	~8	*Bingham and Stone* [1976]
Aleutian	Kanaga (KAN;RDH)	51.9	182.9	0.0-0.2		21	AF	~7	*Bingham and Stone* [1972]
Aleutian	Umnak (NJC;ASH;CCR)	53.4	191.9	0.0-2.1		46	AF	~7	*Bingham and Stone* [1972]
Aleutian	Unalaska (DFB)	54.0	193.2	Pleistocene		21	AF	~7	*Bingham and Stone* [1972]
Amsterdam	17,18,19	-39.8	77.5	Brunhes		3	AF	2	*Watkins and Nougier* [1973]
Arizona	Hackberry (lavas)	34.4	248.2	7.9-11.5		38	AF	3+	*McKee and Elston* [1980]
British Columbia	Edziza (A;B;C)	57.5	229.2	0.0-6.0		72	AF	8	*Souther and Symons* [1974]
British Columbia	Level	58.5	228.7	1.0-6.6		45	AF	6	*Hamilton and Evans* [1983]
Canary	La Palma (LL;LS)	28.6	342.2	0.8	10	58	AF,T	~10+	*Quidelleur and Valet* [1996]
Canary	La Palma (ET;ME)	28.6	342.2	0.8	47	65	AF,T	~10+	*Valet et al.* [1999]
Canary	El Hierro	27.8	342.0	0.1-0.4		68	AF,T	~15	*Szérémét́a et al.* [1999]
Chile	Tatara-San Pedro	-36.0	289.0	0.3-1.0		12	AF,T	~3+	*Brown et al.* [1994]
China	Datong	40.2	113.4	0.2	2	3	AF,T	~7	*Zhu et al.* [1990]
China	Tongjing	37.8	120.8	0.8	4	4	T	14	*Zhu et al.* [1991]
Easter	32,33	-27.1	250.8	0.2		2	AF	6	*Isaacson and Heinrichs* [1976]
Georgia	Akhalkalaki (W;X;Y;Z)	41.5	43.3	3.6	14	52	T	~7	*Camps et al.* [1996]
Hawaii	Niihau	22.0	200.0	3.0		5	AF	~4+	*Doell* [1972b]
Hawaii	Nihoa	23.1	198.0	3.0		14	AF	~4+	*Doell* [1972b]
Hawaii	Necker	23.6	195.3	10.0		7	AF	~4+	*Doell* [1972b]
Hawaii	Oahu (X,Y;O;N;B;F)	21.4	201.9	1.9-3.6	10	78	AF,T	~5+	*Doell and Dalrymple* [1973], *Coe et al.* [1984]
Hawaii	Kauai (KT;A;P;DG-OK)	22.0	199.5	3.8-5.1	13	57	AF,T	~5+	*Bogue and Coe* [1984]
Hawaii	Hawaii (HW05,3,PO01,HW01,2,4,WA01)	20.1	204.3	0.0-0.4	7	7	T	10+	*Brassart et al.* [1997]
Hawaii	Oahu (KA51-KA48;HN51-HN01)	21.6	208.7	3.1-3.2		105	AF,T	14	*Laj et al.* [1999]
Hawaii	Oahu (Kamai'leunu;Heleakala)	21.4	208.8	3.3-3.6		64	AF,T	8	*Herrero-Bervera and Coe* [1999]
Iceland	A;B;C;L;M	65.2	346.3	12.1-16.3		33	AF	3	*Dagley et al.* [1967], *Dagley and Lawley* [1974]
Iceland	Jökuldalur (GH1-GL5;GJ;GK)	65.2	344.8	1.6	2	40	AF	2	*Watkins et al.* [1975], *Senanayake et al.* [1982]
Iceland	Bessastadaa (EQ;EW)	65.0	345.0	4.8-6.5	3	50	AF	3	*McDougall et al.* [1976], *Senanayake et al.* [1982]
Iceland	Borgarfjördur (NP1-NT112)	64.5	337.5	1.6-6.7	2	320	AF	2	*Watkins et al.* [1977], *Senanayake et al.* [1982]
Iceland	Esja (FA02-SC11)	64.2	338.0	1.8-4.2		256	AF	2	*Kristjánsson et al.* [1980]
Iceland	Tröllaskagi (PA02-PG60)	66.0	341.0	8.2-11.2		280	AF	2	*Saemundsson et al.* [1980]
Iceland	SK1-JF159	65.7	337.0	11.0-14.0		385	AF	2	*McDougall et al.* [1984]
Iceland	SR0-BX08	65.7	338.5	8.0-14.0		322	AF	2	*McDougall et al.* [1984]
Iceland	BT1-BV55	65.7	338.5	14.0		107	AF	2	*McDougall et al.* [1984]
Iceland	Tjörnes (NU;GF;BA;GM;GS)	66.0	342.8	0.7		48	AF	~3+	*Kristjánsson et al.* [1988]
Iceland	Langidalur (TL1-TN85)	65.6	339.7	7.3-8.2		133	AF	2-4	*Kristjánsson et al.* [1992]
Iceland	BO;MU;SE;MO	64.2	338.0	2.1		18	AF	3+	*Kristjánsson and Sigurgeirsson* [1993]
Iceland	SH	64.2	338.0	3.4		21	AF	3+	*Kristjánsson and Sigurgeirsson* [1993]
Iceland	Mjóifjörður (DA1-MC56)	65.3	346.5	10.0-13.0		195	AF	3+	*Kristjánsson et al.* [1995]
Iceland	RK;RG	64.4	338.5	2.5	9	51	AF,T	11	*Tanaka et al.* [1995b]

Table 1. (continued)

Locality	Name	Lat °N	Long °E	Age Myr	N_F	N_{ID}	Demag Method	Demag Steps	Source
Iceland	N4-R3 (FI)	64.5	338.8	2.5		24	AF	3-4	*Kristjánsson* [1995]
Iceland	Ísafjaðardjúp (DO1-DM14)	65.4	337.5	12.0-13.7		227	AF	4	*Kristjánsson and Jóhannesson* [1996]
Iceland	SB';PV;PV';HU;FL;FL*;KY	64.2	338.0	2.1	40	40	AF,T	6+	*Goguitchaichvili et al.* [1999]
Iceland	Snæfellsnes (HH1-HA54)	64.7	337.8	2.1		260	AF	3	*Kristjánsson and Jóhannesson* [1999]
Idaho	Rocky (RC1-17)	46.0	243.0	14.5-16.0		14	AF	2	*Hooper et al.* [1979]
Japan	Ningyoishi-yama (KM55-42)	35.0	139.0	7.0-10.6		7	AF	1+?	*Ozima et al.* [1968]
Japan	Usami (UV)	35.0	139.0	0.8	2	11	AF,T	5	*Kono* [1968]
Japan	Kuju	33.1	131.2	Pleistocene	5	5	AF,T	8	*Nishida et al.* [1969], *Sasajima and Maenaka* [1969]
Japan	Kyushu Kuju	33.1	131.2	Pliocene	3	3	AF,T	8	*Nishida et al.* [1969], *Sasajima and Maenaka* [1969]
Japan	Nagao-toge (HN)	35.0	139.0	Brunhes	3	8	AF,T	∼3+	*Kono* [1971]
Japan	Fuji (FJ9,1)	35.5	138.9	0.0	2	2	T	∼7+	*Tanaka* [1990]
Japan	Daisen (DS02,4)	35.3	133.6	0.0	2	2	AF,T	∼8+	*Tanaka et al.* [1994]
Kenya	Lengitoto (GT)	-1.5	37.4	6.9		5	AF	12+	*Patel and Raja* [1979]
Nevada	Lousetown (F2-34;F35-43)	39.4	240.4	1.1-6.8		40	AF	∼8+	*Heinrichs* [1967]
Nevada	Santa Rosa	41.8	242.5	15.0		12	AF	20	*Roberts and Fuller* [1990]
New Mexico	Valles Caldera	36.0	253.5	0.1-0.9		14	AF	8	*Doell et al.* [1969]
New Zealand	Swampy (Fig3)	-46.0	170.0	12.4		5	AF	10	*Sherwood* [1988]
New Zealand	Akaroa	-44.0	173.0	8.2-9.4		53	AF	10	*Sherwood* [1988]
New Zealand	Ruapehu (NR07-01;NR29-13)	-39.3	175.6	0.2	7	26	AF,T	∼7+	*Tanaka et al.* [1997]
Norfolk	1,3-7;9-11;14,15;16,18,19; 20,22,23;30,31;40-44	-29.0	167.8	2.3-3.1		23	AF	7	*Aziz-Ur-Rahman and McDougall* [1973], *Senanayake et al.* [1982]
Oregon	Coast (DB2-CF1)	46.0	236.0	14.0-16.0		7	AF	3+	*Choiniere and Swanson* [1979]
Oregon	FL3-1;GRJ7-1	46.0	243.0	16.0		5	AF	2	*Hooper et al.* [1979]
Oregon	Steens (A,B,C), except A41,A42	42.6	241.4	15.5	52	127	AF,T	∼8+	*Mankinen et al.* [1985], *Prévot et al.* [1985]
Polynesia Huahine	83H21-D40;J10-M43;E;F;K;TG-TK	-16.0	209.0	2.9-3.1		66	AF,T	∼5+	*Roperch and Duncan* [1990]
Polynesia Tahiti	Punaruu Valley	-17.7	210.3	0.6-1.2	9	117	AF,T	∼4+	*Chauvin et al.* [1990]
Réunion	RN29-GC1	-20.9	55.4	2.0		26	AF,T	1	*McDougall and Watkins* [1973]
Réunion	RA;RB	-21.1	55.5	0.0	19	27	AF,T	∼15+	*Chauvin et al.* [1991]
Réunion	RE	-21.1	55.5	0.0	24	58	AF,T	∼15+	*Raïs et al.* [1996]
Sicily	Etna	37.6	15.0	0.0	22	31	T,S	10+	*Rolph and Shaw* [1986], *Tanguy et al.* [1985]
Sicily	Vulcano (VU;G)	38.0	15.0	0.0-0.1	10	47	T	10+	*Laj et al.* [1997]
Sicily	Lipari (G5-G1)	38.0	15.0	0.1		6	AF,T	10	*Zanella and Laurenzi* [1998]
Syria	Levant	33.3	36.3	19.5		19	AF,T	∼5	*Roperch and Bonhommet* [1986]
Tanzania	Ngorongora	-3.3	35.6	2.5		19	AF	∼4	*Grommé et al.* [1970]
Turkey	Gürün (G)	38.7	37.4	Quaternary		4	AF	6	*Sanver* [1968]
Washington	OI1-LM1;RM1-RZ1;GR24-2	46.3	242.8	6.0-16.0		48	AF	3+	*Choiniere and Swanson* [1979]
Washington	GR10-19	45.5	243.0	14.5-16.0		7	AF	3+	*Hooper et al.* [1979]

Locality is general region of sampling; Name specifies each stratigraphic section; N_F is number of intensity data, N_{ID} is number of directional data; Demag Method is AF (alternating field), T (thermal), S (Shaw); Demag Steps is the number of steps in step-wise demagnetization (not counting uncleaned remanent magnetization).

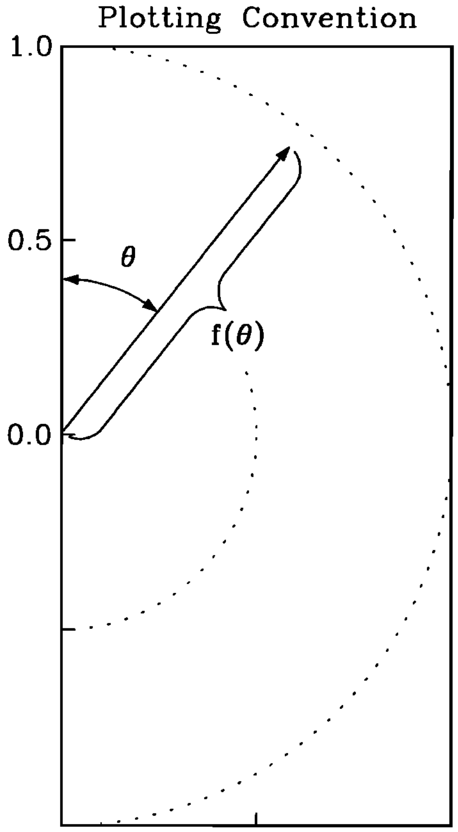


Figure 2. We use semipolar plots for displaying the anisotropy of the secular variation. The distance from the origin is proportional to the scalar of interest, in this case represented generically as f. The angle θ is the off-dipole angle, equation (4), with $\theta = 0°$ ($\theta = 180°$) representing the direction, at a given site, parallel to the direction of a normal (reverse) axial dipole.

each correlation r and each angular difference ξ depends upon a pair of paleovectors, we bin r and ξ once for θ_j and once for θ_{j+1}, and once for λ_j and once for λ_{j+1}. Within each bin we then calculate the mean correlation coefficient $\langle r \rangle$ and the mean angular difference $\langle \xi \rangle$. Since these means become independent of the number of correlation coefficients within each bin, N_k, as $N_k \to \infty$, then, provided there are enough data in each bin, we avoid sampling bias caused by the over representation of transitional directions in the literature. Moreover, since our database consists of data from serially ordered lava flows, and since volcanic eruptions are uncorrelated with variations in the magnetic field, there is no reason to expect that either $\langle r \rangle$ or $\langle \xi \rangle$ is a biased measure of the secular variation. Of course, our faith in this straightforward interpretation can be enhanced if we find consistency among multiple subsets of the database.

It might be thought that our analysis can give spurious results when ξ is large, larger than (say) 90°, which could happen, for example, if we were trying to estimate relative secular difference using reverse and normal vectors. Obviously, the finite difference measures of secular variation become meaningless if the temporal difference in depositional times is too large. For most of the analysis we consider all consecutive directions such that $\xi < \xi_c = 60°$. Given the present rate of angular secular variation, this cutoff amounts (roughly) to durations less than ~ 1000 years. Such a timescale is shorter than the duration of most reversals and is comparable to the timescale for a convective overturn in the core, which might be considered appropriate for studies of secular variation, although, obviously, secular variation occurs over a wide variety of timescales and as such this estimated timescale should not be overemphasized. Near the end of our discussion we will consider the effects of different cutoffs of ξ.

If the paleomagnetic data are serially correlated, which is what we expect if successive lava depositions occur closely in time, then the mean correlation $\langle r \rangle$ of the data should exceed that for a random and uniform (isotropic) distribution of directions; equivalently, the mean angular difference $\langle \xi \rangle$ should be less than that for a random and uniform (isotropic) distribution of directions. The expected value of ξ for a uniform distribution of directions falling within a cutoff of ξ_c is obtained by integration of ξ over a spherical cap of angular radius ξ_c:

$$\overline{\xi}(\xi_c) = \frac{\int_0^{\xi_c} \varepsilon \sin \varepsilon d\varepsilon}{\int_0^{\xi_c} \sin \varepsilon d\varepsilon} = \frac{\sin \xi_c - \xi_c \cos \xi_c}{1 - \cos \xi_c}. \tag{11}$$

The corresponding angular correlation is

$$\cos \overline{\xi} = \overline{r}. \tag{12}$$

Average correlations in the data can be deemed to be statistically significant with a certain degree of confidence if the correlation minus the confidence limit exceeds the expected correlation $\overline{r}$ or, equivalently, if the mean angular difference plus the confidence limit is less than the expected angular difference $\overline{\xi}$.

5. Symmetry

The equations of magnetohydrodynamics are invariant under change in sign of the magnetic field [*Merrill et al.*, 1979], and thus, provided reversals involve the entire magnetic field [*Gubbins and Zhang*, 1993], our analysis of field direction should be symmetric under the transformation $\mathbf{B} \to -\mathbf{B}$. Since we are here unconcerned with variation in azimuth ϕ and VGP longitude φ, it should be irrelevant whether the field direction deviates from a dipole by θ or by $180° - \theta$, or whether a VGP falls on latitude λ or $-\lambda$. Thus in most of the analysis which follows we impose normal-reverse (N-R) symmetry:

$$r(180° - \theta) = r(\theta), \qquad \xi(180° - \theta) = \xi(\theta), \tag{13}$$

$$r(-\lambda) = r(\lambda), \qquad \xi(-\lambda) = \xi(\lambda). \tag{14}$$

Imposing this symmetry has the effect of reducing some of the scatter in the mean correlation $\langle r \rangle$ and the mean angular difference $\langle \xi \rangle$ since it doubles the number of points within each bin. Near the end of our discussion we examine briefly the case of no imposed symmetry.

6. Bootstrapping

We estimate the reliability of $\langle r \rangle$ and $\langle \xi \rangle$ by a bootstrap analysis [*Efron*, 1982]. Let us consider the estimation of the reliability of the mean correlation; the reliability of the mean angular difference is calculated similarly. Denote by $\mathcal{R}$ the population of individual correlation coefficients r within the kth bin. A population of test coefficients, the nth being denoted $\mathcal{R}^n$, is generated by random sampling with replacement from $\mathcal{R}$. Because of the replacement, the test correlations typically have some duplicate coefficients and, of course, are also missing a corresponding number of coefficients contained in the actual data set. The dispersion of the test means $\langle r \rangle^n$ gives a measure of the reliability of the mean correlation $\langle r \rangle$, something we express in terms of confidence limits.

7. Serial Relationships

We begin by examining the serial correlation of the data (Figure 3). Note that the absolute intensities (F) and the directions (I, D) show significant serial correlation; this is true during both normal and reverse periods (the declinations are concentrated near 0° and ±180°), and there is even some hint of serial correlation during transitional periods as well. These results might indicate that the data are sufficient to resolve some aspects of secular variation, though as we have remarked, a high degree of correlation between paleomagnetic data from stratigraphically adjacent flows is to be expected either if the flows were deposited closely in time or if the magnetic field did not change much between successive depositions; the off-diagonal scatter seen in Figure 3 could be due to either long intervening periods of time or the field changing relatively rapidly between depositions. Figure 3 by itself offers no clue as to the relative importance of these two effects.

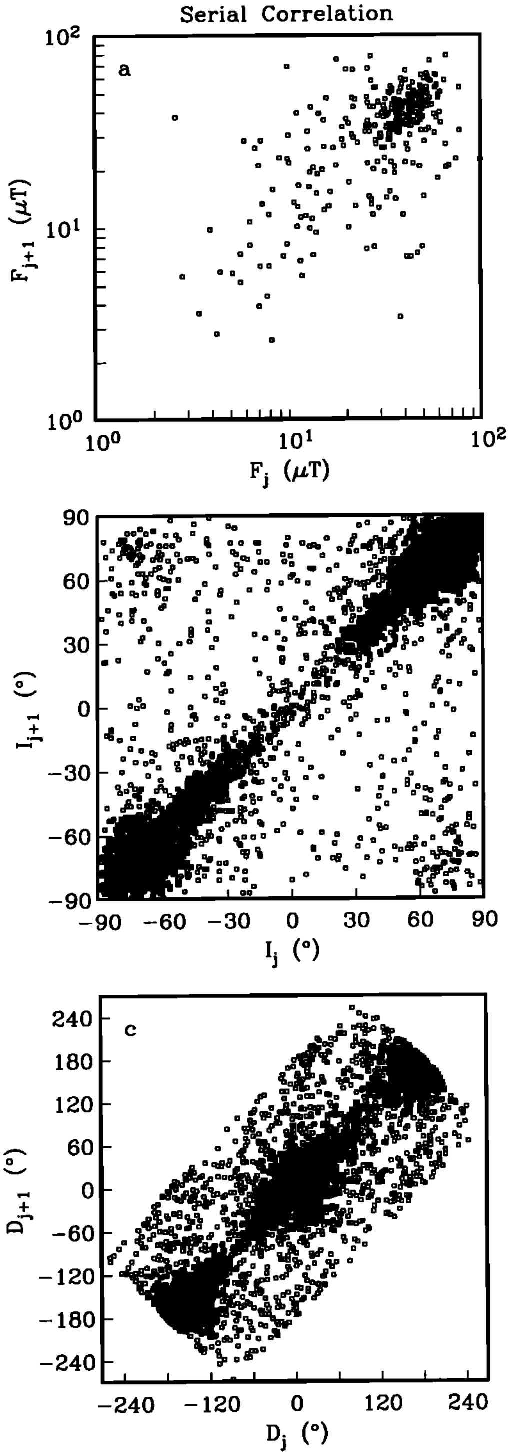


Figure 3. Serial correlation of the paleomagnetic data from stratigraphically neighboring lava flows: (a) absolute intensities F, (b) inclinations I, and (c) declinations D.

Following *Love* [1998], in Figure 4 we compare the difference in field direction between successive flows ξ versus the absolute difference in field intensity ΔF between (the same) successive flows. Since our database encompasses reversals and excursions, both difference in direction and difference in intensity between successive depositions can be large. However, notice that sometimes the direction changes by only a few degrees, while the intensity changes by tens of microteslas, an amount comparable to the present surface intensity of the Earth's magnetic field. Given the present rate of westward drift in the Atlantic, it might be thought that relatively small differences in field direction represent only a few years of intervening time; on the other hand, given the rate of decay of the dipole, the intervening times between these successive depositions could be centuries. Similar interpretations can be made concerning difference in field direction versus the relative difference in field intensity $\Delta F/F$ between successive flows, where we see no obvious relationship between the two quantities. Clearly, differences between successive flows

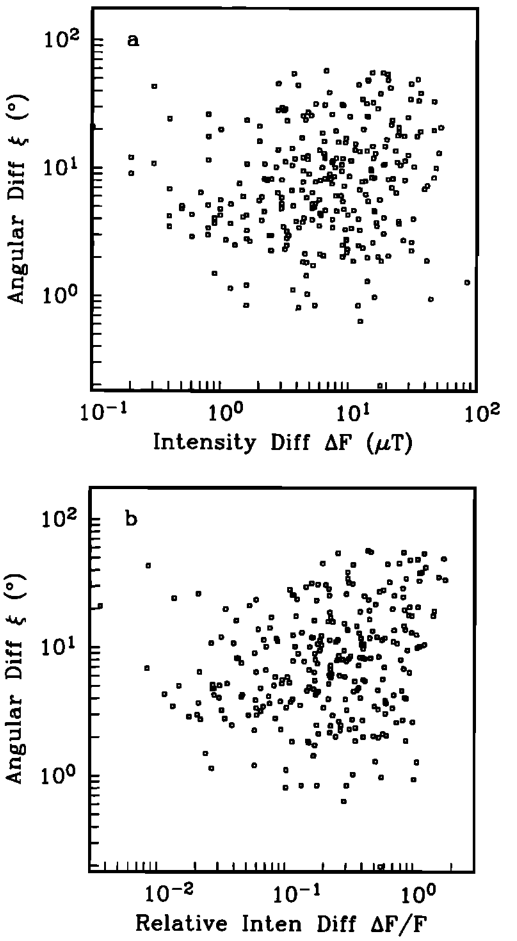


Figure 4. Angular difference ξ between stratigraphically adjacent lava flows versus (a) ikntensity difference ΔF, and (b) relative intensity difference $\Delta F/F$. The lack of correlation between angular differences and intensity differences demonstrates that the rate of secular variation is itself variable.

represent a broad range of times, and thus we conclude that similar consecutive directions are not necessarily due exclusively to rapid sequential depositions of lava flows; they are also reflective of the secular variation. The rate of secular variation is itself variable. It is this variation of the variation and its possible functional dependence on direction that we seek to measure.

These observations have important implications for the analysis of paleomagnetic data. With the temporal irregularity of volcanic activity in mind some investigators consider similar consecutive paleomagnetic data to be redundant, and they attempt to "fix" the lava records by combining or removing similar data taken from stratigraphically adjacent lava flows [*Doell*, 1972a; *Mankinen et al.*, 1985; *McElhinny et al.*, 1996; *Quidelleur et al.*, 1994]. Although it is not difficult to appreciate the motivation for such treatment, it should be recognized that it reflects a prejudice that secular variation is somehow temporally stationary. In fact, we do not a priori know the time dependence of the paleomagnetic field. Indeed, one of the reasons for studying paleomagnetism is to discover the secular variation. Averaging or deleting similar paleovectors, while at the same time leaving others intact and unaveraged, defeats the purpose of the analysis. Since we see clearly in the paleomagnetic data themselves (Figure 4) that secular variation is complex and is itself variable; like volcanic activity, geomagnetic secular variation might even be sporadic; see, for example, *McElhinny and Merrill* [1975]. Successive lava flows with depositional dates differing by centuries can yield paleomagnetic directions that can range from nearly identical to very different. Thus the practice of selectively combining or removing similar directions will result in a biased analysis and does not solve the problems of uneven temporal sampling. Having said all of this, statistical analyses can be conducted, even on data which are not uniformly distributed in time, so long as the analysis accounts for bias introduced by the paleomagnetists' preferential sampling of transitional data. However, statistical analysis should not be conducted on data which have undergone subjective averaging or have been edited beforehand.

Because volcanic activity tends to occur intermittently, we expect that the elapsed time between successive depositions within a single lava pile is almost always relatively short compared to the timescales characterizing secular variation or to the duration (say) of a polarity transition. Within a lava pile each pair of flows represents a certain duration of time, although without accurate radiometric dating individual durations remain unknown. Figure 4 highlights the problem with interpreting individual or just a few correlations; this does not mean, however, that we cannot interpret mean correlations among large numbers of paleovectors. Volcanic activity is unrelated to, and therefore uncorrelated with, geomagnetic secular variation. Therefore one might expect that, on average, small (large) differences in stratigraphic position represent short (long) periods of time, during which the field will have changed by a certain amount and that the mean correlation between paleomagnetic vectors will be good (poor). This expectation is borne out in Figure 5, where we see that the mean correlation $\langle r \rangle$ decreases (increases) with an increase (decrease) in stratigraphic positional difference, and, equivalently, the mean angular difference $\langle \xi \rangle$ increases (decreases) with an decrease (increase) in stratigraphic positional difference. Thus we can conclude that the mean correlation between stratigraphically adjacent lava flows contains information about the secular variation of the magnetic field.

8. Correlation and Off-Dipole Angle

In Figure 6 we show the correlation as a function of off-dipole angle θ for the Icelandic data; all angular differences ξ are considered such that $\xi < 60°$. The individual correlation coefficients r show a great deal of scatter, but the mean correlation coefficients $\langle r \rangle$ are

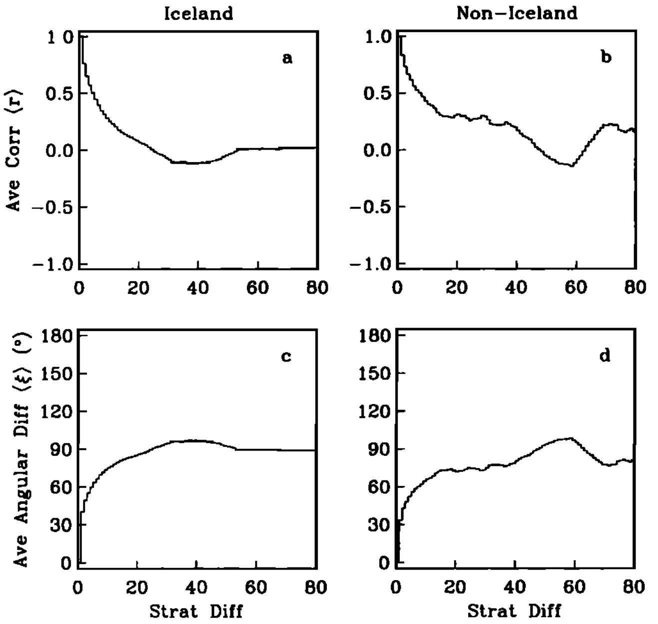


Figure 5. Average correlation $\langle r\rangle$ as a function of difference in stratigraphic position (height) for (a) Icelandic data and (b) non-Icelandic data. Note that the correlations decrease (increase) in with an increase (decrease) in stratigraphic positional difference. Equivalently, in terms of the mean angular difference $\langle\xi\rangle$, for (c) Icelandic data and (d) non-Icelandic data, we note that the mean angular difference increases (decreases) with a decrease (increase) in stratigraphic positional difference.

more systematically distributed in θ. The correlations can be said to be statistically significant; note that the mean correlation minus the 95% confidence limit exceeds the expected correlation for random isotropic data; equivalent observations hold for the mean angular differences $\langle\xi\rangle$. Furthermore, there is a general decrease in the mean correlation during nonaxial dipolar states and a corresponding increase in the mean angular difference when $\theta \simeq 45°$ and 135°. These observations might indicate an enhancement of secular variation during transitional periods, perhaps by a factor of 2. Interestingly, when $\theta \simeq 90°$, the mean correlation is somewhat enhanced, and the mean angular difference is less, which might reflect a certain midtransitional quiescence in secular variation.

The corresponding results for the non-Icelandic data are shown in Figure 7. Generally speaking, there is a great deal of consistency between the Icelandic and non-Icelandic data; both indicate an enhancement of secular variation during transitional periods, but with some relative quiescence at midtransition. Note, however, that the mean correlations for the non-Icelandic data are higher, and the mean angular differences are lower, than they are for the Icelandic data. This is probably due to differences in average eruptive frequencies between Iceland and the remaining sites. None of these interpretations about the anisotropy of secular variation can be deduced from a simplistic inspection of the directional dispersion; instead, a differential analysis, like that conducted here, is necessary.

It is somewhat disconcerting that in both Figures 6 and 7 we see that the mean precision parameter $\langle\alpha_{95}\rangle$ is greatest during midtransitional periods ($\theta \simeq 45°$) when the correlation coefficient is also smallest. Could lower mean correlations during midtransitional periods be due to a slight increase in the scatter of the mean directions as measured by the precision parameter? In

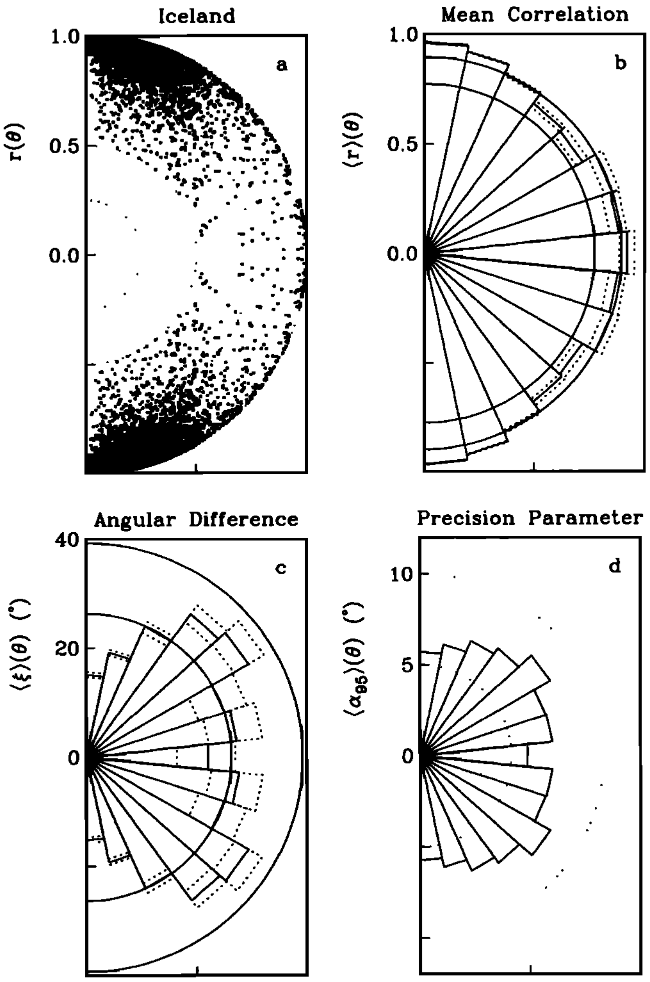


Figure 6. Anisotropy of Icelandic data as a function of off-dipole angle θ. (a) Individual correlation coefficients r. (b) Mean correlation coefficients $\langle r\rangle$ (solid-line histograms) and 95% confidence limits on the mean correlations (dashed lines) as determined by bootstrap analysis. The outside semicircle represents the average of the mean correlations for all off-dipole bins. The inside semicircle represents the expected mean correlation $\bar{r}(60°)$ for random and isotropically distributed directions. (c) Mean angular differences $\langle\xi\rangle$ (solid-line histograms) and 95% confidence limits on the mean differences (dashed lines) as determined by bootstrap analysis. The inside semicircle represents the average of the mean differences for all off-dipole bins. The outside semicircle represents the expected mean angular difference $\bar{\xi}(60°)$ for a random and isotropic distribution of directions. (d) The mean precision parameter $\langle\alpha_{95}\rangle$. All angular differences are such that $\xi < 60°$; N-R symmetry imposed. Compare with non-Icelandic data in Figure 7.

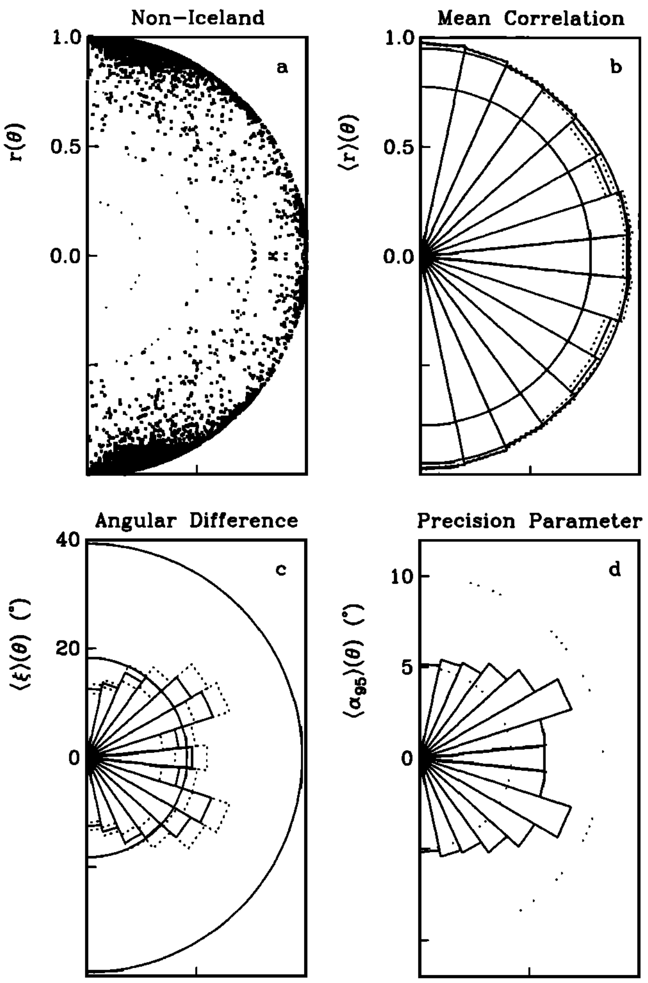


Figure 7. Same as Figure 6, except for non-Icelandic data.

Appendix B we show how to estimate statistically the effects of slightly erroneous directions on our correlation analysis. It turns out that differences in $\langle\alpha_{95}\rangle$ do not significantly affect our conclusions, and thus our observations appear to be fairly robust. Further confidence can be gained by examination of multiple subsets of the database, something we discuss below.

9. Correlation and VGP Latitude

To check *Hoffman*'s [1992] suggestion that transitional fields may at times assume quasi-stationary, dipolar, intermediate states, we examine the mean angular difference $\langle\xi\rangle$ between paleodirections from stratigraphically adjacent flows as a function of VGP latitude λ. For both the Icelandic data and the non-Icelandic data (Figure 8) we see a general increase in mean angular difference during transitional periods. Moreover, similar to what we saw with the off-dipole angle, there is a slight increase in the mean correlation when the VGPs fall near the equator. It is difficult to conclude that this variation of angular difference with VGP latitude actually corresponds to the clustering of directions that Hoffman observes, in part because Hoffman's clusters are actually fairly diffuse: For his Molokai record, Hoffman reports a clustering of VGPs at about −60° latitude; other records that he discusses show VGPs at latitudes nearer the equator (see his Figure 2). Interestingly, Hoffman's clusters tend to fall on the preferred American and Asian longitudes that *Laj et al.* [1991], on the basis of sedimentary data, suggest characterize transitional VGPs. Whether or not transitional VGPs fall along preferred longitudes is itself controversial, principally because the volcanic data exhibit a great deal of scatter and remain relatively few in number. *Prévot and Camps* [1993] and *Love* [1998, 1999] come to different conclusions on this matter, but both have examined databases significantly larger than that considered by Hoffman, and yet neither find any apparent clustering of midlatitude VGPs. Indeed, if a given transition shows a bilongitudinal distribution of VGPs, then this is incompatible with the intermediate dipolar states suggested by Hoffman.

10. Angular-Difference Cutoffs

In Figure 9 we show the anisotropy of the mean angular difference $\langle\xi\rangle$ for a variety of different angular-difference cutoffs, $\xi < \xi_c$. From this figure we see that the mean angular difference, particularly for midtransitional states, increases with increasing ξ_c. When ξ_c is large instead of capturing a measure of secular variation we are also partially measuring the inhomogeneous bimodal distribution of field directions. Obviously, angu-

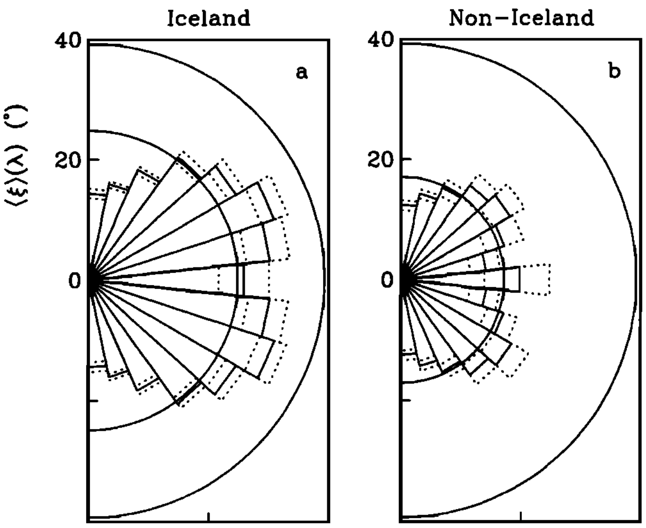


Figure 8. Anisotropy of the mean angular difference $\langle\xi\rangle$ as a function of VGP latitude λ for the (a) Icelandic data and (b) non-Icelandic data. The 95% confidence limits on the mean correlations (dashed lines) are determined by bootstrap analysis. The inside semicircle in each window represents the average of the mean angular differences for all bins. The outside semicircle represents the expected mean angular difference $\bar{\xi}(60°)$ for a random and isotropic distribution of directions. N-R symmetry is imposed. Compare with Figures 6c and 7c.

lar differences larger than (say) 90° probably represent long hiatuses in lava deposition, and we feel that our adoption of $\xi < \xi_c = 60°$ throughout most of this analysis represents a reasonable value for rough estimation of the secular variation.

11. Subsets of the Database

In Figure 10 we show the anisotropy of the mean angular difference $\langle\xi\rangle$ for lava flows of differing but younger ages groups, namely, 0-5 and 0-10 Myr. Our original motivation for considering lava flows as old as 20 Myr was simply to have as large a database as possible. Some of the data considered in this analysis have been corrected for tilt, and it is possible that there have been tectonic displacements for which there has been no accounting, particularly for the older sections. This could affect the directions, but, provided the intervening time between successive depositions is relatively short, it should not affect the (relative) angular differences. In Figure 10 we see that both the younger Icelandic and non-Icelandic data show a general increase in mean angular difference during transitional periods, usually with a slight decrease midtransition. In other

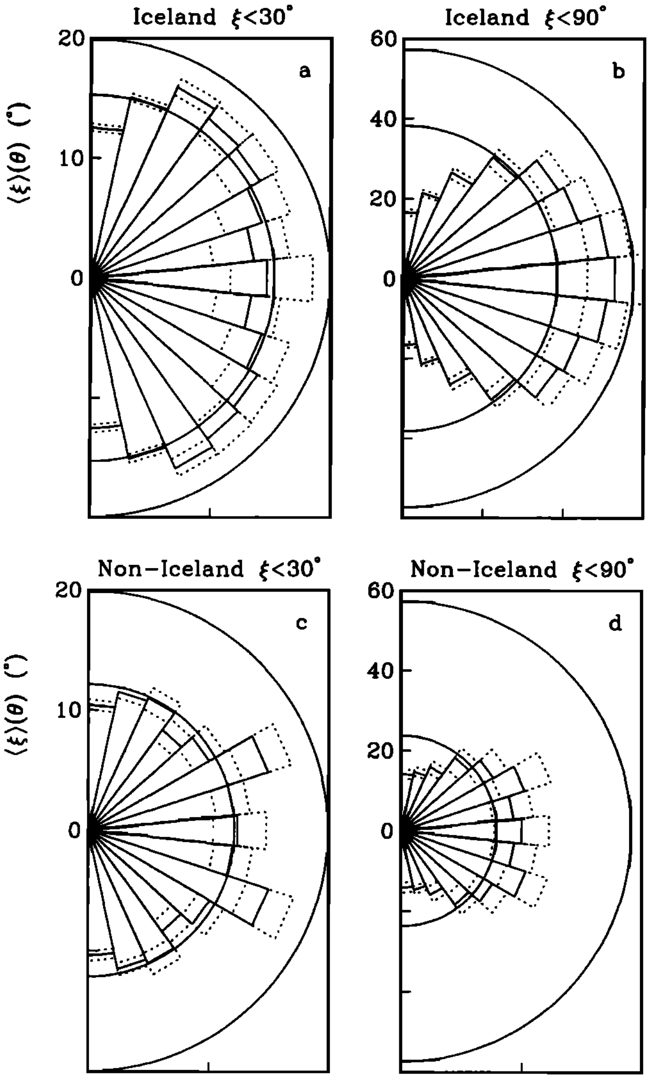


Figure 9. Anisotropy of the mean angular difference $\langle\xi\rangle$ as a function of off-dipole angle θ using different angular-difference cutoffs for the Icelandic data, (a) $\xi_c = 30°$ and (b) $\xi_c = 90°$, and, correspondingly, for the non-Icelandic data, (c) $\xi_c = 30°$ and (d) $\xi_c = 90°$. The 95% confidence limits on the mean correlations (dashed lines) are determined by bootstrap analysis. The inside semicircle in each window represents the average of the mean angular differences for all bins. The outside semicircle represents the expected mean angular difference $\bar{\xi}(\xi_c)$ for a random and isotropic distribution of directions. N-R symmetry is imposed. Compare with Figures 6c and 7c.

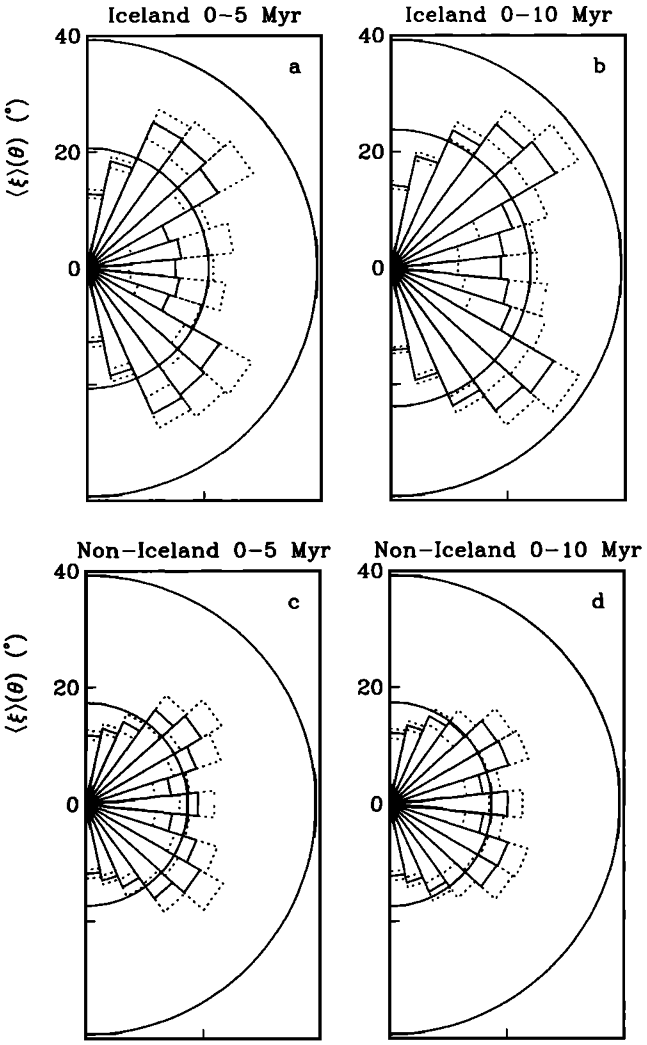


Figure 10. Anisotropy of mean angular differences $\langle\xi\rangle$ for Icelandic data from lava flows of various ages, all as functions of off-dipole angle θ: (a) 0-5 Myr, (b) 0-10 Myr, and, correspondingly, for the non-Icelandic data, (c) 0-5 Myr and (d) 0-10 Myr. The 95% confidence limits on the mean correlations (dashed lines) are determined by bootstrap analysis. The inside semicircle in each window represents the average of the mean angular differences for all bins. The outside semicircle represents the expected mean angular difference $\bar{\xi}(60°)$ for a random and isotropic distribution of directions. N-R symmetry is imposed.

words, our results appear to be relatively insensitive to smallish tectonic displacements.

Next we examine our database without supposing magnetic and geographical symmetries. Until now we have imposed a normal-reverse (N-R) symmetry on our correlation analysis, equations (13) and (14). Although there are good theoretical reasons for expecting secular variation (and therefore the mean angular difference) to be independent of the sign of the magnetic field, it is possible that reverse data could be adversely affected by overprinting of the modern field; see, for example, *McElhinny and McFadden* [1997]. In Figure 11 we see that our previous observations still hold: even without the imposition of normal-reverse symmetry, there is a general increase in angular difference during transitional periods with a slight decrease midtransition. As for geographical symmetry, generally speaking the dispersion of field directions decreases with increasing latitude, whilst the opposite holds for the dispersion of VGPs [*Cox*, 1970]. As we have remarked, such directional dispersion should not be confused with our correlation analysis. To check the sensitivity of our results on site latitude, we performed separate analyses for low and high-latitude sites. Once again, we see an increase in angular difference during transitional periods with a slight decrease midtransition.

In Figure 11 we also examine the importance of some of the data selection criteria. If for each individual direction we were to utilize stricter standards, namely, four or more magnetically cleaned samples per flow

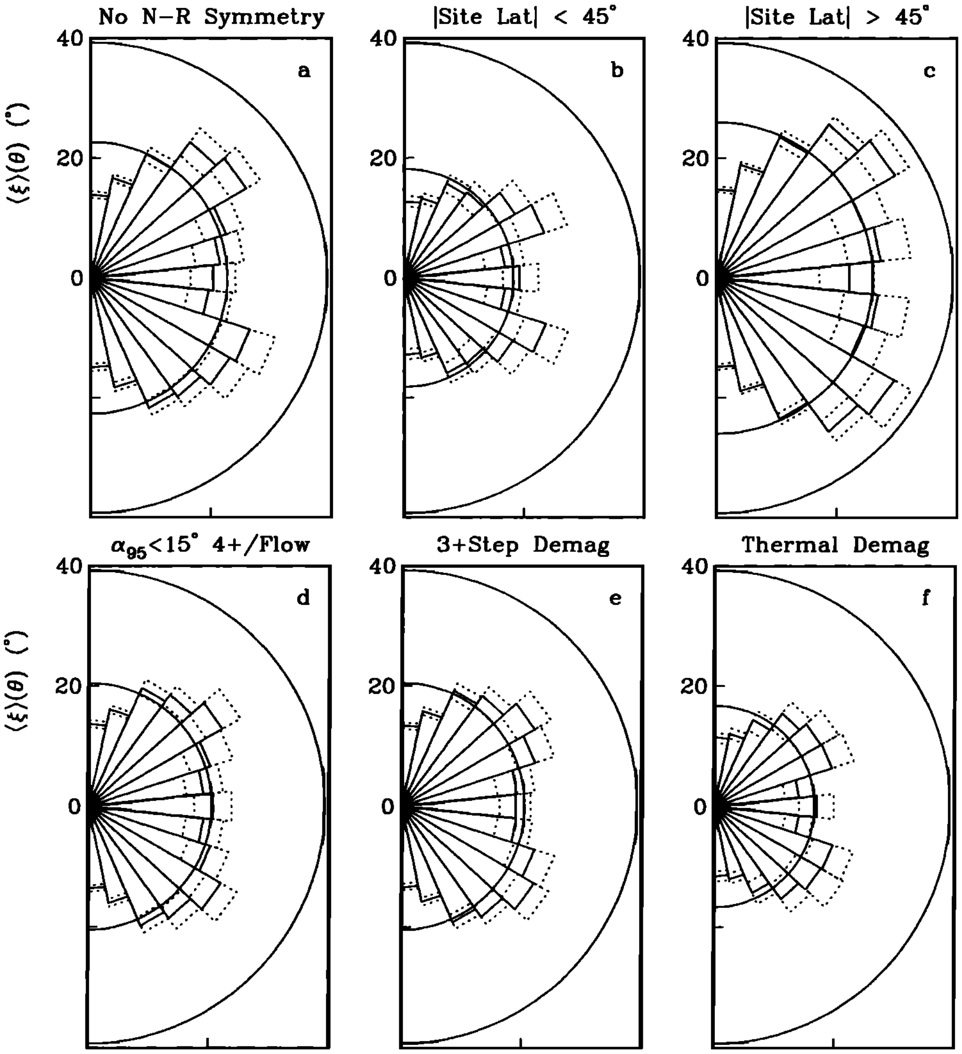


Figure 11. Anisotropy of mean angular differences $\langle\xi\rangle$ for all data, but with different symmetries and selection criteria, all as functions of off-dipole angle θ: (a) without N-R symmetry being imposed. (b) low-latitude sites $|\Lambda| < 45°$, (c) high-latitude sites $|\Lambda| > 45°$, (d) data based on four or more samples per flow and where $\alpha_{95} < 15°$, (e) data obtained by step-wise demagnetization with three or more steps, and (f) data obtained by thermal demagnetization. The 95% confidence limits on the mean correlations (dashed lines) are determined by bootstrap analysis. The inside semicircle in each window represents the average of the mean angular differences for all bins. The outside semicircle represents the expected mean angular difference $\bar{\xi}(60°)$ for a random and isotropic distribution of directions. N-R symmetry is imposed in all cases except 11a.

with $\alpha_{95} < 15°$, we see the familiar anisotropic increase in mean angular difference during transitional periods with a slight decrease midtransition. With respect to demagnetization methods, some of the data in our database were obtained by either blanket demagnetization or simple two-step demagnetization. If we restrict ourselves to data which have been demagnetized with three or more steps, we find that this does not dramatically affect our observations on the anisotropy of correlation. Finally, some researchers prefer thermal demagnetization methods, but many of the data considered in this analysis were obtained by alternating field (AF) demagnetization of rock samples. The subset of our database which has been obtained by thermal demagnetization is small, and yet it too shows an anisotropic increase in mean angular difference during transitional periods with a slight decrease midtransition. Taken as a whole, Figure 11 indicates that our conclusions are relatively insensitive to more stringent data selection criteria and small differences in laboratory methods.

12. Conclusions

Our conclusion, similar to *Love* [2000], that secular variation is enhanced (quiet) during transitional (nontransitional) periods, made on the basis of a statistical study of a large number of lava data, is qualitatively consistent with, and a generalization of, the conclusion of *Bogue and Coe* [1982]. They examined a sequence of lava flows recording two reversals; since they found little or no weathering, nor soil, between adjacent flows, they concluded that their flows could have been deposited closely in time, and since differences in the magnetic vector between stratigraphically adjacent flows were sometimes very large, they concluded that secular variation might be enhanced during polarity transitions. Without detailed knowledge of the dates of individual lava flows the interpretations of Bogue and Coe might be considered somewhat subjective. On the other hand, their conclusion that secular variation is enhanced during transitions is similar to that drawn by *Valet et al.* [1986], who examined a high-resolution sedimentary transitional record, and *Aundunsson and Levi* [1997], who examined a thick layer of slowly cooling basalt. We also note that *Glatzmaier and Roberts* [1995] found an enhancement of secular variation during their numerical simulation of a reversal.

Concerning the slight decrease in mean angular difference seen midtransition, which might reflect a decrease in secular variation, we express some cautious hesitation. That it seems to occur for VGPs falling near equatorial latitudes is not especially consistent with the suggestion of *Hoffman* [1992] that transitional fields assume quasi-stationary intermediate configurations which manifest themselves as midlatitude VGPs. It has, of course, been noted that similar consecutive field directions from relatively small databases can be due to rapid successive depositions of lava (clusters might be statistical accidents). Indeed, we have sought to dilute this effect by examining the correlation between literally thousands of stratigraphically adjacent magnetic vectors, a preponderance of data which should help to overcome the effects of volcanic eruptive variability.

We finish by noting some of the implications of this work for statistical modelling of paleosecular variation data. When we started this analysis, one of our intentions was to investigate the validity of the assumption, often made implicitly in statistical modelling, that volcanic data are independent; our initial prejudice was that analysis of the serial correlation of stratigraphically ordered lava data would not yield useful information. In fact, we have shown that serial correlation, which depends on the deviation from an axial dipole, is indicative of anisotropic secular variation. In the future one way to incorporate the information content of serially correlated volcanic data into statistical modelling would be to represent the volcanic record of secular variation by some sort of Markov process; see, for example, *Constable* [1990]. Ideally, one would also incorporate the information content provided by (the few) radiometric dates, along with allowance for their associated errors. Such a program would at least be an improvement over current approaches. Of course, that volcanic paleomagnetic data are not statistically independent, but are instead correlated, is symptomatic of continuous secular variation being sampled randomly and discontinuously with the deposition of each lava flow. In other words, statistical models are not so much descriptions of the Earth's magnetic field, but rather descriptions of the combined magnetic and volcanic system.

Appendix A: Notes on Data Sets

Most of the useful information about our database is summarized in Table 1. Here we mention some technical points relating to stratigraphy, dating and demagnetization.

Alaska, Wait Creek, and Castles, *Bingham and Stone* [1976]: W and C are N-N.

Amsterdam Island, *Watkins and Nougier* [1973]: Only flows 17, 18, 19 are from a stratigraphic section.

Arizona, Hackberry Mountain, *McKee and Elston* [1980]: Omit all sedimentary data. B27b-B9 (B8-T1) are older (younger) than 10 Myr; see Figure 2.

Arizona, Hackberry Mountain, *McKee and Elston* [1980]: Omit all sedimentary data. B27b-B9 (B8-T1) are older (younger) than 10 Myr; see Figure 2.

British Columbia, Mount Edziza, *Souther and Symons* [1974]; B1-B15 (A;B18-B53;C) are older (younger) than 5 Myr; see Figure 8.

British Columbia, Level Mountain, *Hamilton and Evans* [1983]: Ay-Ab (Bw-Bt) are older (younger) than 5 Myr; see Figure 2.

Easter Island, *Isaacson and Heinrichs* [1976]: Only flows 32, 33, 34, which come from a stratigraphic section, are considered; of these, 34 has $\alpha_{95} > 20°$.

Iceland, Bessastadaa, *McDougall et al.* [1976]; EQ1-EQ27;EW (EQ28-EQ45) are older (younger) than 5 Myr; see Table 3.

Iceland, Borgarfjördur, *Watkins et al.* [1977]: NP1-NP113 (NP115-NT112) are older (younger) than 5 Myr; see Table 1 of *McDougall et al.* [1977].

Iceland, Tröllaskagi, *Saemundsson et al.* [1980]: PA02-PC39 (PC40-PG60) are older (younger) than 10 Myr; see Figure 4.

Iceland, SR0-BX08, *McDougall et al.* [1984]: SR0-BD10 (BD12-BX08) are older (younger) than 10 Myr; see Figure 7.

Iceland, Langidalur, *Kristjánsson et al.* [1992]: TL1-33 were demagnetized with two steps; the remaining flows were demagnetized with three or more steps; see page 38.

Iceland, Snæfellsnes, *Kristjánsson and Jóhannesson* [1999]: HH01-HF21 (HF22-HA54) are older (younger) than 10 Myr; see Figure 4.

Japan, Kuju, *Nishida et al.* [1969]: Keep only those data described in Table 1 of *Sasajima and Maenaka* [1969] as stable.

Japan, Kyushu Kuju, *Nishida et al.* [1969]: Keep only those data described in Table 1 of *Sasajima and Maenaka* [1969] as stable.

Nevada, Lousetown, *Heinrichs* [1967]: *Roberts and Shaw* [1990] conclude that Heinrichs's measurements of flow F1 may be erroneous.

Norfolk, *Aziz-Ur-Rahman and McDougall* [1973]: Stratigraphic information on the many small sections is given in Figure 1.

Oregon, Steens Mountain, *Mankinen et al.* [1985], *Prévot et al.* [1985]: Measurements from flows A41 and A42 appear to record extremely rapid geomagnetic variations over their thicknesses, possibly during their thermal cooling, but this is controversial; omit measurements from A41 and A42. Directional groups not accepted.

Polynesia, Huahine, *Roperch and Duncan* [1990]: Some data do not come from stratigraphic sections. No clear stratigraphic relationship between small sections could be worked out (see page 2714). We do not use the composite section of the data in Table 2 (page 2722), nor do we accept directional groups.

Washington, Saddle Mountain, *Choiniere and Swanson* [1979]: OI1-EM1 (BC3-LM1) are older (younger) than 10 Myr; see Figure 2 of *Hooper et al.* [1979].

Appendix B: Corrections to Mean Correlations

Each paleomagnetic direction (θ, ϕ) considered here is the mean of paleomagnetic measurements taken from a set of samples from a given lava flow. However, each paleomagnetic direction is, of course, a somewhat erroneous estimate of the true magnetic direction (θ^0, ϕ^0). Ignoring possible bias in the paleomagnetic method, an ensemble of paleodirections would be scattered symmetrically about the true magnetic direction at the time of remanent acquisition. Let us assume that this distribution is described by the Fisherian probability density function:

$$f(\theta, \phi | \theta^0, \phi^0) = f(\mu) = \frac{\kappa}{4\pi \sinh \kappa} \exp(\kappa\mu). \qquad \text{(B1)}$$

the angle between (θ, ϕ) and (θ^0, ϕ^0) is $\cos^{-1}\mu$, so that

$$\mu = \cos\theta \cos\theta^0 - \sin\theta \sin\theta^0 \cos(\phi - \phi^0). \qquad \text{(B2)}$$

The width of the probability density function is measured by κ, which is related to α_{95} by

$$\cos\alpha_{95} \simeq 1 + \frac{\ln(0.05)}{\kappa}. \qquad \text{(B3)}$$

Now, the mean correlation of an ensemble of directional pairs (θ_1, ϕ_1) and (θ_2, ϕ_2), taken (say) from a pair of lava flows, is just

$$\langle r \rangle = \int\int f_1 f_2 \mu_{1,2} d\Omega_1 d\Omega_2, \qquad \text{(B4)}$$

where $d\Omega_i$ is an element of solid angle and where

$$f_i = f(\theta_i, \phi_i | \theta_i^0, \phi_i^0). \qquad \text{(B5)}$$

the angle between (θ_1, ϕ_1) and $(\theta_2, \phi_2)$is $\cos^{-1}\mu_{1,2}$, so that

$$\mu_{1,2} = \cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2). \qquad \text{(B6)}$$

Here, we do not have an ensemble of mean directions for each flow, but instead an ensemble of lava flows for which we have typically one mean direction from each flow. The mean correlation between stratigraphically adjacent lava flows is then given by

$$\langle r \rangle = \frac{1}{N} \sum_i \int\int f_i f_{i+1} \mu_{i,i+1} d\Omega_i d\Omega_{i+1}, \qquad \text{(B7)}$$

where N denotes the number of stratigraphic pairs.

To evaluate (B7) (A. Jackson, personal communication, 1999) we expand each probability density function in terms of Legendre polynomials:

$$f_i = \sum_l c_l^i P_l(\mu_i). \qquad \text{(B8)}$$

By the addition theorem for spherical harmonics,

$$P_l(\mu_i) = \sum_m Y_l^m(\theta_i, \phi_i) Y_l^m(\theta_i^0, \phi_i^0) \qquad \text{(B9)}$$

and

$$\mu_{i,i+1} = P_1(\mu_{i,i+1}) = \sum_m Y_1^m(\theta_i, \phi_i) Y_1^m(\theta_{i+1}, \phi_{i+1}), \qquad \text{(B10)}$$

where each spherical harmonic Y_l^m is Schmidt-normalized. After substituting into (B7) and rearranging we have

$$\langle r \rangle = \frac{1}{N} \sum_{ijklmn} c_j^i c_l^{i+1} Y_j^k(\theta_i^0, \phi_i^0) Y_l^m(\theta_{i+1}^0, \phi_{i+1}^0) \times$$
$$\int Y_j^k(\theta_i, \phi_i) Y_1^n(\theta_i, \phi_i) d\Omega_i \times$$
$$\int Y_l^m(\theta_{i+1}, \phi_{i+1}) Y_1^n(\theta_{i+1}, \phi_{i+1}) d\Omega_{i+1}. \qquad \text{(B11)}$$

By orthogonality

$$\int Y_j^k(\theta, \phi) Y_l^m(\theta, \phi) d\Omega = \frac{4\pi}{2l+1} \delta_{j,l} \delta_{k,m}, \qquad \text{(B12)}$$

so that (B11) reduces to

$$\langle r \rangle = \frac{1}{N} \left(\frac{4\pi}{3}\right)^2 \sum_i c_1^i c_1^{i+1} \mu_{i,i+1}^0, \qquad \text{(B13)}$$

where

$$c_1^i = \frac{3}{2}\int_{-1}^{1} f_i(\mu)\mu d\mu = \frac{3}{4\pi}\left(\frac{\kappa_i \coth\kappa_i - 1}{\kappa_i}\right) \qquad \text{(B14)}$$

and where

$$\mu^0_{i,i+1} = \sum_m Y_1^m(\theta_i^0, \phi_i^0) Y_1^m(\theta_{i+1}^0, \phi_{i+1}^0). \qquad \text{(B15)}$$

An approximation of equation (B13) is given by

$$\langle r\rangle \simeq \left[\frac{1}{N}\left(\frac{4\pi}{3}\right)^2 \sum_j c_1^j c_1^{j+1}\right]\left[\frac{1}{N}\sum_i \mu^0_{i,i+1}\right] \qquad \text{(B16)}$$

and since we seek the mean correlation between the true magnetic directions

$$\frac{1}{N}\sum_i \mu^0_{i,i+1} \simeq \langle r\rangle \left[\frac{1}{N}\left(\frac{4\pi}{3}\right)^2 \sum_j c_1^j c_1^{j+1}\right]^{-1}. \qquad \text{(B17)}$$

For our analysis here, however, this correction to $\langle r\rangle$ is very small; for our database it is much less than 1%. Thus we are confident that the correlations discussed here are not significantly affected by the slight differences in α_{95}.

Acknowledgments. We thank A. Jackson for useful discussions, and we thank Anonymous and R. Merrill for reviewing critically our manuscript. This work was supported by the Leverhulme Trust and a "Bourse Châteaubriand" from the French government.

References

Aundunsson, H., and S. Levi, Geomagnetic fluctuations during a polarity transition, *J. Geophys. Res.*, *102*, 20,259–20,268, 1997.

Aziz-Ur-Rahman, and I. McDougall, Palaeomagnetism and palaeosecular variation on lavas from Norfolk and Philip Islands, south-west Pacific Ocean, *Geophys. J. R. Astron. Soc.*, *33*, 141–155, 1973.

Bingham, D. K., and D. B. Stone, Palaeosecular variation of the geomagnetic field in the Aleutian Islands, Alaska, *Geophys. J. R. Astron. Soc.*, *28*, 317–335, 1972.

Bingham, D. K., and D. B. Stone, Evidence for geomagnetic field excursions and secular variation from the Wrangell volcanics of Alaska, *Can. J. Earth Sci.*, *13*, 547–554, 1976.

Bloxham, J., D. Gubbins, and A. Jackson, Geomagnetic secular variation, *Philos. Trans. R. Soc. London Ser. A*, *329*, 415–502, 1989.

Bogue, S. W., and R. S. Coe, Successive palaeomagnetic reversal records from Kauai, *Nature*, *295*, 399–401, 1982.

Bogue, S. W., and R. S. Coe, Transitional paleointensities from Kauai, Hawaii, and geomagnetic reversal models, *J. Geophys. Res.*, *89*, 10,341–10,354, 1984.

Brassart, J., E. Tric, J. P. Valet, and E. Herrero-Bervera, Absolute paleointensity between 60 and 400 ka from the Kohala Mountain (Hawaii), *Earth Planet. Sci. Lett.*, *148*, 141–156, 1997.

Brown, L., J. Pickens, and B. Singer, Matuyama-Brunhes transition recorded in lava flows of the Chilean Andes: Evidence for dipolar fields during reversals, *Geology*, *22*, 299–302, 1994.

Camps, P., and M. Prévot, A statistical model of the fluctuations in the geomagnetic field from paleosecular variation to reversal, *Science*, *273*, 776–779, 1996.

Camps, P., G. Ruffet, V. P. Shcherbakov, V. V. Shcherbakova, M. Prévot, A. Moussine-Pouchkine, L. Sholpo, A. Goguitchaichvili, and B. Asanidzé, Paleomagnetic and geochronological study of a geomagnetic field reversal or excursion recorded in Pliocene rocks from Georgia (Lesser Caucasus), *Phys. Earth Planet. Inter.*, *96*, 41–59, 1996.

Chauvin, A., P. Roperch, and R. Duncan, Records of geomagnetic reversals from volcanic islands of French Polynesia 2. Paleomagnetic study of a flow sequence (1.2-0.6 Ma) from the island of Tahiti and discussion of reversal models, *J. Geophys. Res.*, *95*, 2727–2752, 1990.

Chauvin, A., P. Y. Gillot, and N. Bonhommet, Paleointensity of the Earth's magnetic field recorded by two late quaternary volcanic sequences at the island of La Réunion (Indian Ocean), *J. Geophys. Res.*, *96*, 1981–2006, 1991.

Choiniere, S. R., and D. A. Swanson, Magnetostratigraphy and correlation of Miocene basalts of the northern Oregon coast and Columbia Plateau, southeast Washington, *Am. J. Sci.*, *279*, 755–777, 1979.

Coe, R. S., S. Grommé, and E. A. Mankinen, Geomagnetic paleointensities from excursion sequences in lavas on Oahu, Hawaii, *J. Geophys. Res.*, *89*, 1059–1069, 1984.

Constable, C. G., A simple statistical model for geomagnetic reversals, *J. Geophys. Res.*, *95*, 4587–4596, 1990.

Constable, C. G., and R. L. Parker, Statistics of the geomagnetic secular variation for the past 5 m.y., *J. Geophys. Res.*, *93*, 11,569–11,581, 1988.

Courtillot, V., and J. L. LeMouël, Time variations of the Earth's magnetic field: From daily to secular, *Annu. Rev. Earth Planet. Sci.*, *16*, 389–476, 1988.

Courtillot, V., and J. P. Valet, Secular variation of the Earth's magnetic field: From jerks to reversals, *C. R. Acad. Sci., Ser. II*, *320*, 903–922, 1995.

Cox, A., Latitude dependence of the angular dispersion of the geomagnetic field, *Geophys. J. R. Astron. Soc.*, *20*, 253–260, 1970.

Dagley, P., and E. Lawley, Palaeomagnetic evidence for the transitional behaviour of the geomagnetic field, *Geophys. J. R. Astron. Soc.*, *36*, 577–598, 1974.

Dagley, P., R. L. Wilson, J. M. Ade-Hall, G. P. L. Walker, S. E. Haggerty, T. Sigurgeirsson, N. D. Watkins, P. J. Smith, J. Edwards, and R. L. Grasty, Geomagnetic polarity zones for Icelandic lavas, *Nature*, *216*, 25–29, 1967.

Doell, R. R., Paleosecular variation of the Honolulu volcanic series, Oahu, Hawaii, *J. Geophys. Res.*, *77*, 2129–2137, 1972a.

Doell, R. R., Paleomagnetism of volcanic rocks from Niihau, Nihoa, and Necker Islands, Hawaii, *J. Geophys. Res.*, *77*, 3725–3730, 1972b.

Doell, R. R., and G. B. Dalrymple, Potassium-argon ages and paleomagnetism of the Waianae and Koolau volcanic series, Oahu, Hawaii, *Bull. Geol. Soc. Am.*, *84*, 1217–1242, 1973.

Doell, R. R., G. B. Dalrymple, R. L. Smith, and R. A. Bailey, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico, *Mem. Geol. Soc. Am.*, *116*, 211–248, 1969.

Efron, B., *The jackknife, the bootstrap and other resampling* *plans*, Soc. for Ind. and Appl. Math., Bristol, England, 1982.

Glatzmaier, G. A., and P. H. Roberts, A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, *Nature*, *377*, 203–209, 1995.

Goguitchaichvili, A. T., M. Prévot, and P. Camps, No evidence for strong fields during the R3-N3 Icelandic geomagnetic reversal, *Earth Planet. Sci. Lett.*, *167*, 15–34, 1999.

Grommé, C. S., T. A. Reilly, A. E. Mussett, and R. L. Hay, Palaeomagnetism and potassium-argon ages of volcanic rocks of Ngorongoro Caldera, Tanzania, *Geophys. J. R. Astron. Soc.*, *22*, 101–115, 1970.

Gubbins, D., and K. Zhang, Symmetry properties of the dynamo equations for paleomagnetism and geomagnetism, *Phys. Earth Planet. Inter.*, *75*, 225–241, 1993.

Hamilton, T. S., and M. E. Evans, A magnetostratigraphic and secular variation study of Level Mountain, northern British Columbia, *Geophys. J. R. Astron. Soc.*, *73*, 39–49, 1983.

Heinrichs, D. F., Paleomagnetism of the Plio-Pleistocene Lousetown formation, Virginia City, Nevada, *J. Geophys. Res.*, *72*, 3277–3294, 1967.

Herrero-Bervera, E., and R. S. Coe, Transitional field behavior during the Gilbert-Gauss and Lower Mammoth reversals recorded in lavas from the Waianae Volcano, O'ahu, Hawaii, *J. Geophys. Res.*, *104*, 29,157–29,173, 1999.

Hoffman, K. A., Dipolar reversal state of the geomagnetic field and core-mantle dynamics, *Nature*, *359*, 789–794, 1992.

Hooper, P. R., C. R. Knowles, and N. D. Watkins, Magnetostratigraphy of the Imnaha and Grande Ronde basalts in the southeast part of the Columbia Plateau, *Am. J. Sci.*, *279*, 737–754, 1979.

Hulot, G., and J. L. LeMouël, A statistical approach to the Earth's main magnetic field, *Phys. Earth Planet. Inter.*, *82*, 167–183, 1994.

Isaacson, L. B., and D. F. Heinrichs, Paleomagnetism and secular variation of Easter Island basalts, *J. Geophys. Res.*, *81*, 1476–1482, 1976.

Kono, M., Paleomagnetism of Pleistocene Usami Volcano, Izu Penninsula, Japan--Intensity of the Earth's magnetic field in geological time II, *J. Geomagn. Geoelectr.*, *20*, 353–366, 1968.

Kono, M., Intensity of the Earth's magnetic field in geological time III. Pleistocene and Pliocene data from Japanese volcanic rocks, *J. Geomagn. Geoelectr.*, *23*, 1–9, 1971.

Kono, M., Reliability of palaeointensity methods using alternating field demagnetization and anhysteretic remanence, *Geophys. J. R. Astron. Soc.*, *54*, 241–261, 1978.

Kristjánsson, L., New palaeomagnetic results from Icelandic Neogene lavas, *Geophys. J. Int.*, *121*, 435–443, 1995.

Kristjánsson, L., and H. Jóhannesson, Stratigraphy and paleomagnetism of the lava pile south of Ísafjaðardjúp, NW-Iceland, *Jökull*, *44*, 3–16, 1996.

Kristjánsson, L., and H. Jóhannesson, Secular variation and reversals in a composite 2.5 km thick lava section in central western Iceland, *Earth Planets Space*, *51*, 261–276, 1999.

Kristjánsson, L., and M. Sigurgeirsson, The R3-N3 and R5-N5 palaeomagnetic transition zones in SW-Iceland revisited, *J. Geomagn. Geoelectr.*, *45*, 275–288, 1993.

Kristjánsson, L., I. B. Fridleifsson, and N. D. Watkins, Stratigraphy and paleomagnetism of the Esja, Eyrarfjall and Akrafjall Mountains, SW-Iceland, *J. Geophys.*, *47*, 31–42, 1980.

Kristjánsson, L., H. Jóhannesson, J. Eiríksson, and A. I. Gudmundsson, Brunhes-Matuyama paleomagnetism in three lava sections in Iceland, *Can. J. Earth Sci.*, *25*, 215–225, 1988.

Kristjánsson, L., H. Jóhannesson, and I. McDougall, Stratigraphy, age and paleomagnetism of Langidalur, northern Iceland, *Jökull*, *42*, 31–44, 1992.

Kristjánsson, L., A. Gudmundsson, and H. Haraldsson, Stratigraphy and paleomagnetism of a 3-km-thick Miocene lava pile in the Mjóifjördur area, eastern Iceland, *Geol. Rundsch.*, *84*, 813–830, 1995.

Laj, C., A. Mazaud, R. Weeks, M. Fuller, and E. Herrero-Bervera, Geomagnetic reversal paths, *Nature*, *351*, 447, 1991.

Laj, C., A. Raïs, J. Surmont, P. Y. Gillot, H. Guillou, C. Kissel, and E. Zanella, Changes of the geomagnetic field vector obtained from lava sequences on the island of Vulcano (Aeolian Islands, Sicily), *Phys. Earth Planet. Inter.*, *99*, 161–177, 1997.

Laj, C., H. Guillou, N. Szérémeta, and R. Coe, Geomagnetic paleosecular variation at Hawaii around 3 Ma from a sequence of 107 lava flows at Kaena Point (Oahu), *Earth Planet. Sci. Lett.*, *170*, 365–376, 1999.

Love, J. J., Paleomagnetic volcanic data and geometric regularity of reversals and excursions, *J. Geophys. Res.*, *103*, 12,435–12,452, 1998.

Love, J. J., Statistical assessment of preferred transitional VGP longitudes based on paleomagnetic lava data, *Geophys. J. Int.*, *140*, 211–221, 1999.

Love, J. J., Geomagnetic secular variation as a function of intensity, *Philos. Trans. R. Soc. London Ser. A*, *in press*, 2000.

Mankinen, E. A., M. Prévot, C. S. Grommé, and R. S. Coe, The Steens Mountain (Oregon) geomagnetic polarity transition 1. Directional history, duration of episodes, and rock magnetism, *J. Geophys. Res.*, *90*, 10,393–10,416, 1985.

McDougall, I., and N. D. Watkins, Age and duration of the Réunion geomagnetic polarity event, *Earth Planet. Sci. Lett.*, *19*, 443–452, 1973.

McDougall, I., N. D. Watkins, and L. Kristjánsson, Geochronology and paleomagnetism of a Miocene-Pliocene lava sequence at Bessastadaa, eastern Iceland, *Am. J. Sci.*, *276*, 1078–1095, 1976.

McDougall, I., L. Kristjánsson, and K. Saemundsson, Magnetostratigraphy and geochronology of northwest Iceland, *J. Geophys. Res.*, *89*, 7029–7060, 1984.

McDougall, I., K. Saemundsson, H. Johannesson, N. D. Watkins, and L. Kristjánsson, Extension of the geomagnetic polarity time scale to 6.5 m.y.: K-Ar dating, geological and paleomagnetic study of a 3,500-m lava succession in western Iceland, *Geol. Soc. Am. Bull.*, *88*, 1–15, 1977.

McElhinny, M. W., and P. L. McFadden, Palaeosecular variation over the past 5 Myr based on a new generalized database, *Geophys. J. Int.*, *131*, 240–252, 1997.

McElhinny, M. W., and R. T. Merrill, Geomagnetic secular variation over the past 5 m.y., *Rev. Geophys. Space Phys.*, *13*, 687–708, 1975.

McElhinny, M. W., P. L. McFadden, and R. T. Merrill, The myth of the Pacific dipole window, *Earth Planet. Sci. Lett.*, *143*, 13–33, 1996.

McKee, E. H., and D. P. Elston, Reversal chronology from a 7.9- to 11.5-M.Y.-old volcanic sequence in central Arizona: Comparison with ocean floor polarity record, *J. Geophys. Res.*, *85*, 327–337, 1980.

Merrill, R. T., and P. L. McFadden, Paleomagnetism and the nature of the geodynamo, *Science*, *248*, 345–350, 1990.

Merrill, R. T., M. W. McElhinny, and D. J. Stevenson, Evidence for long-term asymmetries in the Earth's magnetic field and possible implications for dynamo theories, *Phys. Earth Planet. Inter.*, *20*, 75–82, 1979.

Nishida, J., M. Shimada, and S. Sasajima, Paleomagnetic study on some Pliocene and Pleistocene volcanic rocks in southwest Japan, *Mem. Fac. Sci. Kyoto Univ., Ser. Geol. Mineral.*, *34*, 1–8, 1969.

Ozima, M., I. Kaneoka, M. Kono, H. Kinoshita, K. Kobayashi, N. Ohnaka, and T. Nagata, Paleomagnetism and K-Ar ages of successive lava flows (2), *J. Geomagn. Geoelectr.*, *20*, 85–92, 1968.

Patel, J. P., and P. K. S. Raja, Paleomagnetic results from the Narosura and Magadi volcanics of Kenya, *Phys. Earth Planet. Inter.*, *19*, P7–P14, 1979.

Prévot, M., and P. Camps, Absence of preferred longitudinal sectors for poles from volcanic records of geomagnetic reversals, *Nature*, *366*, 53–57, 1993.

Prévot, M., and M. Perrin, Intensity of the Earth's magnetic field since Precambrian from Thellier-type palaeointensity data and inferences on the thermal history of the core, *Geophys. J. R. Astron. Soc.*, *108*, 613–620, 1992.

Prévot, M., E. A. Mankinen, R. S. Coe, and C. S. Grommé, The Steens Mountain (Oregon) geomagnetic polarity transition 2. Field intensity variations and discussion of reversal models, *J. Geophys. Res.*, *90*, 10,417–10,448, 1985.

Quidelleur, X., and J. P. Valet, Geomagnetic changes across the last reversal recorded in lava flows from La Palma, Canary Islands, *J. Geophys. Res.*, *101*, 13,755–13,773, 1996.

Quidelleur, X., J. P. Valet, V. Courtillot, and G. Hulot, Long-term geometry of the geomagnetic field for the last 5 million years: An updated secular variation database from volcanic sequences, *Geophys. Res. Lett.*, *21*, 1639–1642, 1994.

Raïs, A., C. Laj, J. Surmont, P. Y. Gillot, and H. Guillou, Geomagnetic field intensity between 70 000 and 130 000 years B.P. from a volcanic sequence on La Réunion, Indian Ocean, *Earth Planet. Sci. Lett.*, *140*, 173–189, 1996.

Roberts, N., and M. Fuller, Similarity of new palaeomagnetic data from Santa Rosa Mountains with those from Steens Mountain gives wide regional evidence for a two-stage process of geomagnetic field reversal, *Geophys. J. Int.*, *100*, 521–526, 1990.

Roberts, N., and J. Shaw, Secondary magnetizations cast doubt on exceptional palaeointensity values from the Lousetown Creek lavas of Nevada, USA, *Geophys. J. Int.*, *101*, 251–257, 1990.

Rolph, T. C., and J. Shaw, Variations of the geomagnetic field in Sicily, *J. Geomagn. Geoelectr.*, *38*, 1269–1277, 1986.

Roperch, P., and N. Bonhommet, Paleomagnetism of Miocene volcanism from south Syria, *J. Geophys.*, *59*, 98–102, 1986.

Roperch, P., and R. A. Duncan, Records of geomagnetic reversals from volcanic islands of French Polynesia 1. Paleomagnetic study of a polarity transition in a lava sequence from the island of Huahine, *J. Geophys. Res.*, *95*, 2713–2726, 1990.

Saemundsson, K., L. Kristjánsson, I. McDougall, and N. D. Watkins, K-Ar dating, geological and paleomagnetic study of a 5-km lava succession in northern Iceland, *J. Geophys. Res.*, *85*, 3628–3646, 1980.

Sanver, M., A palaeomagnetic study of quaternary volcanic rocks from Turkey, *Phys. Earth Planet. Inter.*, *1*, 403–421, 1968.

Sasajima, S., and K. Maenaka, Variation of the geomagnetic field intensity since the late Miocene, *J. Geophys. Res.*, *74*, 1037–1044, 1969.

Senanayake, W. E., M. W. McElhinny, and P. L. McFadden, Comparison between the Thelliers' and Shaw's palaeointensity methods using basalts less than 5 million years old, *J. Geomagn. Geoelectr.*, *34*, 141–161, 1982.

Sherwood, G. J., Paleomagnetism and magnetostratigraphy of Miocene volcanics in eastern Otago and Banks Peninsula, New Zealand, *N. Z. J. Geol. Geophys.*, *31*, 207–224, 1988.

Souther, J. G., and D. T. A. Symons, Stratigraphy and paleomagnetism of Mount Edziza volcanic complex, northwestern British Columbia, *Pap. Geol. Surv. Can.*, *73-32*, 1–48, 1974.

Szérémeta, N., C. Laj, H. Guillou, C. Kissel, A. Mazaud, and J. C. Carracedo, Geomagnetic paleosecular variation in the Brunhes period, from the island of El Hierro (Canary Islands), *Earth Planet. Sci. Lett.*, *165*, 241–253, 1999.

Tanaka, H., Paleointensity high at 9000 years ago from volcanic rocks in Japan, *J. Geophys. Res.*, *95*, 17,517–17,531, 1990.

Tanaka, H., A. Otsuka, T. Tachibana, and M. Kono, Paleointensities for 10-22 ka from volcanic rocks in Japan and New Zealand, *Earth Planet. Sci. Lett.*, *122*, 29–42, 1994.

Tanaka, H., M. Kono, and H. Uchimura, Some global features of palaeointensity in geological time, *Geophys. J. Int.*, *120*, 97–102, 1995a.

Tanaka, H., M. Kono, and S. Kaneko, Paleosecular variation of direction and intensity from two Pliocene-Pleistocene lava sections in southwestern Iceland, *J. Geomagn. Geoelectr.*, *47*, 89–102, 1995b.

Tanaka, H., K. Kawamura, K. Nagao, and B. F. Houghton, K-Ar ages and paleosecular variation of direction and intensity from Quaternary lava sequences in the Ruapehu Volcano, New Zealand, *J. Geomagn. Geoelectr.*, *49*, 587–599, 1997.

Tanguy, J. C., I. Bucur, and J. F. C. Thompson, Geomagnetic secular variation in Sicily and revised ages of historic lavas from Mount Etna, *Nature*, *318*, 453–455, 1985.

Valet, J. P., C. Laj, and P. Tucholka, High-resolution sedimentary record of a geomagnetic reversal, *Nature*, *322*, 27–32, 1986.

Valet, J. P., J. Brassart, X. Quidelleur, V. Soler, P. Y. Gillot, and L. Hongre, Paleointensity variations across the last geomagnetic reversal at La Palma, Canary Islands, Spain, *J. Geophys. Res.*, *104*, 7577–7598, 1999.

Watkins, N. D., and J. Nougier, Excursions and secular variation of the Brunhes epoch geomagnetic field in Indian Ocean region, *J. Geophys. Res.*, *78*, 6060–6068, 1973.

Watkins, N. D., L. Kristjánsson, and I. McDougall, A detailed paleomagnetic survey of the type location for the Gilsa geomagnetic polarity event, *Earth Planet. Sci. Lett.*, *27*, 436–444, 1975.

Watkins, N. D., I. McDougall, and L. Kristjánsson, Upper Miocene and Pliocene geomagnetic secular variation in the Borgarfjördur area of western Iceland, *Geophys. J. R. Astron. Soc.*, *49*, 609–632, 1977.

Watson, G. S., and R. J. Beran, Testing a sequence of unit vectors for randomness, *J. Geophys. Res.*, *72*, 5655–5659, 1967.

Zanella, E., and M. A. Laurenzi, Evidence for the Blake event in volcanic rocks from Lipari (Aeolian Archipelago), *Geophys. J. Int.*, *132*, 149–158, 1998.

Zhu, R., C. Liu, and K. K. Tshu, Paleointensity determined from Datong volcano lava and its geologic significance (*in Chinese*), *J. Grad. School, USTC*, *7*, 72–77, 1990.

Zhu, R., C. Liu, H. Wu, and B. Zhu, Transitional field behaviour for the Matuyama-Brunhes, *Sci. China, Ser. B, Engl. Transl.*, *34*, 1252–1257, 1991.

J. J. Love, School of Earth Sciences, University of Leeds, LS2 9JT, England, U.K. (e-mail: J.Love@earth.leeds.ac.uk)

(Received November 17, 1998; revised October 19, 1999; accepted November 4, 1999.)